THE WORLD NUCLEAR WASTE REPORT 2019

Focus Europe.

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This report would have not been possible without the generous support of a diverse group of friends and partners, in particular – listed in alphabetical order – the Altner-Combecher Stiftung, Bäuerliche Notgemeinschaft Trebel, Bund für Umwelt und Naturschutz (BUND), Bürgerinitiative Umweltschutz Lüchow-Dannenberg e.V., Climate Core and Green/EFA MEPs Group in the European Parliament, Heinrich-Böll-Stiftung (HBS) and its offices in Berlin, Brussels, Paris, Prague, and Washington DC, KLAR! Schweiz, Annette und Wolf Römmig, and the Swiss Energy Foundation. Thank you all for making this possible!

FOREWORD

More than 40 years ago in my home region, the forest near the village of Gorleben was chosen as the location for the German National Nuclear Waste Disposal Center. The site, which is now at the country's center but at the time was located directly on the border between East and West Germany, was meant to host all facilities for reprocessing, treatment, storage, and a deep geological repository. The company responsible (which has long since closed) intended to open the repository for spent fuel in the salt dome named Gorleben-Rambow in 1999.

After Fukushima, the German government decided to phase out nuclear energy for the second time. The experience of the nuclear catastrophe in Japan in 2011 also set in motion the review of the plans for the repository at Gorleben. After around 40 years of debating and fighting over Gorleben, the German government and parliament decided in favor of a new participatory site selection process for the repository for high-level nuclear waste. Looking back at the last 40 years and forward over the many decades until a repository might be available illustrates the difficulties for humankind to cope with the eternal legacies of nuclear energy. Considering the 40-year history of attempted disposal at Gorleben, and the many problems and challenges we now know about, it is unrealistic to expect the commissioning of a repository before the second half of this century.

Germany is not the only country in search of a suitable repository or facing difficult decisions about nuclear waste. For the last 15 years, as a member of the European Parliament, I followed the attempts at phasing out nuclear energy in and outside of the European Union. An important initiative came from Mycle Schneider, Paris, who suggested refuting the fairytale of a global nuclear renaissance. He and his team of authors release the yearly *World Nuclear Industry Status Report*, which proves that renewable energy is defeating nuclear power both because of tremendous risks of nuclear technology, and because of its high price. During the presentation of the status report in recent years, we had more and more questions about the absence of the nuclear waste issues, especially since these issues are also a factor for the costs of nuclear power. In the past years I also followed the European Commission's efforts to establish a better overview and a common framework for decommissioning, nuclear waste management, disposal, and financial provisions.

The recurring questions and the disappointing outcome of the European Commission's initiative motivated me to tackle this challenge with the idea of the **WORLD NUCLEAR WASTE REPORT (WNWR)**. In this first edition our team of European experts describes the technologies, strategies, preparatory processes, and financial provisions for disposal. We are convinced that information from national contexts should be both better accessible and comparable. In spite of international conventions on nuclear waste, even categories for waste classification differ from country to country.

Deep geological disposal is one of the most ambitious and most difficult tasks on earth.

The specific risks of nuclear waste require a safe enclosure for one million years. In addition, disposal strategies promise the possibility of retrieval and recovery at least for a limited period. The carelessness and the hubris in the nuclear industry and in pro-nuclear governments around the risks of nuclear waste have created mistrust rather than confidence among citizens. We face a difficult task ahead: the search for the best possible and most responsible solution. Addressing this task demands from society, politicians, citizens, science and industry to be more open and patient, money, and willing to admit mistakes and failures and to rethink approaches and strategies. This applies to all countries which have used nuclear energy or which are nuclear arms states.

This first edition of the **WNWR** covers a broad range of key issues on the topic and grew much longer than initially planned; yet it is obviously not fully comprehensive. Funding limits define its scope in part. But it is also due to the fact that we did not have access to full data and qualified authors for all countries. We plan the **WNWR** as a periodical that should be regularly updated, expanding on new themes and covering more countries in the future. Future issues could include important and under-researched issues like bottlenecks of interim storage and the comparison of immediate dismantling versus safe confinement after the final shutdown of nuclear power plants. The latter question emerges when large nuclear power plants are decommissioned without available storage and disposal capacities, as is the case in Germany. In all countries the amount of nuclear waste is growing, the capacities for storage are limited, final disposal is not yet available and the costs for managing the waste are rising. Some governments respond to this challenge by weakening standards for the industry, for example lowering the levels for when waste from decommissioning must be classified as radioactive. This clearance of fractions of the waste by free measurement should be also an issue of the next volume.

Among our current group of authors, the majority favors deep geological disposal for high-level waste if it is tied to clear and ambitious conditions for the site selection, exploration, and approval processes. There is a strong consensus that the current research and the scientific debate and exchange with politicians and involved citizens is severely insufficient. In spite of the support for deep geological disposal we are convinced that the debate on alternatives should not be avoided and that this issue deserves more attention, likely in the next volume. Currently there is no guarantee for the feasibility of the intended deep geological repositories. All in all, while the work on this first edition of the World Nuclear Waste Report is completed, I see many issues to be addressed in future volumes.

After working on nuclear waste issues and the German site selection process since 1975, I have to assume that it will take still several generations before a repository which is based on the best available solutions could be opened and operating. That is why I think it is our duty to pass to the next generation some experience and knowledge which we as critics of nuclear power have gained so far. It is the next generations which will bear the responsibility for finding a solution for nuclear waste, the eternal legacy of the short nuclear age. In the making of this report I see the cooperation of old and young as a valuable contribution to the generational change. A critical debate and reflection must be integrated part of the search for the best available and feasible solution for disposal of nuclear waste. The process must always be focused on solutions. We can phase out nuclear power, but we cannot phase out the nuclear waste and its eternal risks.

My thanks and appreciations go to all our authors, contributors and all those who supported us with work, knowledge, and funds.

Dickfeitzen, Wendland, not far from Gorleben in July 2019
REBECCA HARMS

ACKNOWLEDGMENTS

The **WORLD NUCLEAR WASTE REPORT (WNWR)** is a common project by a group of renowned experts who want to draw more attention to radioactive waste as a significant and growing challenge with no long-term solutions yet available. The project was initiated by Rebecca Harms, and the original outline was produced by Wolfgang Neumann, Mycle Schneider and Gordon MacKerron.

The core team of the **WNWR** project (Rebecca Harms, Mycle Schneider, Arne Jungjohann, and Anna Turmann) has been working since mid-2018 to win partners and raise funds for the project, to identify contributors, and to publish the report. Rebecca Harms took on the overall project lead. Arne Jungjohann served as the lead editor and project coordinator. Anna Turmann provided invaluable coordination, organization, editing, and budget planning. Mycle Schneider and Gordon MacKerron contributed effective and thoughtful advice in shaping the project.

We are very grateful for the excellent work delivered by the contributors, a diverse group of international experts, who each drafted one or more chapters: Manon Besnard, Marcos Buser, Ian Fairlie, Gordon MacKerron, Allison Macfarlane, Eszter Matyas, Yves Marignac, Edvard Sequens, Johan Swahn, and Ben Wealer. *A list of bios* can be found in the back of the report.

The **WNWR** greatly benefitted from partial or comprehensive proofreading, edits and comments by Andrew Blowers, Craig Morris, Mycle Schneider, Marcos Buser, Gordon MacKerron, Johan Swahn, and Markku Lehtonen. Silvia Weko served as an invaluable help with precise proofreading, editing tables and footnotes, and developing the author styleguide.

We would like to thank the Berlin-based Agency for Renewable Energies and in particular Andra Kradolfer for developing the design and the successful implementation of graphs and tables.

The **WNWR** project's website is *www.worldnuclearwastereport.org* and was designed by Arne Jungjohann. It includes more information and possible future updates.

The **WNWR** contains a very large amount of factual and numerical data. While we do our utmost to verify and double-check, nobody is perfect. The contributors and editors are grateful for corrections and suggested improvements (*info@worldnuclearwastereport.org*).

HOW TO CITE THIS REPORT:
The World Nuclear Waste Report. Focus Europe. 2019. Berlin & Brussels.
www.worldnuclearwastereport.org

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KEY INSIGHTS

WASTE MANAGEMENT CONCEPTS

- **No country in the world has a deep geological repository for spent nuclear fuel in operation.** Finland is the only country currently constructing a permanent repository.

- **Despite multiple failed selection procedures and abandoned repositories, a preference for geological disposal remains.** There is a strong consensus that the current state of research and exchange with civil society is inadequate for the challenges faced.

- With deep geological repositories not available for decades to come, **the risks are increasingly shifting to interim storage facilities which are running out of capacity:** for example, storage capacity for spent fuel in Finland has reached 93 percent saturation.

QUANTITIES OF NUCLEAR WASTE

- **Over 60,000 tons of spent nuclear fuel are in storage across Europe** (excluding Russia and Slovakia), most of which in France. Spent nuclear fuel is considered high-level waste and makes up the vast bulk of radioactivity. As of 2016, 81 percent of Europe's spent fuel has been moved into wet storage, which comes with its own safety risks.

- **Around 2.5 million m^3 of low- and intermediate-level waste has been generated in Europe.** Around 20 percent of this waste (0.5 million m^3) has been stored; 80 percent (close to 2 million m^3) has been disposed of.

- Decomissioning Europe's reactors **may generate at least another 1.4 million m^3 of low- and intermedaite level waste.**

- **Over its lifetime, European nuclear reactors may produce around 6.6 million m^3 of nuclear waste.** If stacked in one place, this would fill up a football field 919 meters high, 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai. Four countries account for over 75 percent of this waste: France (30 percent), the UK (20 percent), Ukraine (18 percent), and Germany (8 percent).

- Apart from Russia, which is still produces uranium, **Germany and France have the largest inventory of nuclear waste from uranium mining in Europe.**

KEY INSIGHTS

COSTS AND FINANCES

- **Governments do not apply the polluter-pays-principle consistently.** While operators are liable for the costs of managing, storing, and disposing of nuclear waste, costs may end up being borne by taxpayers.

- **Governments fail to properly estimate the costs for decommissioning, storage, and disposal of nuclear waste** due to underlying uncertainties. Many governments base their cost estimates on overly optimistic discount rates and outdated data, leading to serious funding gaps for waste management costs.

- **Overall, no country has both estimated costs precisely and closed the gap between secured funds and cost estimates.**

ORIGINS AND CLASSIFICATIONS

- **Countries differ significantly in how they define and categorize nuclear waste and in how they report about generated amounts of nuclear waste.** All countries publish regularly information, yet not all report in a thorough way.

- Despite international efforts to establish common safety principles and practices, such **inconsistencies remain and make comparison very complex.** The different national approaches reflect a lack of coherency in how countries manage nuclear waste.

RISKS FOR THE ENVIRONMENT AND HUMAN HEALTH

- **Nuclear waste constitutes a health hazard** due to routine gaseous and liquid waste emissions from nuclear facilities and the global collective doses from reprocessing.

- **Reprocessing of spent nuclear fuel poses increased challenges,** including proliferation risks, high exposures to humans, and contamination of the environment.

- **Overall, there is a lack of comprehensive, quantitative and qualitative information on risks associated with nuclear waste.**

EXECUTIVE SUMMARY

The **WORLD NUCLEAR WASTE REPORT (WNWR)** shows that governments around the world have been struggling for decades to develop and implement comprehensive nuclear waste management strategies. Much of the task will fall onto future generations.

WASTE MANAGEMENT CONCEPTS

More than 70 years after the start of the nuclear age, no country in the world has a deep geological repository for spent nuclear fuel in operation. Finland is the only country that is currently constructing a permanent repository for this most dangerous type of nuclear waste. Besides Finland, only Sweden and France have de facto determined the location for a high-level waste repository in an early confinement process. The US is operating the Waste Isolation Pilot Project (WIPP). However, this repository is only used for long-lived transuranic waste from nuclear weapons, not for spent nuclear fuel from commercial reactors.

Despite multiple examples of failed selection procedures and abandoned repositories, current national and international governance show a preference for geological disposal. This requires clear and ambitious conditions for the site selection, exploration, and approval processes. Still, there is no guarantee for the feasibility of deep geological disposal. This is why the process of searching for such repositories must be implemented with extraordinary care on the basis of industrial feasibility and accompanied by appropriate monitoring. Some scientists consider that monitored, long-term storage in a protected environment is more responsible, much faster to achieve and should therefore be implemented. Overall there is a strong consensus that the current state of research and scientific debate and exchange with politicians and involved citizens is not adequate for the magnitude of the challenge.

The conditioning, transport, storage and disposal of nuclear waste constitute significant and growing challenges for all nuclear countries. These developments show that **governments and authorities are under pressure to improve the management of interim storage and disposal programs.** Accordingly, standards must be implemented for the governance of the programs, including planning quality and safety, quality assurance, citizen participation and safety culture.

Interim storage of spent nuclear fuel and high-level waste will continue for a century or more. With deep geological repositories not available for decades to come, the **risks are increasingly shifting to interim storage.** The current storage practices for spent nuclear fuel and other easily dispersible intermediate- and high-level waste forms were not planned for the long-term. These practices thus represent a growing and particularly high risk, especially when other options are available (solidification, dry storage) in hardened facilities. Extended storage of nuclear waste increases risks today, adds billions in costs, and shifts these burdens to future generations.

QUANTITIES OF NUCLEAR WASTE

European countries have produced several million cubic meters of nuclear waste (not even including uranium mining and processing wastes). By the end of 2016, **France, the United Kingdom and Germany were Europe's biggest producers of nuclear waste** along the nuclear fuel chain.

Over 60,000 tons of spent nuclear fuel are stored across Europe (excluding Russia and Slovakia), most of which in France. Within the EU, France accounts for 25 percent of the current spent nuclear fuel, followed by Germany (15 percent) and the United Kingdom (14 percent). Spent nuclear fuel is considered high-level waste. Though present in comparably small volumes, it makes up the vast bulk of radioactivity. In the UK, for instance, high-level waste amounted to less than 3 percent of nuclear waste's volume, but almost 97 percent of the inventory's radioactivity. Most of spent fuel has been moved into cooling pools (so-called wet storage) to reduce heat and radioactivity. As of 2016, 81 percent of Europe's spent nuclear fuel was in wet storage. It would be safer to transfer the spent nuclear fuel into dry storage in separate facilities. A large share of the stored spent nuclear fuel in France and the Netherlands is planned to be reprocessed. Most other European nuclear countries (Belgium, Bulgaria, Germany, Hungary, Sweden, Switzerland, and most recently the UK) have indefinitely suspended or terminated reprocessing. Not all countries report about the quantities of spent fuel that have been reprocessed. In most cases only vitrified high-level waste from reprocessing is reported. The same accounts for the vast amounts of reprocessed uranium, plutonium, intermediate-level waste, and spent mixed oxide fuel (MOX) that requires an extensive additional intermediate storage period.

Around 2.5 million m³ of low- and intermediate-level waste has been generated in Europe (excluding Slovakia and Russia). Around 20 percent of this waste (0.5 million m³) has been stored across Europe, waiting for final disposal. This amount is constantly increasing with no full disposal route anywhere. Around 80 percent of this waste (close to 2 million m³) has been disposed of. However, this does not mean that the waste is successfully eliminated for the coming centuries. For instance, the Asse II disposal site in a former salt mine in Germany suffers from continuous inflow of groundwater. The 220,000 m³ of mixed disposed waste and salt need to be retrieved, which is a complex and costly task. The quantities are now five times the original amount of waste due to the mixture of salt and radioactive waste. Therefore, the term final disposal should be used with caution.

The decommissioning of nuclear facilities will create additional very large amounts of nuclear waste. Exlcuding fuel chain facilities, **Europe's power reactor fleet alone may generate at least another 1.4 million m³ of of low- and intermediate level waste from decommissioning.** This is a conservative estimate as decommissioning experiences are scarce. As of 2018, 142 nuclear power plants were in operation in Europe (excluding Russia and Slovakia).

The ongoing generation of nuclear waste and the upcoming decommissioning of nuclear facilities poses an increasing challenge, because **storage facilities in Europe are slowly running out of capacity, especially for spent nuclear fuel.** For example, storage capacity for spent fuel in Finland has reached already 93 percent saturation. Sweden's decentralized storage facility CLAB is at 80 percent saturation. However, not all countries report on saturation levels of storage capacities, making a complete overview impossible.

Over its lifetime, **the European nuclear reactor fleet is estimated to produce around 6.6 million m³ of nuclear waste** (excluding Russia and Slovakia). If stacked in one place, this would fill up a football field 919 meters high, 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai. The calculation includes waste from operation, spent nuclear fuel, and reactor decommissioning. This estimate and the ones above are based on conservative assumptions. The actual quantities of nuclear waste in Europe are likely higher. **With a share of 30 percent, France would be Europe's greatest producer of nuclear waste, followed by the UK (20 percent), the Ukraine (18 percent), and Germany (8 percent).** These four countries account for more than 75 percent of the European nuclear waste.

Apart from Russia, which is still an active producer of uranium, **Germany and France have the largest inventory of nuclear waste from uranium mining in Europe.** Officially, the former French uranium mining industry generated 50 million tons of mining residues, but independent experts estimate that it is much higher. The former German Democratic Republic (GDR) mined much larger quantities of uranium ore than France. The mining legacies comprise some 32 km^2 of facility areas, 48 heaps with a volume of low active rocks of 311 million m^3 and four tailing ponds holding a total of 160 million m^3 of radioactive sludge. Today, the EU imports most uranium, creating large amounts of nuclear waste outside of Europe.

COSTS AND FINANCES

Nearly every government claims to apply the polluter-pays-principle, which makes operators liable for the costs of managing, storing, and disposing of nuclear waste. In reality, however, **governments fail to apply the polluter-pays-principle consistently.** Most countries enforce it only on decommissioning, although there are some cases where the government takes over the liability for decommissioning (for example, for the reactors in former East Germany). Bulgaria, Lithuania, and the Slovak Republic receive EU support for decommissioning in exchange for having closed their older Soviet-era nuclear power plants. Most countries do not enforce the polluter-pays-principle for the disposal costs of nuclear waste. For this, national authorities more or less end up assuming liability as well as the responsibilities for long-term waste management and disposal. The operator is, however, required to contribute to financing the long-term costs. Even in countries in which the polluter-pays-principle is a legal requirement, it is applied incompletely. For instance, a nuclear power plant operator will not be held financially liable for any problems arising once a final disposal facility is closed; this is the case for the German Asse II disposal facility, where the retrieval of large amounts of waste has to be paid for by taxpayers.

Governments fail to properly estimate the costs for decommissioning, storage, and disposal of nuclear waste. All cost estimates have underlying uncertainties due to long time-scales, cost increases, and estimated discounting (fund accumulation) rates. A major reason for the uncertainty is the lack of experience in decommissioning and waste disposal projects in particular. Only three countries, the US, Germany and Japan, have completed decommissioning projects including full dismantling and thus generated data. As of mid-2019, of 181 closed power reactors in the world, only 19 had been fully decommissioned, of which only 10 to “green field”. But even these limited experiences show a wide range of uncertainty, up to a factor of five. In the US, decommissioning costs varied between reactors from US$280/kW to US$1,500/kW. In Germany, one reactor was decommissioned for US$1,900/kW, another one for US$10,500/kW.

Many governments base their cost estimates on outdated data. Many countries reviewed here such as France, Germany, and the US base their estimates on studies from the 1970s and 1980s, rather than on the few existing real-data cases. Using outdated data, in most cases drawn up by operators, industry, or state agencies, likely leads to low-cost estimates and overly optimistic conclusions.

Many governments apply overly optimistic discount rates. One key factor leading to the underestimation of the costs for decommissioning and nuclear waste management is the systematic use of overly optimistic discount rates. A fundamental aspect of funding decommissioning and waste management is the expectation that the funds will grow over time. In Germany, for instance, the funds of €24 billion set aside for all waste management-related activities are expected to grow nearly fourfold to €86 billion by 2099. The discount rates employed range widely, and not all countries calculate cost increases, although it is likely that costs will increase faster than the general inflation rates.

In order to guarantee the availability of sufficient funding for decommissioning, waste management and disposal, the financing schemes need to create secure holding conditions for the funds (“ring-fencing”). They also need to make sure that the resources set aside are sufficient to cover the real costs. Some countries fulfill one condition but fail on the other.

Countries differ significantly on how they plan the financing of nuclear waste management, storage, and disposal. Not all nuclear countries require decommissioning funds to be managed externally and segregated from the operator or licensee. Decommissioning is in some cases still financed through internal segregated and restricted funds, although the money for long-term waste management is managed externally in most countries. Financing decommissioning and storage is complex; in most cases, multiple funding systems are in place in one country.

In light of different national approaches, governments do not always define what “decommissioning” includes. Nuclear waste management is an important aspect of decommissioning, as is spent fuel management. But both are not always defined under “decommissioning”, making it hard to compare costs across different countries. **The processes of decommissioning, storage, and disposal are heavily interlinked. That is why an integrated external segregated and restricted fund seems to be the most suitable approach to finance the future costs for these processes.** Only a few countries have opted for this solution, notably Sweden, the UK, and Switzerland; although, Switzerland has two funds, one for decommissioning and one for waste management. **No country has secured the complete financing of decommissioning, storage, and disposal of its nuclear waste.** Doing so will be a challenge for all countries using nuclear power.

Today, no country has both estimated costs precisely and closed the gap between secured funds and cost estimates. In most cases, only a fraction of the funds needed has been set aside. For instance, Sweden has set aside funds for decommissioning and waste management of two thirds of the estimated costs so far, the United Kingdom less than half for its operational reactors, and Switzerland not even a third. The same can be observed of funding waste disposal. France and the US have set aside funds for disposal that would cover only around a third of the estimated costs. As an increasing number of reactors are closing ahead of schedule due to unfavorable economic conditions, the risk of insufficient funds is increasing. These early closures, shortfalls in funds, and rising costs are pushing some nuclear power plant operators to delay other closures and decommissioning in order to build up additional funds. Countries are also considering ways to enable facilities to recover their costs through higher fees, subsidized prices and lifetime extensions, for instance in the US and Japan.

ORIGINS AND CLASSIFICATIONS

Countries differ significantly in how they define nuclear waste. They differ in whether spent nuclear fuel and some of its separated products (plutonium and reprocessed uranium) are considered waste or a resource. For instance, spent fuel and the plutonium it contains qualify as waste in most countries because of the hazardous nature and the high costs of plutonium separation and use. However, France defines plutonium as a potential resource and requires reprocessing by law. Reprocessing both postpones the waste issue and makes it more complex and expensive.

Countries differ significantly in how they categorize nuclear waste. No two countries have identical systems. Germany differentiates only between heat-generating and other waste. The UK uses the level of radioactivity to classify its waste. France and the Czech Republic consider both, the level of radioactivity and the time period of radioactive decay (half-life). The US system differs fundamentally from that of European countries in that it bases classification on the origins of waste, not its characteristics.

Countries differ significantly in how they report about generated amounts of nuclear waste. All countries publish regularly information on the amount of waste they produce and associated management schemes. Yet not all countries report in a thorough way. In some cases, the reported information cannot be used to estimate volumes (such as Slovakia). Some country reports (such as the Dutch and the Belgian) lack an up-to-date inventory of spent nuclear fuel. Russia gives little information on the classification and state of its nuclear waste inventory.

These differences and inconsistencies of how countries define, categorize and report about nuclear waste makes gathering data and comparing countries very complex. The different national approaches reflect a lack of coherency in how countries manage nuclear waste. They occur in the face of international attempts to establish common safety principles and creating a peer review process of country practices. The International Atomic Energy Agency (IAEA) provides a broad framework of classification for nuclear waste. The 2001 Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management constitutes a default position for many countries, however, but with largely differing implementation practices. With the 2011 Euratom Directive, the EU attempted to harmonize waste classification systems for its member states, but with limited success.

RISKS FOR THE ENVIRONMENT AND HUMAN HEALTH

Nuclear waste constitutes a health hazard for several reasons. First are the reported health impacts from routine gaseous and liquid waste emissions from nuclear facilities. Second are the very large global collective doses from reprocessing. And third is the unsatisfactory and unstable condition of much of the nuclear waste already created. High-level waste (HLW) in the form of spent nuclear fuel and vitrified waste from reprocessing contains more than 90 percent of the radioactivity in nuclear waste. However, there is no fully operational HLW final disposal site in the world. The continued practise of storing spent nuclear fuel for long periods in pools at nuclear power plants (wet storage) constitutes a major risk to the public and to the environment. **Reprocessing of spent nuclear fuel in particular creates more accessible and dispersible forms of highly dangerous radioactive wastes, and poses increased challenges,** including proliferation risks, high exposures to workers and the public, and radioactive contamination of the environment.

Information is limited to properly assess risks from nuclear waste and develop hazard rankings. Only a few countries publish information, for example, on nuclide inventories in wastes. National governments or state agencies are primarily responsible for collecting and disseminating such data. This data is needed to properly assess the potential causal relationship between exposures and health effects. So far, no comprehensive hazard scheme exists for the radionuclides in nuclear waste.

There is a lack of comprehensive, high quality studies to assess risks from nuclear waste. Risks may be derived from epidemiological studies, but the few specific ones that exist are of limited quality. Some studies suggest increased cancer rates, for example, but are individually too small to give statistically significant results. Meta-analyses could combine smaller studies to generate larger datasets, which could produce statistically significant findings. However, meta-analyses on the health impacts of nuclear waste are notable for their virtual absence. In addition, in order to assess risks, it is also necessary to measure doses accurately. Overall, the analysis reveals an astonishing lack of quantitative and qualitative information on risks associated with nuclear waste.

COORDINATOR NOTE ON METHODOLOGY AND OUTLOOK

The **World Nuclear Waste Report (WNWR)** provides an international comparison how countries manage nuclear waste, outlining their current status and historical trends. With its focus on Europe, it begins filling a significant research gap. Outside of Europe, there is even more variation of practices by operators and governments in dealing with the challenge of nuclear waste. Social, political, technical, and financial challenges on the way to finding a sound long-term solution for these particular problem wastes are high.

As this is the first of its kind, the report faced many hurdles in its aim to provide a meaningful overview based on a large amount of complete factual and numerical data. Not only do countries differ significantly how they define nuclear waste, how they classify its different types, and how they report about its generated amounts. The research also revealed a lack of data, faced language barriers, varying uses of terminology in countries, and inconsistencies in sources. All of this makes the assessment highly complex.

To overcome these hurdles and to avoid errors, the project team developed a specific quality management approach for contributors, editors, and proofreaders. Elements included a workshop in Brussels (February 2019), developing an author stylesheet (including terminology), developing a template for country chapters, and implementing a thorough review process with several feedback loops. Each chapter has been drafted by a single author with a specific expertise on the topic; some authors have drafted more than one chapter. However, the chapters are not attributed to individual authors to ensure a high-quality editorial process. Each chapter draft went through a four-stage review process:

- an initial editing by the lead editor and two more persons from the project team;
- a cross-chapter review by the lead editor;
- an overall review of the full text by the lead editor, by three other members of the project team, and by two external proofreaders;
- and a final review to develop the executive summary.

Producing the report has been a tremendous task of more than a dozen experts in this field over the course of one and a half years. It allowed for the text to improve significantly over time. The authors, editors, and proofreaders have done their utmost to verify and double-check. However, this intense process does not guarantee that the report is free of errors. In case there are, we are grateful for corrections and suggested *improvements*.

This first edition of the **WNWR** aims at laying the groundwork for future research on the topic. New questions have come up, and some should be addressed in the next edition of the report, such as the risks that the extended use of unsuitable interim storage poses and the foreseeable lack of capacities for interim storage, proliferation, the threat of terrorism and other security issues when assessing the risk of nuclear power, the practice of uranium mining, the clearance of fractions of the waste by free measurement, and the role of public participation in site selection processes. The next edition could also expand its geographical scope to other nuclear countries. Among them are Canada, China, Finland, Japan, Russia, South Korea, Spain, and Ukraine.

1 INTRODUCTION

No country in the world has a final disposal site for high-level nuclear waste in operation yet; Finland is the only country that is currently constructing a permanent repository for this most dangerous type of radioactive waste. Most countries have yet to develop and implement a functioning waste management strategy for all kinds of nuclear waste. For instance, after spending four decades on exploring one site, Germany has just started over with a completely new search process for finding a location to bury its most radioactive waste. The French government has unilaterally opted for a deep geological disposal in northeastern France, but since then public protests will not stop. In Sweden, courts rejected the technical concept of the operator and put the seemingly ready site and storage plan on hold.

> *After more than 70 years of using nuclear power for electricity generation, large amounts of nuclear waste have accumulated worldwide. How much of it and what exact types remains unknown.*

A first glance reveals that governments worldwide have not only been struggling to develop waste management strategies, but also differ widely on their approaches: how to determine a site for a final repository, how to classify nuclear waste, which safety standards to require from operators, and how to secure funding to cover the ever-growing costs.

With reactors across the world approaching the end of their lifetimes and many countries phasing out nuclear power—whether by active policy or "organically" through non-renewal—decommissioning and dismantling of nuclear facilities will become increasingly important issues entailing additional challenges in terms of nuclear waste management. The decommissioning of a single reactor takes almost 20 years on average, but in many cases even longer. It is clear that this process will produce additional large volumes of radioactive waste. In absence of final disposal sites, most of the spent nuclear fuel and other high-level waste must be stored for several decades, challenging the safety and security requirements for intermediate storage facilities and causing much higher costs than previously estimated.

In short, there is a lack of understanding about where countries around the world stand in trying to address the complex challenges that nuclear waste management and disposal poses. This report tries to change that.

The **WNWR** aims to make a substantial contribution to understanding nuclear waste challenges for countries around the world. It does so by describing national and international classification systems, the risks posed by specific radioactive waste forms, generated and estimated future waste quantities, the waste management and disposal strategies of governments and their financing mechanisms.

CHAPTER 2 ORIGINS AND CLASSIFICATION describes the origins of nuclear waste across the nuclear fuel chain, from uranium mining through to operation, spent fuel management and decommissioning of nuclear facilities. It explains how different categories of waste vary in volume and activity, and presents international systems and national examples for classifying nuclear waste.

CHAPTER 3 QUANTITIES OF WASTE gives an overview about the reporting obligation that countries have under the key international framework which deals with nuclear waste, the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (referred to as the Joint Convention throughout the report). It presents an estimate of waste quantities that are typically generated along the nuclear fuel chain. In addition, the chapter assesses the current waste inventories of European countries and provides an estimate of future quantities.

CHAPTER 4 RISK FOR THE ENVIRONMENT AND HUMAN HEALTH presents which risks arise from the various steps along the nuclear fuel chain: uranium mining, milling, enrichment, and fuel fabrication, the operation of nuclear power plants; spent nuclear fuel reprocessing, and decommissioning. The chapter focuses on higher activity wastes, assesses the state of research on these risks, and highlights potential dangers and problems.

CHAPTER 5 WASTE MANAGEMENT CONCEPTS reviews the approaches that governments have developed over the past decades to manage nuclear waste. It looks at the variety of disposal paths that have been pursued, which differ in terms of host rocks, requirements for repositories of low- and intermediate-level and high-level waste, and the option of deep borehole disposal. The chapter describes the challenges of interim storage, which becomes increasing relevant due to the lack of operational final repositories.

CHAPTER 6 COSTS AND FINANCING presents the nature of the funding systems for decommissioning, storage, and disposal. It compares methodologies to develop cost estimates and compares these to the practice in reviewed countries. The chapter gives an overview of national funding systems for decommissioning, storage, and disposal.

CHAPTER 7 COUNTRY STUDIES offers a selection of case studies, including the Czech Republic, France, Germany, Hungary, Sweden, Switzerland, the United Kingdom, and the United States. Each section describes the national classification system, the quantities of waste involved, the waste management policies and facilities, and the approach on costs and financing.

Taking into account the project's budget constraints and the complexity of the topic, the **WNWR** needed to set priorities of what it can cover and what not:

- First, the **WNWR** focuses geographically on Europe and here those countries that produce nuclear waste. Due to insufficient data, however, Russia and Slovakia could not be included systematically. Following the overview chapters, the report presents eight specific country cases. The countries were selected to represent a broad variety of characteristics, such as small (Czech Republic, Hungary, Switzerland) and large nuclear states (France, the United Kingdom, and Germany), old (France, Germany, Sweden, United Kingdom) and new EU member states (Czech Republic, Hungary) as well as a non-EU country (Switzerland), countries that phase out nuclear power (Germany, Sweden) and also those still building nuclear plants (France, United Kingdom). The report also includes the case of the United States, the world's largest nuclear country, which allows the comparison European strategies with those of another major player. There are some absentees in the European group, notably Finland (with the only geological repository under construction in the world), Spain (which is a substantial player) and Russia (a major operator with numerous facilities, reprocessing and legacy waste challenges). On a global level, Canada would be an interesting candidate to include (in particular due to its large-scale uranium mining), as well as some major producers in Asia (China, India, South Korea, and Japan).

- Second, the **WNWR** focuses on waste from nuclear power for electricity generation. It does not cover radioactive waste from sectors like the military, medicine, research and industry. This focus has been set for several reasons: a) the quantities of waste generated by the commercial nuclear power industry, including those from decommissioning power reactors and other facilities of the nuclear fuel chain, represent the lion's share of the radioactive inventories; b) this focus includes spent nuclear fuel waste, which is extremely relevant because the radioactivity levels contained here are much higher than anywhere else in nuclear activities; c) all countries struggle to develop long-term management routes for spent nuclear fuel. Problem of managing wastes from nuclear power production are therefore major political issues. Radioactive waste from medicine, industry and research are only touched upon briefly in this report, though they certainly would deserve more attention. Similarly, less attention is paid to legacy wastes and especially those arising from the military operations, such as the production of nuclear weapons. Comparing countries with military wastes with those with only a civil cycle is highly complex. All nuclear waste is radioactive, but the report uses the term (as opposed to 'radioactive waste') as it is focuses on waste deriving from civil nuclear power activities.

- Third, readers may notice the **WNWR** does not provide in-depth analysis of a variety of issues related to nuclear waste that deserve further scrutiny. This includes complex topics such as reprocessing and the threat of nuclear weapons proliferation. It may also be worthwhile to look into the role nuclear waste has played in the history of major nuclear accidents such as Kyshtym, Three Mile Island, Chernobyl or Fukushima. The **WNWR** does not provide any analysis of the social and political issues concerning radioactive waste governance. While we fully acknowledge that nuclear waste management and disposal are not simply technical problems, but also raise profound social and political challenges, such issues are beyond the scope of this first edition of the report.

The approach of the **WNWR** is descriptive, empirical, technical and analytical. The intention is to assess the state of current affairs, to provide data as accurate as available, and to describe the approaches of a range of utility, industry and state operators to address the challenges of nuclear waste.

The report does not aim, however, to lead readers taking certain technical or political positions or to develop recommendations for best practice approaches. The examination of the conflicts and consequences inherent to nuclear policy and waste management choices is not the objective of the analysis. The underlying hypotheses of the report is that radioactive waste management and disposal constitute significant and growing challenges, and that sustainable long-term solutions are lacking. Despite many plans and declared political intentions, huge uncertainties remain, and much of the costs and challenges will fall onto future generations.

The **WNWR** should allow for comparison across countries and, as we aim for a periodical format, for monitoring over time. It identifies sources of uncertainty, such as inconsistencies, contradictions and data gaps. While every effort has been made to ensure consistency and accuracy, there are inevitable problems of categorization, definition, and information which make comparisons of costs, risks, inventory, and management approaches often difficult, sometimes even impossible.

This report is the first of its kind. With its focus on Europe, it aims to begin filling a significant research gap. Outside the EU and Europe, there is even more variation in waste classification and practices by operators and governments agencies on nuclear waste. Social, political, technical, and financial hurdles on the way to finding a sound long-term solution for these particular problem wastes are high.

2 ORIGINS AND CLASSIFICATIONS

Nuclear waste is radioactive, but here the term 'nuclear waste' is used as opposed to 'radioactive waste' as the coverage of this report is focused on waste deriving from civil nuclear power. The term 'nuclear waste' is also used in the military nuclear sector for waste from the production of nuclear weapons or from naval propulsion systems. Similarly, the much smaller volumes of radioactive waste, generally representing lower hazards that originate from industrial, research and medical uses, are only touched upon in this report.

What exactly constitutes waste, as opposed to a useful substance or material, turns out not to be a matter of common sense. For example, the UK government's guidelines on whether a substance is any kind of waste are complex. Waste may, in this categorization, be something that the producer or owner intends to discard; has low or negative economic value; or is hazardous. However, in any of these cases recycling or re-use may be possible, turning the relevant substance into a 'non-waste'.[1]

Applied in the nuclear sector, the major issue is whether or not some substances produced by nuclear reactions are to be considered waste or potential resources. One question is whether depleted uranium from the enrichment of uranium is or is not waste; and large volumes—hundreds of thousands of tons—are involved. However, the main dispute surrounds the products that arise when spent fuel from nuclear reactors is 'reprocessed'. Reprocessing is where spent fuel is separated into its component parts: plutonium, uranium and various fission products and actinides as well as other process waste streams. Most reprocessing, for example in France and the UK, is clearly intended to reuse the separated plutonium, and possibly the reprocessed uranium, as fuel in nuclear reactors. Significant quantities of plutonium have already been re-used in this way in various countries.

However, plutonium may qualify as waste by virtue of its indisputably hazardous nature and/or its low or negative economic value. Whether or not plutonium and reprocessed uranium are categorized as waste or a resource varies by country and over time. For example, in the UK in the 1950s, official economic appraisals of nuclear projects included a 'plutonium credit'. It was intended to reflect the expected value of separated plutonium as a future nuclear fuel. Forty years later, this early optimism had faded. By the mid-1990s, plutonium was classified as a 'zero-valued asset' or of 'zero book value' in the two main producer countries, the UK and France, a category puzzling to economists. By the 2010s, the status of plutonium had become uncertain. The UK Nuclear Decommissioning Authority (NDA) declared that its preferred option was to re-use plutonium as a component of future nuclear fuel.[2] It also argued that a small quantity of plutonium would have to be treated as waste because it was unsuitable for incorporation into mixed oxide fuel. If re-use turned out to be unfeasible, the immobilization planned for the contaminated plutonium might be extended to the whole stockpile, at which point plutonium in general would unambiguously be waste. In any event, the total net cost of managing plutonium in the

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[1] Department for Environment, Food and Rural Affairs (DEFRA) 2012, Guidance on the legal definition of waste and its application, viewed 11 June 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69590/pb13813-waste-legal-def-guide.pdf

[2] Nuclear Decommissioning Authority (NDA) 2014, Separated plutonium: progress on approaches to management, position paper, viewed 11 June 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/457874/Progress_on_approaches_to_the_management_of_separated_plutonium_position_paper_January_2014.pdf

UK is expected to be at least £3 billion (US$3.8 billion).[3] In France, the only remaining country separating plutonium in large quantities for commercial use, reprocessing remains required by law.

While plutonium in some cases may appear as a resource in the short term, it is currently almost exclusively re-used in fuel only once as mixed oxide (MOX) fuel; here plutonium re-use simply leads to another form of spent nuclear fuel. In addition, spent MOX fuel is more radioactive and difficult to manage than the spent fuel produced using uranium-only fuel. In other words, reprocessing both postpones the waste issue and makes it more complex.

> *Managing the various products of nuclear reactions, whether formally categorized as waste or not, is politically and socially contentious and involves potentially high hazards.*

The point here is not to adjudicate on the status of plutonium or other materials. It is rather to recognize that the issue of managing the various products of nuclear reactions, whether formally categorized as waste or not, is politically and socially contentious and involves potentially high hazards. While this chapter covers the range of waste products resulting from nuclear reactions, the special importance of spent fuel is that it is 100 million times more radioactive than fresh fuel.[4] It is therefore necessary to give particular attention to spent fuel waste.

2.1 TYPES OF WASTE: THE NUCLEAR FUEL CHAIN

Nuclear waste arises ('arisings' is a term widely used in this context) at all stages of the nuclear fuel chain, often also referred to as the nuclear fuel cycle. While it is possible to use thorium as a primary nuclear fuel, in practice uranium is overwhelmingly the dominant source of fuel for nuclear power. All the waste described and classified here ultimately stems from the ways in which uranium is currently used in electricity production. There is thus no consideration of the types of waste that would arise if nuclear fusion were ever a serious power source.

The sequential stages of the nuclear fuel chain are as follows (*see Figure 1*):

1. Uranium mining, milling, enrichment and fuel fabrication.
2. Irradiation of nuclear fuel in power or research reactors (nuclear fission).
3. Management of spent fuel, whether or not reprocessed.
4. Reactor decommissioning

The activities in stage 1 are often referred to as the 'front end' of the fuel chain. Stages 3 and 4 are often known as the 'back end' of the fuel chain.

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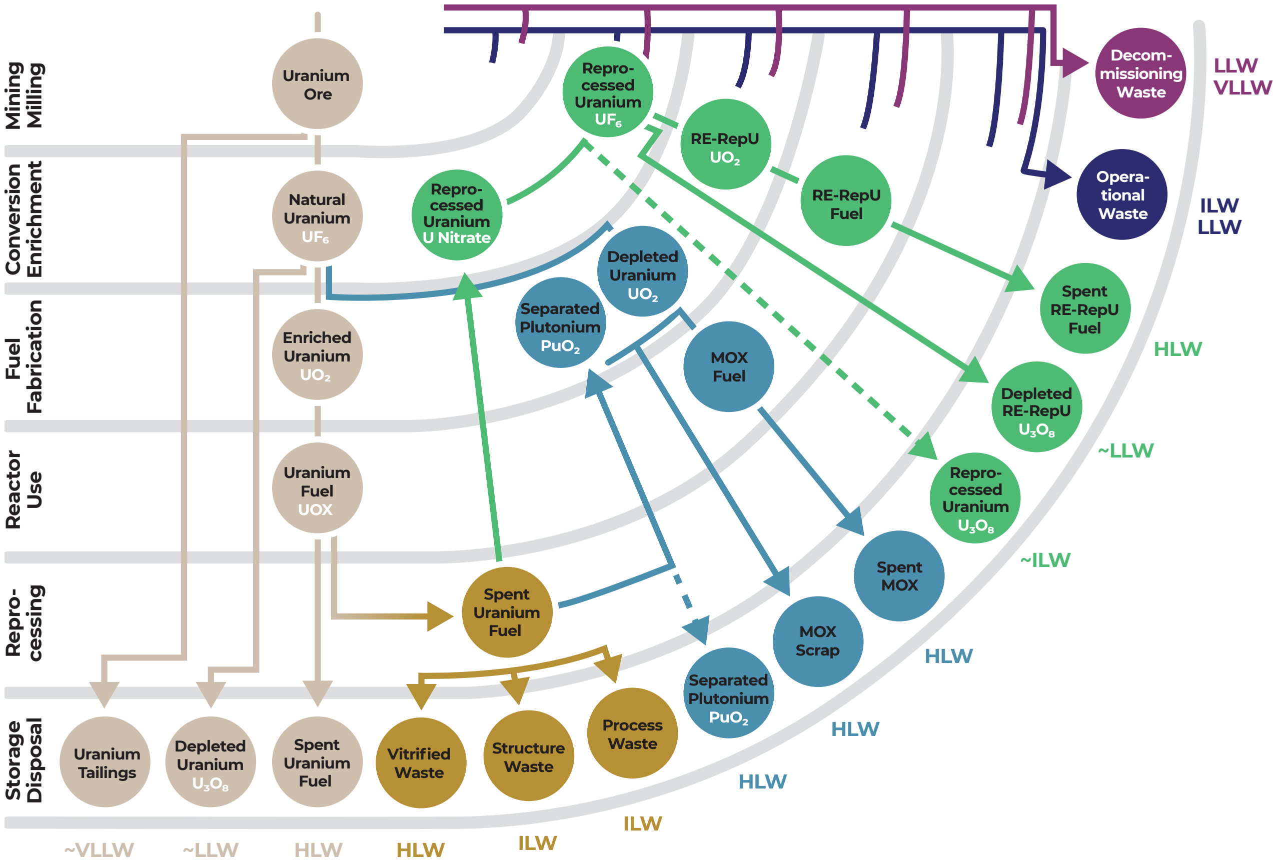
[3] Nuclear Decommissioning Authority (NDA) 2010, Plutonium: credible options analysis (redacted), viewed 11 June 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/457827/Plutonium_-_credible_options_analysis_2010__redacted_.pdf

[4] Open University 2011, 'Inside Nuclear Energy Science'. Short Module, ST174, Milton Keynes.

FIGURE 1 | The nuclear fuel chain



Source: WISE-Paris.

The waste that arises at these various stages can be gaseous, liquid or solid. For some forms of gaseous waste, for instance radon in underground uranium mines, measurements are rarely attempted, and management consists in reducing exposures rather than measuring or capturing existing levels, even though gases like radon are extremely harmful. In some cases, radioactivity is filtered out of exhaust gases and injected with liquid effluents into the sea, which is another form of reducing immediate exposure, without reducing toxicity at the source. Solid forms of waste are generally the most stable and easiest to manage, and a substantial aim in policy is therefore commonly to convert less stable waste forms into more manageable solid forms. For example, reprocessing of spent fuel produces a waste stream of boiling and radioactive nitric acid, which is then subject to evaporation and turned into a vitrified (glass) product.

Along the four stages of the nuclear fuel chain, a variety of waste types occur:

URANIUM MINING, MILLING, PROCESSING AND FUEL FABRICATION

An important waste and major health risk is radon gas in underground uranium mines. Radon gas is an alpha emitter and decays to solid polonium, which has similar characteristics. Another source of radioactivity from uranium mining of any kind is the persistent presence of uranium, which decays into radon, in mine tailings: waste heaps of discarded rock material from mining operations. These tailings take up very large volumes and can cause significant health problems, especially in developing countries, where management practices are sometimes poor. Because radon is released as a gas, it is not possible to directly capture it. The other stages of uranium processing (conversion, enrichment and fuel fabrication) produce very limited amounts of waste.

NUCLEAR FISSION (FUEL IRRADIATION)

In the process of fission, significant quantities of waste are generated as 'operational waste', broadly from maintenance, refueling and transport of spent fuel. Operational waste includes: debris from fuel elements, including steel and various alloys; core or heat exchanger components from maintenance, repairs or refurbishment, which are often highly active; contaminated liquid waste and sludge; resins and filters; and clothing and equipment, generally at low levels of activity.

MANAGEMENT OF SPENT FUEL

Nuclear fission in reactors is the area of nuclear technology that produces by far the largest amount of radioactivity. Irradiation produces a variety of fission products and actinides that multiply the radioactivity in the original uranium fuel by more than 100 million times. Management of spent fuel, whether via reprocessing or regarding it as a waste for possible direct disposal, is therefore by far the most important waste management activity arising from the nuclear fuel chain. Initially, spent fuel has to be stored under water for several years in a cooling pool in the reactor building or in an adjacent building to allow the decay heat to decrease. Water also provides some shielding against radiation.

The spent fuel can later also be transported to a central wet or dry storage facility. The main central wet storage centers are the reprocessing facilities such as Sellafield (UK), La Hague (France) and Ozersk (Russia). In the past twenty years intermediate-storage of spent fuel in dry casks has become more common mainly at nuclear power sites.

If fuel is reprocessed, then very large quantities of further low- and intermediate-level waste is created, meaning that the total volume of waste to be managed (though not the total activity) is much greater than if the spent fuel is treated directly as a waste. The residual fission products and actinides in liquid form (after uranium and plutonium are separated) are then evaporated and converted to solids by a vitrification process prior to intended further disposition. In addition, decommissioning reprocessing plants will be costly. Where spent fuel is treated directly as waste, it is encapsulated prior to disposal.

REACTOR (AND FUEL CHAIN FACILITY) DECOMMISSIONING

To date, very few reactors or other nuclear structures have been fully decommissioned (such as complete demolition), even where reactors have been closed for decades.[5] One reason for the delay, other than the obvious one of postponed costs, is that some radionuclides contained in these structures have relatively short half-lives, so access for demolition is easier later. However, delays could make the physical operations of dismantling more difficult, and relevant skills and oversight capacity may be lost. Reactor structures contain significant quantities of radioactivity in their cores, as many components are contaminated by radioactivity from the fuel that has been irradiated within them. Large quantities of materials like steel and concrete from decommissioning therefore constitute radioactive waste, though their total activity levels are small compared to the activity in the spent fuel.

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[5] Schneider, M., Froggatt, A., Hazemann, J., Katsuta, T., Stirling, A., Wealer, B., Johnstone, P., Ramana, M.V. and Stienne, A. 2018. The World Nuclear Industry Status Report 2018, Mycle Schneider Consulting.

2.2 WASTE QUANTITIES AND ACTIVITY

The total quantities and activity levels of these various categories of waste are inversely related. In other words, the lower-level waste is produced in large volumes but contributes very little to the overall inventory of radioactivity. Conversely, high-level waste (HLW) is present in very small volumes but makes up the vast bulk of radioactivity. This result is not surprising, given that the radioactivity in spent fuel from which HLW is derived is more than 100 million times greater than the radioactivity in fresh uranium fuel.[6]

> *Lower-level waste is produced in large volumes but contributes very little to the overall inventory of radioactivity. Conversely, high-level waste is present in very small volumes but makes up the vast bulk of radioactivity.*

An illustration of this comes from the waste inventory that the UK Committee on Radioactive Waste Management considered when it examined UK nuclear waste policy in the early 2000s.[7] High-level waste (here including spent fuel, plus HLW separated in reprocessing) amounted to 96.8 percent of the inventory's radioactivity, but only 2.6 percent of its volume. ILW, with much larger volumes, contained only 3.2 percent of the total radioactivity, while the LLW contribution to total activity level was less than 0.001 percent).

2.3 CLASSIFICATION SYSTEMS AND CATEGORIES

Classification systems for nuclear waste can differentiate waste in terms of three characteristics:

- By level of radioactivity: low, intermediate and high
- By time period of radioactive decay: short-lived and long-lived
- By management option: type of storage/disposal facility.

The first two of these characteristics concern the inherent properties of the waste itself, while the third starts from decisions about management. In practice, all systems of classification refer to elements of level of radioactivity and management, while some ignore the decay periods.

Despite attempts over the years to agree within the EU on a consistent classification system for nuclear waste[8], there remain quite different classification systems across the EU, some of which are summarized below. However, with its General Safety Guide on the Classification of Radioactive Waste, the International Atomic Energy Agency (IAEA) provides a broad framework of classification.[9] It constitutes a default position; countries without nuclear power programs almost universally adopt it directly. For countries with significant nuclear programs, their national classifications of waste often refer back to the IAEA system for comparative purposes.

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[6] Open University, 2011.

[7] Committee on Radioactive Waste Management (CoRWM) 2006, Managing our Radioactive Waste Safely: CoRWM's Recommendations to Government doc 700, July, pp. 20.

[8] LLW Repository Ltd. 2016. "International Approaches to Radioactive Waste Classification." NSWP-REP-134, October.

[9] International Atomic Energy Agency (IAEA) 2009, Classification of Radioactive Waste: General Safety Guide GSG-1, viewed 11 June 2019, https://www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf

The IAEA identifies six types of waste, focusing on solid waste. There have been limited disputes over the management strategies for the first four categories of waste described below (up to and including low-level waste). While some countries have in place long-term management strategies for waste that falls into these categories (for example, the UK and France), others pursue at best interim storage strategies (such as Germany and Japan).

The main issues where political controversies arise, and where there are not yet any agreed and operational long-term management facilities anywhere in the world, concern the categories of intermediate-level and, especially, high-level waste. In relating waste categories to management options, the IAEA assumes that these options will always take the form of various kinds of land-based disposal. This includes surface disposal and a variety of sub-surface options, in the latter case including 'disposal' in deep geological repositories.

2.3.1 THE IAEA CLASSIFICATION

The IAEA system takes varying account of all three characteristics outlined above and defines the six following categories:

EXEMPT

This category involves very low concentrations of radionuclides so that there is no need, in the view of the IAEA, for any specific radiation protection measures. The IAEA safety guide suggests that this is waste suitable for exemption (from regulatory control)[10], exclusion, or clearance. In principle, such material can thus be transferred from one country to another without any form of regulatory oversight.

VERY SHORT-LIVED WASTE (VSLW)

This category contains radionuclides with a very short half-life, which are often stored until their activity levels allow them to be re-categorized as exempt. Some gaseous and liquid waste is categorized as VSLW. In general terms, the recommended management strategy is storage for decay and is supposed to be applied for radionuclides with half-lives of the order of 100 days or less.

VERY LOW-LEVEL WASTE (VLLW)

Within this category, substantial amounts of waste stem from the operation and decommissioning of nuclear facilities, as well as waste arising from the mining and processing of uranium ores. Managing this waste, unlike those in the two categories above, requires full account of radiation protection and safety. Characteristic activity levels of radionuclides that fall within this category are between ten and a hundred times those of levels for exempt waste. The IAEA suggests that safe management for this waste will involve engineered surface landfill facilities, requiring both active and passive institutional controls over a significant but unspecified period.

The classification systems for many countries do not recognize the categories Exempt and VSLW, and some like the US reject the idea that any radioactive material should fall outside continuing regulatory oversight.

LOW-LEVEL WASTE (LLW)

Low-level waste (LLW) is defined as waste with levels of radioactivity low enough for near-surface or sub-surface disposal, if the disposal sites offer robust containment and isolation for what the IAEA describes as "limited periods of time". However, these limited periods of time turn out to be up to a few

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[10] In the US, the term Below Regulatory Control (BRC) is used for this categorization.

hundred years. In a number of countries, the essentially arbitrary assumption is made that institutional controls can be relied on for periods up to 300 years. However, for waste from mining and processing of uranium, activity levels fall slowly, so control needs to be postulated for longer periods than 300 years (and disposal in near-surface facilities is rare in developing countries).

This category covers a very wide range of waste and may contain low levels of long-lived radionuclides. Typical materials that fall into the LLW category include clothing, packaging material, soil, and significant products of reactor decommissioning, such as steel and piping. Depending on the exact composition of the wastes, the IAEA recommends disposal practices ranging from surface storage to burial at depths of up to 30 meters. Precise boundaries between LLW and the next category (intermediate-level waste or ILW) are not provided generically, as much depends on the characteristics of different kinds of disposal facility designs. Some countries have combined disposal of LLW and short-lived ILW with planned separate disposal of long-lived ILW. For the waste categories above, there are, for most countries, operational facilities to manage this waste.

INTERMEDIATE-LEVEL WASTE (ILW)

This is waste of higher activity levels than LLW, containing relatively large quantities of long-lived radionuclides. There is hence a need to engineer facilities that do not depend on institutional controls in the long-term. However, ILW does not produce heat from radioactive decay and thus does not need to take heat into account in its management. Characteristic sources of ILW are nuclear fuel cladding, some reactor components during decommissioning, and various types of sludge from treating radioactive liquid effluents. In addition, where spent fuel is reprocessed, large volumes of ILW are also created.

Today, in most cases, this waste is packaged in cement-based materials and enclosed within large drums or containers, often of steel. In France, tens of thousands of bituminized waste packages stem from the early commercial reprocessing activities that are not suitable for final disposal and thus need complex, expensive reconditioning. The IAEA recommends disposal at depths of between a few tens and a few hundreds of meters below ground in sites where natural geological barriers and engineered barriers have the potential to achieve long periods of isolation from the surface environment.

HIGH-LEVEL WASTE (HLW)

High-level waste (HLW) is the category comprising the most radioactive wastes. It contains large concentrations of both short-lived and long-lived radionuclides. It is also defined as waste that generates significant quantities of heat from radioactive decay, and will continue to do so for long periods into the future. Heat dissipation thus has to be taken into account in designing management routes. Many official and independent experts consider that deep geological disposal is necessary, in stable geological formations, and with the additional use of multiple engineered barriers to try to ensure that the chances of radioactivity returning to the biosphere are extremely low.

Essentially, HLW arises from nuclear fission (the irradiation of nuclear fuel), and is managed either as spent fuel, where this is treated directly as waste, or as the streams of actinide and fission products separated in reprocessing.

2.3.2 THE EU CLASSIFICATION

The EU has some regulatory powers across its member states in the area. Its 2011 Radioactive Waste Management and Decommissioning Directive set out generic targets for waste management.[11] The EU has no powers to require a common process of waste classification across member states, but did translate member state data on waste into a common system of its own based on the IAEA categories described above. In addition, as far back as 1999, the European Commission published recommendations for waste classification systems across all member states based on the IAEA system (which were then amended in 2008).[12] This system included the following five categories:

- Transition waste (equivalent to short-lived low-level waste)
- Very low-level waste
- Short-lived (half-life of less than 31 years) low-level and intermediate-level waste
- Long-lived (half-life longer than 31 years) low-level and intermediate-level waste
- High-level waste (heat generating).

The most significant divergence from the IAEA system is the division of both LLW and ILW into short-lived and long-lived categories, with implications for management strategies. However, no EU member state has exactly followed this recommended system, although France, Sweden and the Czech Republic have come close, especially in relation to the distinction between short- and long-lived waste.

To exemplify the variety of national classification systems used in the EU, four examples are described below. These have been chosen according to two criteria: there are substantial quantities of waste at all activity levels; and they illustrate the diversity of approaches that different national governments take to classification issues. There are of course many other systems in the EU. Outside the EU, there is even more variation in waste classification. Thus, a brief description follows of another national system of a country with substantial waste volumes, the United States. It illustrates the even greater variety of classification systems outside the EU.

2.3.3 EXAMPLES OF NATIONAL CLASSIFICATIONS

GERMANY: The German system of classification is relatively simple.[13] It distinguishes two main categories based on requirements for disposal: heat-generating waste and all other, described as waste with negligible heat generation. The first category corresponds to the IAEA category of HLW (including both, waste from reprocessing spent fuel, as well as spent fuel itself), while the second category is essentially a combination of the IAEA's ILW and LLW categories. German policy is to dispose of both categories of waste in deep geological repositories, but in different sites with different design characteristics.

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[11] European Union (EU) 2011, Council Directive 2011/70 establishing a Community Framework for the responsible and safe management of spent fuel and radioactive waste, 19 July.

[12] European Commission (EC), 1999, Commission Recommendation of 15 September 1999 on a classification system for solid radioactive waste (SEC (1999) 1302 final) 99/669/EC, EURATOM, o. Official Journal L 265, 13/10/1999, pp. 37-45, viewed 11 June 2019, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:51999SC1302

[13] LLW Repository Ltd. 2016, International Approaches to Radioactive Waste Classification. NSWP-REP-134, viewed 11 June 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/697667/NWP-REP-134-International-Approaches-to-RW-Classification-Oct-2016.pdf

FRANCE: The French system is more complex than the German. It uses five main categories, ignoring the category of VSLW.[14] The French system adds to the IAEA system each waste category's half-life. The categories are:

- Very low-level waste
- Low- and intermediate-level waste (short-lived)
- Low-level waste (long-lived)
- Intermediate-level waste (long-lived)
- High-level waste (heat generating)

In this system, only the first and last categories (VLLW and HLW) broadly correspond to the IAEA classification. In relation to LLW and ILW, the French system takes account of the longevity of the potential harm represented by different types of waste and the initial level of activity, thus creating further distinctions than the IAEA does in both ILW and LLW. In line with EU guidelines, the French system categorizes waste as short-lived if their half-lives are shorter than 31 years and as long-lived if their half-life exceeds 31 years. This second dimension, the half-life, is related to French policy for disposal. Thus, while HLW and ILW (long-lived) are both expected to go to deep geological repositories, ILW (short-lived) and LLW (long-lived) is expected to be managed in surface disposal facilities.

THE UK: Compared to France and Germany, the UK's system is more closely aligned to the IAEA's.[15] Its four categories correspond to the final four of those outlined above in relation to the IAEA and are therefore:

- Very low-level waste
- Low-level waste
- Intermediate-level waste
- High-level waste (heat generating, mostly products of reprocessing).

While these are the main operational waste categories in the UK, there is also another distinction, closely related to current disposal options:

- Higher activity waste, defined as HLW, ILW and that part of LLW not currently disposable. At present, there is no long-term management routes for this waste.
- Lower activity waste, which is the bulk of LLW and VLLW, all of which is currently disposed of in engineered surface facilities.

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[14] French Authority for Nuclear Safety (ASN), with Ministere de la Transition Ecologique et Solidaire, undated. French National Plan for the Management of Radioactive Materials and Waste 2016-2018.

[15] LLW Repository Ltd. 2016. International Approaches to Radioactive Waste Classification. NSWP-REP-134, October, viewed 11 June 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/697667/NWP-REP-134-International-Approaches-to-RW-Classification-Oct-2016.pdf

THE CZECH REPUBLIC: Among the more recent EU member states, the Czech Republic has the largest volumes of nuclear wastes. Its classification system is similar to that of France and to the EU's recommendations.[16] Its categorization is as follows:

- Transition waste and VLLW (equivalent to short-lived low-level waste)
- Low-level waste (short-lived)
- Intermediate-level waste (long-lived)
- High-level waste (heat generating).

THE UNITED STATES: The US has two quite distinct sets of categories: one for military-origin waste and the other for civilian-origin waste. The US system for civilian-origin waste recognizes five categories:[17]

- Mill tailings
- Low-level waste, which is then divided into four further categories (one of which would be classified as ILW under the IAEA system)
- Transuranic waste
- Spent nuclear fuel
- High-level waste: products of the reprocessing of spent fuel.

While the US system recognizes some categories that are similar to those of the IAEA (such as HLW), it differs fundamentally from all others in that it bases classification on the origins of waste, and not its characteristics or the risks it poses. The LLW category also includes material that would count as VLLW and VSLW under IAEA classification, as the US does not recognize any radioactive waste that is exempt from regulatory controls. The four categories of LLW relate to the extent to which the particular waste is related to protection of the public and for inadvertent intruders to a waste site. Finally, by-product material is a miscellaneous grouping of reactor or fuel fabrication material (other than uranium and plutonium) and tailings from uranium mining.

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[16] LLW Repository Ltd. 2016

[17] Blue Ribbon Commission 2012, Report to the Secretary of Energy, January 2012, pp. 96, viewed 2 August 2019, https://www.energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf

2.4 SUMMARY

What exactly constitutes waste turns out not to be a matter of common sense. Some countries define certain products by nuclear reactions as waste, others as potential resources. For instance, plutonium qualifies as waste in many countries because of its hazardous nature and its low or negative economic value. However, France requires reprocessing by law, thus separating plutonium in large quantities for commercial use. Reprocessing both postpones the waste issue and makes it more complex. Managing the various products of nuclear reactions, whether formally categorized as waste or not, is politically and socially contentious and involves potentially high hazards.

Classification systems for nuclear waste can differentiate waste in terms of three characteristics: by level of radioactivity (low, intermediate and high), by time period of radioactive decay (short-lived and long-lived), and by management option (type of storage and disposal facility). Though lower-level waste is produced in large volumes, it carries little levels of radioactivity. This is the case, for instance, for steel and concrete from decommissioning. Conversely, high-level waste occurs in small volumes but makes up the vast bulk of radioactivity and generates significant quantities of heat, such as spent nuclear fuel.

The International Atomic Energy Agency provides a broad framework of classification for nuclear waste. The 2001 Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management constitutes a default position for many countries. With the 2011 directive 2011/70/EURATOM the EU attempted to harmonize waste classification systems for its member states, but with limited success. No member state has exactly followed the EU's recommendations, with France, Sweden and the Czech Republic have come closest.

Overall, countries in Europe differ significantly in their classification systems for nuclear waste. First, they differ in whether spent nuclear fuel and some of its potential separated products (plutonium and uranium) are waste or a resource. Second, there are significant differences in the categorizations of waste, with no two countries having identical systems. While all agree on the category of heat-generating (high-level) waste, there are several alternative ways of characterizing other nuclear waste streams. Some countries distinguish between short- and long-lived wastes at both low- and intermediate-level while others use the low and intermediate categories without distinguishing between short and long lifetimes. Some systems are based largely on the origins of waste, some on potential or actual disposal sites or other management options, and others still on a mixture of activity levels and half-lives. These differences make comparing waste classification systems across countries highly complex.

3 QUANTITIES OF WASTE

Large amounts of nuclear waste have accumulated worldwide after more than 70 years of using nuclear power for electricity generation. Despite the lack of adequate disposal facilities, more waste is generated, leading to steadily increasing stored quantities of nuclear waste.

3.1 REPORTING OBLIGATIONS

Worldwide, the management and reporting of nuclear waste is governed by national legislation and international conventions. Within the EU, the key framework is Directive 2011/70/EURATOM for the responsible and safe management of spent fuel and radioactive waste. Its requirements are based on the IAEA Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (see below). In 2015, EU member states were required, for the first time, to submit a waste inventory and a strategy for their radioactive waste program to the European Commission. Every three years thereafter, EU member states have to report on the implementation of Directive 2011/70. Two years later, in 2017, a report for the European Commission translated the reported inventories of the EU member states into the common IAEA GSG-1 classification system of very low-level waste (VLLW), low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW).[18] The report showed that the waste quantities in the EU are increasing steadily and that adequate disposal facilities are limited.[19]

The 2001 Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (hereafter Joint Convention) is the first legal instrument to address the issue of spent nuclear fuel and radioactive waste management safety through establishing safety principles and creating a "peer review process" to the Convention on Nuclear Safety.[20] The agreement with the International Atomic Energy Agency (IAEA) includes the requirement to list the facilities for spent nuclear fuel (SNF) and radioactive waste management and to list the inventories of SNF and radioactive waste (Article 32). These national reports should be submitted for every review meeting, which has to take place no later than three years after the previous meeting (Article 30). The national reports from the sixth review meeting (in 2018) are the primary source for the waste quantities *in Section 3.3.*[21]

3.2 WASTE QUANTITIES ALONG THE SUPPLY CHAIN

URANIUM MINING AND FUEL FABRICATION

In order to use uranium as a fuel for electricity generation in nuclear reactors, uranium ore (a natural resource) has to undergo several processing stages. First, the ore has to be mined, separated from waste material, and milled to produce the so-called "yellow cake" that is then converted to uranium hexafluoride, enriched, and fabricated into fuel elements.

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[18] International Atomic Energy Agency (IAEA) 2009, Classification of Radioactive Waste

[19] European Commission 2017, Inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects, viewed 12 June 2019, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017SC0161&from=EN

[20] International Atomic Energy Agency (IAEA) 2001, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, viewed 11 June 2019, https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste

[21] The National Reports can be found on the following IAEA page: https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste/documents?keywords=&type=4797&language=All&field_extres_date_value%5Bvalue%5D%5Byear%5D=&country=All

All these processes produce nuclear waste. The first waste that emerges is the tailings (excavated rocks to access the uranium ore) at the mine. In some cases, these tailings were stockpiled in heaps to fill open-cast mines or to redevelop areas. Six countries supply around 85 percent of the world's mined uranium: Canada, Kazakhstan, Australia, Niger, Namibia, and Russia.[22] Mining (and subsequent processes) creates large amounts of nuclear waste in the exporting countries, of which only Canada and Russia operate nuclear power plants. France, Russia, Canada, China, and the US commercially convert yellow cake into uranium hexafluoride (UF_6). England, France, Germany, the Netherlands, Russia, Japan, and the US provide commercial enrichment services. Uranium-containing waste is generated in both stages.

OPERATIONAL WASTE

The operation of nuclear power plants for electricity generation produces different kinds of nuclear waste in different kinds of physical states, of which the lion's share is low- and intermediate-level waste (LILW). The IAEA classifies operational waste into two main categories: unconditioned (as-generated) and conditioned operational waste. For unconditioned operational waste, an indication of the physical state (such as liquid or solid) is important:[23]

- Raw waste (waste in its original form) is unconditioned and often listed in tons for solid waste and cubic meters (m^3) for liquid waste.[24]

- But this category also includes pre-treated waste. This waste has undergone some form of preconditioning and is often measured in tons for solids and m^3 for liquids.

To bring the waste into a stable and immobilized form and to make it suitable for transportation, storage, and eventually disposal, it needs to be conditioned. Waste compaction is also applied in order to minimize the waste quantities; compaction can be a part of conditioning but does not have to be.[25]

- An additional category is conditioned waste that has to be reconditioned for safety or acceptance reasons or both.[26]

- After conditioning, the waste is stored in drums, storage, transport, or disposal casks. The stored waste is measured in m^3, metric tons, or number of casks or drums.

- A last waste category is disposed waste. In Europe, only less than half of the nuclear countries have installed disposal facilities for LILW (UK, France, Spain, Hungary, Finland, Czech Republic, Sweden). Disposed waste is often measured in m^3 or waste packages or casks.

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[22] Mendelevitch, R., Dang, T. 2016, "Nuclear Power and the Uranium Market: Are Reserves and Resources Sufficient?", DIW Berlin — Deutsches Institut für Wirtschaftsforschung.

[23] Solid waste is for example protective clothing, replaced plant components, or insulation material. Liquid waste is for example cooling water contamination, oils, vaporizer concentrates, filter substances, or sludge, which forms when solid matter collects as sediment at the bottom of pumps. See IAEA, "Categorizing Operational Radioactive Wastes", International Atomic Energy Agency, 2007.

[24] Or mega gram (Mg) of heavy metal (HM).

[25] For more details on the waste production techniques, see Homberg, Pavageau, and Schneider 1997 "Cogema — La Hague The Waste Production Techniques", Greenpeace International.

[26] For example, bituminized sludges from reprocessing that AREVA client countries refuse to take back and that turn out sub-spec for final disposal in France.

The generation of waste depends on many factors, such as the deployed reactor technology and the age of the reactor. The IAEA gives an overview of generation of unconditioned LILW per 1-Gigawatt (GW[27]) nuclear power by reactor technology:[28]

- Pressurized Heavy Water Reactor (PHWR): 200 m^3
- Light-water Reactor[29]
    - Pressurized (Light-)Water Reactor (PWR): 250 m^3
    - Boiling (Light-)Water Reactor (BWR): 500 m^3
    - PWR VVER: 600 m^3
- Fast Breeder Reactor (FBR): 500 m^3
- Advanced Boiling Water Reactor (ABWR): 500 m^3
- Advanced Gas-Cooled Reactor (AGR): 650 m^3
- Light-Water Gas-Cooled Reactor (RBMK): 1,500 m^3
- Gas-Cooled Reactor (GCR): 5,000 m^3

These estimates are for unconditioned waste; estimates for the generation of annual conditioned LILW per reactor vary among the observed countries and again depend on many factors, such as reactor technology and conditioning methods. Germany, for instance, estimates 45 m^3 of conditioned LILW each year for its Light Water Reactors (LWRs, including PWRs and/or BWRs)[30], while France estimates 78 m^3 per reactor for its PWRs.[31]

SPENT NUCLEAR FUEL

The IAEA estimates that operating a 1 GW light-water reactor generates around 30 to 50 tons of spent nuclear fuel annually.[32] Applying this estimate to the worldwide installed operating capacity of 363 GW would roughly indicate that 11,000 to 18,000 tons of SNF are produced annually. As of 2013 approximately 370,000 tons have been generated worldwide since the first reactor was connected to the grid, of which roughly one third (124,000 tons) has been reprocessed.[33] To approximate not only the weight but also the volume of the stored spent fuel, one can apply the US Department of Energy's ratio of conversion from mass (t HM) to volume (m^3) of 2.5 for LWRs.[34]

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[27] The units Gigawatt or Megawatt (MW) describe the installed capacity of a power plant to generate electricity. This can also be referred to as Gigawatt of electrical output (GWe). Unless explained otherwise, the report uses GW and MW

[28] IAEA 2007, "Estimation of Global Inventories of Radioactive Waste and Other Radioactive Materials"

[29] Around 80 percent of the world's more than 400 nuclear reactors are either PWR or BWR

[30] Government of Germany 2018, The Sixth Report National Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

[31] Neumann, W. 2010, "Nuclear Waste Management in the European Union: Growing volumes and no solution", intac, the Greens/EFA in the European Parliament, viewed 12 June 2019, https://www.sortirdunucleaire.org/IMG/pdf/thegreens-efa-2010-nuclear_waste_management_in_the_european_union-growing_volumes_and_no_solution.pdf

[32] IAEA 2007, Estimation of Global Inventories of Radioactive Waste and Other Radioactive Materials

[33] IAEA 2018, Status and Trends in Spent Fuel and Radioactive Waste Management

[34] US Department of Energy 1997, Integrated Data Base Report — 1996: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics

The IAEA estimates that reprocessing would convert this 30 to 50 tons of SNF into 15 m^3 of vitrified HLW.[35] This conservative estimate of course does not include the vast amounts of reprocessed uranium, plutonium, intermediate-level waste, and spent mixed oxide fuel (MOX) that require extensive additional intermediate storage periods.[36] In Europe, reprocessing is still part of the waste management concept in some countries (France, the Netherlands, Russia), while most countries have suspended or stopped it for mainly economic reasons (Belgium, Bulgaria, Germany, Hungary, Sweden, Switzerland, and most recently the UK). The latest European country to show interest in reprocessing is Ukraine, which signed a contract for a feasibility study with France's Orano (formerly Areva). The initiative is part of Ukraine's effort to diversify its nuclear fuel chain. An additional spent fuel interim storage facility is being constructed, and the country is cooperating with Westinghouse on fuel supply.[37]

DECOMMISSIONING WASTE

Once a nuclear power plant is closed, the spent fuel has to be removed, cooling systems and moderators drained. The process of defueling, deconstruction, and dismantling of a nuclear power plant is called decommissioning.[38] The IAEA estimates the mass (rather than volume) of the decommissioning waste: a light-water reactor with 1 GW can be expected to produce 5,000 to 6,000 tons of LILW and 1,000 tons of long-lived LILW and HLW.[39] This estimate has to be taken with caution as only one reactor as big as 1 GW has been decommissioned worldwide yet but this reactor (Trojan in the US) was only operational for 17 years. As of 2018, only 19 (smaller) nuclear power plants or about 6 GW have been decommissioned worldwide (*see Table 1*).[40] Similar to operational waste, the quantity of decommissioning waste depends on various factors, such as the clearance level of waste, the decommissioning strategy (immediate dismantling or long-term enclosure), the operating time, and the specific reactor technology. The waste produced in the initial stages of decommissioning has the same characteristics as operational waste and can be characterized using the same approach, with one exception: it is generated in much larger quantities in a shorter period of time.[41]

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[35] IAEA 2019

[36] Over 100 years compared to uranium fuels or much greater volume in disposal sites (about a factor of 3). For a detailed discussion of comparative volumes see Mycle Schneider and Yves Marignac, "Spent Nuclear Fuel Reprocessing in France", IPFM, April 2008.

[37] International Panel on Fissile Materials 2018, "Ukraine to explore reprocessing its spent fuel in France", 3 May, viewed 12 June 2019, http://fissilematerials.org/blog/2018/05/ukraine_to_explore_reproc.html

[38] Schneider et al. 2018, World Nuclear Industry Status Report 2018.

[39] IAEA, Estimation of Global Inventories of Radioactive Waste and Other Radioactive Materials, pp.16.

[40] Schneider et al. 2018, World Nuclear Industry Status Report 2018.

[41] IAEA, 2007

TABLE 1: Decommissioned reactors worldwide as of May 31, 2018

Country	Reactor	Capacity in MW	Decommissioning End in	Operational Years
GERMANY	5	1,017 (total)		
	Niederaichbach	100	1995	1
	HDR Großwelzheim	25	1998	2
	VAK Kahl	15	2010	24
	Würgassen	640	2014	23
	Gundremmingen-A	237	2016	11
JAPAN	1	12 (total)		
	JPDR	12	2002	13
UNITED STATES OF AMERICA	13	4,922 (total)		
	Elk River	22	1974	5
	Shippingport	60	1989	25
	Pathfinder	59	1993	1
	Shoreham	809	1995	0
	Fort St. Vrain	330	1997	13
	Maine Yankee	860	2005	24
	Saxton	3	2005	5
	Trojan	1,095	2005	17
	Yankee NPS	167	2006	31
	Big Rock Point	67	2006	35
	Haddam Neck	560	2007	29
	Rancho Seco-1	873	2009	15
	CVTR	17	2009	4
TOTAL		5,951		

Source: Own depiction based on Schneider et al. (2018).

ESTIMATED WASTE QUANTITIES ALONG THE SUPPLY CHAIN

Figure 2 gives an overview of the estimated unconditioned waste quantities by country, excluding the waste generated during mining and milling and the conversion to uranium fuel. The current (as of 2019) European operational fleet (excluding Russia and Slovakia) of 142 nuclear power plants or around 149 GW along with average age of the fleet (by reactor technology) as well as the shutdown fleet of 90 nuclear power plants or 36 GW along with the average operational time of the fleet (by reactor technology) is respected. This estimate is inaccurate for reasons of simplification as it assumes that the production of waste per GW has been constant through the years. Moreover, uranium waste is excluded in the estimate as most uranium is imported, therefore creating large amounts of waste outside of Europe.

- Operation: The generation rate for operational waste is based on the above cited generation rates of unconditioned LILW per 1-Gigawatt nuclear power by reactor technology.
  This estimate results in 2,916,000 m^3 of LILW (1,560,000 m^3 from operational reactors and 1,356,000 m^3 from shut down reactors). Additional 1,378,000 m^3 of operational waste is expected until the shut down of the reactors. This sums up to 4,294,000 m^3 of LILW from operation.

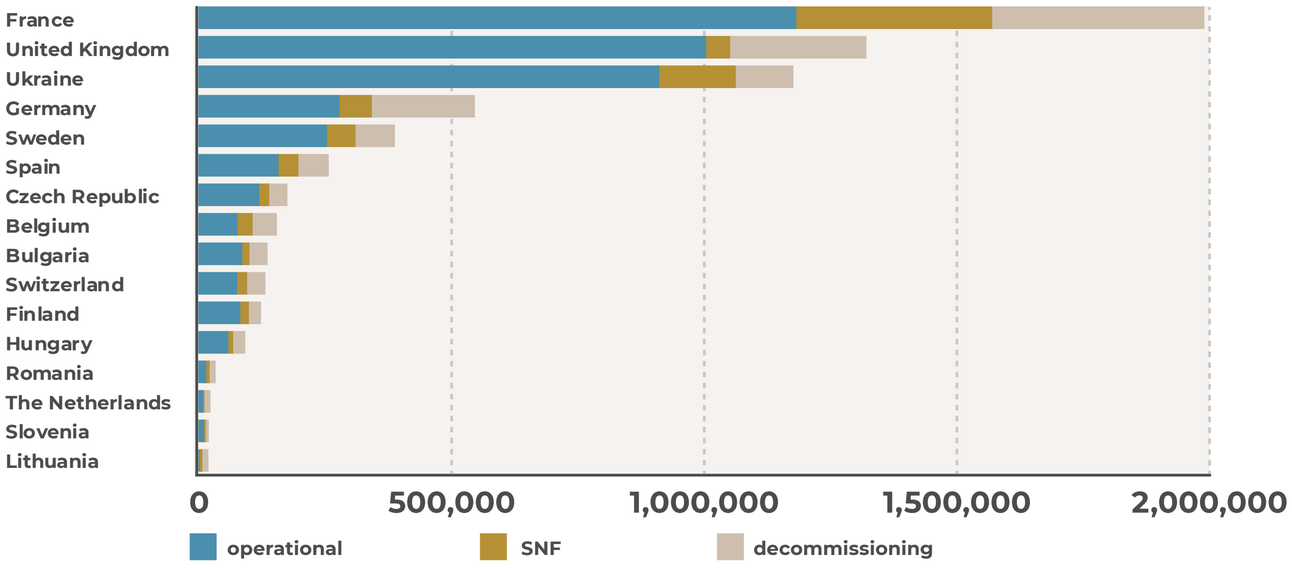
- Spent nuclear fuel: For the generation of spent fuel, an estimate of 40 tons of SNF per 1 GW reactor annually is assumed. This leads to an estimated current inventory of 226,000 tons of SNF in the HLW category (197,000 tons from operational, 30,000 tons from shutdown reactors). Additional 123,000 tons SNF is expected until the shut down of the reactors, summing up to 350,000 tons in total. Applying DOE's ratio of conversion from mass to volume for LWRs, the current amount is 566,000 m³. Until shut down, the total amount will increase to 874,000 m³ of spent nuclear fuel.

- Decommissioning: Applying a conservative assumption[42] by the IAEA of a 6,000 m³/reactor generation rate of decommissioning, an additional 1,400,000 m³ of LILW will arise from decommissioning.

> *The European nuclear fleet is estimated to produce around 6.6 million m³ of nuclear waste over its lifetime. If stacked in one place, it would fill up a football field 919 meters high, 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai.*

Based on these assumptions, the estimated total amount of nuclear waste from operation and spent nuclear fuel produced by the European nuclear fleet (excluding Russia and Slovakia) over its lifetime is around 5.2 million m³. After all of Europe's reactors are decommissionend, the European nuclear fleet is estimated to have produced around 6.6 million m³ of nuclear waste over its lifetime. With a share of 30 percent France would be Europe's greates producer of low- and intermediate level waste, followed by the UK (20 percent), the Ukraine (18 percent), and Germany (8 percent). These four countries account for more than 75 percent of the European nuclear waste. If stacked in one place, all of Europe's nuclear waste would fill up a football field 919 meters high, 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai. All this waste needs conditioning and disposal.

FIGURE 2: Estimated nuclear waste from operation, spent nuclear fuel management, and decommissioning from European NPP fleet (operational and shut down) in m³ as of December 31, 2018



Source: Own compilation and estimation based on generation rate assumptions of IAEA 2007, US DOE 1997.

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[42] This rate depends on the assumed average density of the waste and on conditioning and packaging procedures. See IAEA, 2007.

3.3 REPORTED WASTE QUANTITIES UNDER THE JOINT CONVENTION

For this section, the data for the different European national inventories is drawn from the official documents published by the respective governments, regulatory agencies, or other responsible governmental bodies under the Joint Convention.

URANIUM MINING AND FUEL FABRICATION

The EU imports most uranium. France mined uranium ore in the past. Officially, the former French uranium mining industry generated 50 million tons of mining residues, spread over 17 disposal sites at former mines.[43] Independent experts estimate that it is much higher, because the official national inventory has some "forgotten wastes", as Le Monde put it in a headline.[44]

The former German Democratic Republic (GDR) mined much larger quantities of uranium ore than France, which was discontinued in 1990 following German unification. Around 231,000 tons of uranium were extracted in the GDR, making the country the fourth largest uranium producer of its time worldwide. Today, the mining legacies comprise some 32 km^2 of facility areas, 48 heaps with a volume of low active rocks of 311 million m^3 and four tailing ponds holding a total of 160 million m^3 of radioactive sludge.[45, 46] As in most cases, the rehabilitation of the former uranium sites consisted only in installing a solid cover over the residues.

Today, the Russian Federation is one of the largest uranium producers in the world, with mining workings being the principal source of low-level solid waste generation. In 2016 alone, the Russian mining company PIMCU produced around 700,000 m^3 of mining residues falling in the category of LILW. However, the Russian Joint Convention report does not contain any accumulated data on waste from mining.[47]

The most hazardous waste at commercial enrichment plants and the plants with the most waste are at Capenhurst (UK), Almelo (The Netherlands), Gronau (Germany), and Tricastin (France). In the past, the French, German, and Dutch operator companies transported more than 10,000 tons per year of enrichment byproduct, depleted uranium hexafluoride (UF_6), to Russia, where large amounts remain.[48] Now, the companies operating enrichment plants in the EU have to keep the depleted UF_6. In Germany, the expected waste package volume of waste resulting from uranium enrichment is up to 100,000 m^3 of depleted uranium.[49]

LOW- AND INTERMEDIATE-LEVEL WASTE

Varying national inventory approaches make it difficult to compare the volume of legacy waste in the countries, as operational waste is stored in different physical states (for instance liquid, solid, and pre-compressed), or the waste has already been conditioned, compacted, or disposed of. Sometimes,

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[43] Government of France 2017, National Report Sixth Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

[44] "Le lent poison des déchets radioactifs 'oubliés'" (The slow poison of 'forgotten' nuclear waste), Le Monde, 12 June 2019.

[45] Government of Germany 2018, The Sixth Report National Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

[46] German regulation does not consider heap materials, tailings as well as other waste materials at the contaminated sites of uranium ore mining generally as radioactive waste, and therefore adds an additional report to the report published under the Joint convention agreements.

[47] Government of Russia 2017, The fifth National Report of the Russian Federation on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management

[48] Neumann 2010

[49] Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) 2016, "Germany Profile", viewed 12 June 2019, https://www.oecd-nea.org/rwm/profiles/germany_profile.pdf

the waste is clustered into different categories, such as LLW and ILW or LILW, or is still in other different forms. Russia gives an estimate of around 556 million m³ of radioactive waste with little information given on the origin (large amounts are from mining), waste classification and state. The most striking case is Slovakia, where information about nuclear waste forms such as "in pieces", "drums" or "pallets" does not allow any classification of volumes (neither country is included in *Table 2*).

Table 2 provides an overview of the reported amounts of LILW in interim storage. As the different national Joint Convention reports often lack detailed information about the origin of the waste, it is not always clear if the cited LILW volumes stem only from operations and reprocessing, or if decommissioning waste is included.

TABLE 2: Low- and intermediate level waste in Europe in interim storage and disposed (rounded figures) as of December 31, 2016

Country	LILW in interim storage (m³)	LILW disposed (m³)	Total generated LILW (m³)
BELGIUM	23,200	No disposal facility operational.	**23,200**
BULGARIA	11,900	No disposal facility operational.	**11,900**
CZECH REPUBLIC	1,750	11,500	**13,250**
FINLAND	1,970	7,600	**9,600**
FRANCE	180,000	853,000	**1,033,000**
GERMANY	45,200	84,100	**129,300**
HUNGARY	10,600	876	**11,500**
LITHUANIA	44,000	No disposal facility operational.	**44,000**
THE NETHERLANDS	11,100	No disposal facility operational.	**11,100**
ROMANIA	1,000	No disposal facility operational.	**1,000**
SLOVENIA	3,400	No disposal facility operational.	**3,400**
SPAIN	6,700	32,200	**38,900**
SWEDEN	13,800	39,000	**52,800**
SWITZERLAND	8,400	No disposal facility operational.	**8,400**
UKRAINE *	59,400	No disposal facility operational.	**59,400**
UNITED KINGDOM	130,000	942,000	**1,072,000**
TOTAL	**552,400**	**1,970,000**	**2,522,000**

Source: Own depiction based on reports under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management and ONDRAF/NIRAS 2017.
Note: *Excluding (stored and disposed) waste in the Chernobyl zone.

Adding the data of national reports to the Joint Convention reveals a total of more than 550,000 m³ of LILW wich is currently in interim storage across Europe (excluding Slovakia, and Russia) awaiting a disposal solution. Including the disposed waste, the total amount of generated LILW in Europe amounts to a total of more than 2.5 million m³ of stored and disposed waste.[50] This is close to the estimated 3 million m³ of unconditioned operational waste based on the IAEA estimates (still exluding Slovakia and

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[50] This amount also does not include the large amounts of very low-level wastes (VLLW) that have been generated during operation times. For instance in France alone, an additional 185,000 m³ of VLLW are in interim storage and 352,000 m³ have been disposed of. For the majority of the observed countries no data on the amounts of VLLW has been disclosed.

Russia). Although it is difficult to compare these numbers, due to the lack of detailed information on the stored waste, for example if the waste is conditioned or not.

As of today, less than half of the observed countries have installed disposal facilities, mostly for LLW and not ILW: the UK, France, Spain, Hungary, Finland, Czech Republic, Sweden and Germany. But these countries have disposed of altogether close to 2 million m³ of operational waste. The UK alone has already disposed of around 1 million m³ of LLW, most of which at the near-surface repository at Drigg.[51] The two major nuclear EU countries, France and the UK, each have disposed of nearly twice as much LILW than is currently in interim storage in the EU. Nonetheless, they still account for more than two thirds of the LILW currently in interim storage, awaiting disposal.

In Germany, waste has been disposed of in two geological disposal facilities. However, the waste in the Asse II mine in Lower Saxony between 1967 and 1978 (around 47,000 m³ of LILW in close to 126,000 drums) needs to be retrieved as there has been a continuous inflow of groundwater from the overburden into the mine. So far, no disposal pathway exists for the up to 220,000 m³ of mixed radioactive waste and salt.[52] Waste has never been retrieved from a geological disposal facility before, making this the first such undertaking. It poses technological, logistical, and financial challenges. What's more, retrieval creates a new kind of waste: disposed waste that needs renewed conditioning, storing, and eventual disposal after retrieval (the quantities are now fivefold of the disposed waste in the case of Asse II, it is now a mixture of salt and radioactive waste).

Large quantities of LILW will arise after the reactors are shut down and subsequently decommissioned. As of 2018, only 19 nuclear power plants have been decommissioned worldwide, of which only five were in Europe, namely in Germany.[53] Although decommissioning works are ongoing in Europe, reports of quantities of decommissioning waste are hard to find. The German report under the Joint Convention does not give exact amounts of waste generated during decommissioning, but only an estimate for the waste generation rate: 5,000 m³ of conditioned LILW per reactor.[54] However, decommissioning also produces waste that needs the same treatment as HLW. Decommissioning works at the José Cabrera and Vandellos nuclear power plants in Spain, for example, generated 185 m³ of "special waste" that has to be disposed of with HLW, mainly from cutting of the reactor vessel internals. It is now stored in four dry storage casks on site.[55] Hungary estimates that decommissioning the four Paks units will produce in total 26,700 m³ of LILW (6,700 m³ per reactor) and 300 m³ of HLW.[56]

In addition to the challenge of having to decommission the largest reactor fleets in Europe, three countries (the UK, France, and Russia) face additional challenges, because their legacy fleet includes rare reactor types: gas-cooled reactors (GCRs) in France and UK and the still-operational Soviet-style RBMK reactors in Russia and Ukraine. These reactor cores were constructed using thousands of tons of graphite blocks. A typical Magnox reactor in the UK can contain about 3,000 tons of highly irradiated graphit classified as ILW with the need for shielded and probably deep disposal due to long-lived isotopes.[57]

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[51] Neumann 2010

[52] Kommission Lagerung hoch radioaktiver Abfallstoffe (German Commission on Storage for Highly Radioactive Waste) 2016, Abschlussbericht der Kommission zur Lagerung hochradioaktiver Abfälle K-Drs. 268 (Final Report of the Commission on the Storage of High-Level Radioactive Waste K-Drs. 268).

[53] Schneider et al. 2018

[54] Government of Germany 2018, The Sixth Report National Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management pp. 86

[55] Government of Spain 2017, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management — 6th Spanish National Report.

[56] Government of Hungary 2017, National Report Sixth Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

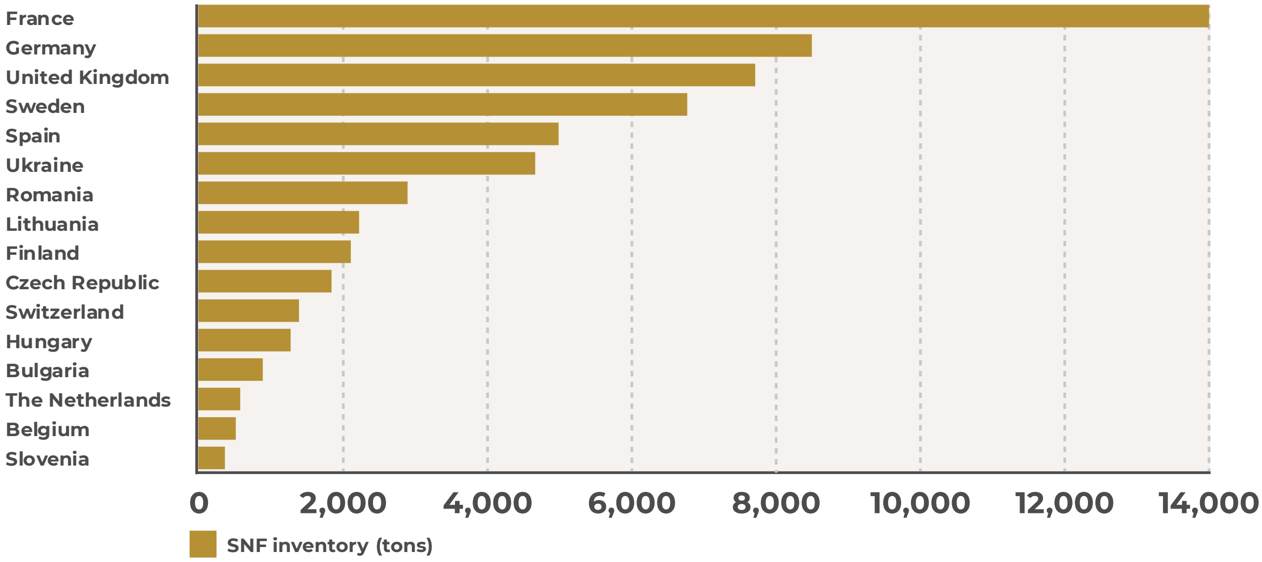
[57] Laraia, M. 2012, Nuclear decommissioning. Planning, execution and international experience.

In France, too, most of the low-level long-lived waste (LL-LLW) is going to be the graphite waste from the gas-cooled reactors, which will arise during the decommissioning of the GCRs. There is no disposal route, not even a theoretically, for the graphite waste.[58]

SPENT NUCLEAR FUEL AND HIGH-LEVEL WASTE

In most cases, the national inventories of spent nuclear fuel (SNF) are given in tons of heavy metal (t HM or Mg HM) or in numbers of fuel assemblies (FA). The reports for Belgium, Hungary, Lithuania, and Slovakia only provide the number of fuel assemblies; here the weight was calculated by assuming the weight per assembly (*see Table 3*). The most recent reports of the Ukraine, Netherlands, and Belgium did not contain any values for SNF, here values from previous reports were used. There are currently around 60,500 tons of spent nuclear fuel stored in various forms across Europe (excluding Russia, and Slovakia), with France, Germany and the UK accounting for nearly 50 percent. Within the EU, around 57,000 tons are stored, France accounts for 25 percent of the current SNF inventory, followed by Germany (15 percent) and the UK (14 percent). These three countries account for over half of the EU's SNF inventory. The inventory is much larger if spent nuclear fuel assigned for reprocessing was included, too.

FIGURE 3: Spent nuclear fuel in interim storage in Europe (excluding Russia, and Slovakia) in tons as of December 31, 2016



Source: Own depiction based on reports published under Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

Russia and Slovakia are excluded in *Figure 3* and *Table 3* as the published LILW category cannot be used for comparison (see above). Nonetheless, the two countries report the amounts of stored SNF: In Russia around 22,388 tons of SNF (with 92 percent of it in wet storage) and in Slovakia 13,102 fuel assemblies or 1,559 tons of SNF (all in wet storage) are stored.

Spent fuel is generally stored in reactor cooling pools or interim storage facilities. The latter can either be dry storage in casks, or wet storage in pools. As illustrated in the *chapter 4 Risks*, wet storage is more dangerous. *Table 3* provides an overview of the amount of SNF still stored in pools. It is found either inside the reactor building or in a separate storage facility. In 2016, 81 percent or about 49,000 tons of European SNF (excluding Russia and Slovakia) was still in wet storage. France and the UK, which account for 40 percent of the current EU inventory, have not transferred any SNF into dry storage.

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[58] Schneider et al. 2018, pp.144.

Even though a dry storage facility has been constructed in the UK at the Sizewell nuclear power plant, no data is given in the UK's reports on dry storage. The estimated total spent fuel arising from 40 years of operation at Sizewell B is just over 1,000 tons. EDF Energy's intention is to switch all the station's spent fuel from pools to dry storage by 2040. Only a few European countries have transferred the majority of the spent fuel into dry storage. Hungary (83 percent) and the Czech Republic (64 percent) have the highest rates of dry storage. No European country has yet installed a final disposal facility for SNF. With the continuing production of nuclear waste, the remaining storage capacity is decreasing. For example, storage capacity for SNF in Finland has reached already 93 percent saturation and the decentralized storage facility CLAB in Sweden 80 percent saturation.

TABLE 3: Reported spent nuclear fuel inventories in Europe and amount in wet storage as of December 31, 2016

Country	SNF inventory [tons]	Fuel Assemblies*	Wet Storage [tons]	SNF in wet storage [%]
BELGIUM	501**	4,173	237	47%
BULGARIA	876	4,383	788	90%
CZECH REPUBLIC	1,828	11,619	654	36%
FINLAND	2,095	13,887	2,095	100%
FRANCE	13,990	n.a.	13,990	100%
GERMANY	8,485	n.a.	3,609	43%
HUNGARY	1,261	10,507	216	17%
LITHUANIA	2,210	19,731	1,417	64%
THE NETHERLANDS	80***	266	80	100%
ROMANIA	2,867	151,686	1,297	45%
SLOVENIA	350	884	350	100%
SPAIN	4,975	15,082	4,400	91%
SWEDEN	6,758	34,204	6,758	100%
SWITZERLAND	1,377	6,474	831	60%
UKRAINE*	4,651****	27,325	4,081	94%
UNITED KINGDOM	7,700	n.a.	7,700	100%
TOTAL	**ca. 60,500**		**ca. 49,000**	**81%**

Source: Own depiction, based on reports under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

Notes: * SNF inventory calculations vary by weight per assembly assumptions: Belgium and Hungary assume 120 kg per assembly; Lithuania 112kg, Slovakia 119kg, and Romania 18.1 kg (Romania lists fuel assemblies in units of CANDU bundles). ** 2011 data (Belgium has not published more recent data). *** 2010 data (the Netherlands has not published more recent data). **** 2008 data (the Ukraine has not published more recent data).

Most countries had to send their SNF abroad for reprocessing to either France, the UK, or Russia (only a few central European countries continue to do so). Vitrified waste (mostly HLW) is sent back to the country of origin. With the closure of the THORP facility in the UK[59] in 2018, La Hague in France remains

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[59] Government of the UK 2018, "End of reprocessing at Thorp signals new era for Sellafield", news, viewed 12 June 2019, https://www.gov.uk/government/news/end-of-reprocessing-at-thorp-signals-new-era-for-sellafield

the last commercial reprocessing plant in Western Europe. After reprocessing has ceased, the THORP facility will continue to store between 5,500 to 6,000 tons of fuel.[60]

Central and Eastern European countries sent their SNF to the Russian Federation for reprocessing. Bulgaria, for example, had long-term commercial contracts for SNF reprocessing services with Russia but has stopped all SNF transports in 2014. Nevertheless, the option for future exports of SNF is still held open.[61] Bulgaria's latest Joint Convention report does not include any indication of the amounts of waste returned to Bulgaria.[62] In Hungary, SNF from Paks (in total 273 tons) was also transported back to the USSR/Russia for reprocessing. In the 1990s, however, Russia wanted Hungary to take back the residual radioactive waste and other by-products created during reprocessing.[63] To cope with the waste, Hungary started construction of a centralized interim storage facility in 1993. With the abandonment of reprocessing, Hungary has to store 1,261 tons of SNF and 102 m³ of HLW (as of December 31, 2016).

Another example of a country that abandoned reprocessing is Germany. Until mid-2005, German utilities sent their SNF to the UK or France for reprocessing. The separated plutonium was used for MOX fuel and reused in German light-water reactors. In the German inventory, the amounts of SNF reprocessed are around 42 percent or 6,343 tons.[64] *Table 4* gives an overview of the amounts of ILW and HLW waste from reprocessing in storage. More than half of the reported HLW comes from France. The only two countries specifying the amounts of ILW associated with reprocessing are France and Belgium.

TABLE 4: High-level and intermediate-level waste from reprocessing in storage as of December 31, 2016

Country	Active Reprocessing	HLW [m³]	ILW [m³]
BELGIUM	No	285	3,132
BULGARIA	No	n.a.	n.a.
FRANCE	Yes	3,740	42,800
GERMANY	No	577	n.a.
HUNGARY	No	102	n.a.
THE NETHERLANDS	Yes*	91	n.a.
RUSSIA	Yes	n.a.	n.a.
SPAIN	No	n.a.**	n.a.
SWITZERLAND	No	114**	n.a.
UNITED KINGDOM	No	1,960	n.a.

Source: Own depiction based on reports under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.
Notes: *in France. ** additional waste stored in France.

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[60] Government of the UK 2017, The United Kingdom's sixth national report on compliance with the obligations of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

[61] In the period between 2009 and 2014, 2,400 VVER-440 FA were transported to Russia.

[62] Government of Bulgaria 2017, Sixth National Report on fulfilment of the obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

[63] Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) 2017, "Hungary Report", viewed 12 June 2019, https://www.oecd-nea.org/rwm/profiles/hungary_report.pdf

[64] The report lists 6,670 tons of SNF being removed form the core for either reprocessing (in La Hague, Sellafield, WAK, and Belgium) or permanently remaining abroad (see Government of Germany 2018, -p.66.)

3.4 SUMMARY

European countries have produced several million cubic meters of nuclear waste (not even including uranium mining and processing wastes). By the end of 2016, France, the United Kingdom and Germany were Europe's biggest producers of nuclear waste along the nuclear fuel chain.

Over 60,000 tons of spent nuclear fuel are stored across Europe (excluding Russia and Slovakia), most of which in France. Within the EU, France accounts for 25 percent of the current spent nuclear fuel, followed by Germany (15 percent) and the United Kingdom (14 percent). Spent nuclear fuel is considered high-level waste. Though present in comparably small volumes, it makes up the vast bulk of radioactivity. In the UK, for instance, high-level waste amounted to less than 3 percent of nuclear waste's volume, but almost 97 percent of the inventory's radioactivity. Most of spent fuel has been moved into cooling pools (so-called wet storage) to reduce heat and radioactivity. As of 2016, 81 percent of Europe's spent nuclear fuel is in wet storage. It would be safer to transfer the spent nuclear fuel into dry storage in separate facilities.

A large share of the stored spent nuclear fuel in France and the Netherlands is planned to be reprocessed. Most other European nuclear countries (Belgium, Bulgaria, Germany, Hungary, Sweden, Switzerland, and most recently the UK) have indefinitely suspended or terminated reprocessing. Not all countries report about the quantities of spent fuel that have been reprocessed. In most cases only vitrified high-level waste from reprocessing is reported. The same accounts for the vast amounts of reprocessed uranium, plutonium, intermediate-level waste, and spent mixed oxide fuel (MOX) that requires an extensive additional intermediate storage period.

Around 2.5 million m^3 of low- and intermediate-level waste has been generated in Europe. This is a partial estimate as it excludes waste from Slovakia and Russia. Around 20 percent of this waste (0.5 million m^3) has been stored across Europe, waiting for final disposal. This amount is constantly increasing with no full disposal route anywhere. Around 80 percent of this waste (close to 2 million m^3) has been disposed of. However, this does not mean that the waste is successfully eliminated for the coming centuries. For instance, the Asse II disposal site in a former salt mine in Germany suffers from continuous inflow of groundwater. The 220,000 m^3 of mixed disposed waste and salt need to be retrieved, which is a complex and very costly task. The quantities are now five times the original amount of waste due to the mixture of salt and radioactive waste. Therefore, the term final disposal should be used with caution.

The decommissioning of nuclear facilities will create additional very large amounts of nuclear waste. Exclcuding fuel chain facilities, Europe's power reactor fleet alone may generate at least another 1.4 million m^3 of nuclear waste from decommissioning. This is a conservative estimate as decommissioning experiences are scarce. As of 2018, 142 nuclear power plants were in operation in Europe (excluding Russia and Slovakia).

The ongoing generation of nuclear waste and the upcoming decommissioning of nuclear facilities poses an increasing challenge, because storage facilities in Europe are slowly running out of capacity, especially for spent nuclear fuel. For example, storage capacity for spent fuel in Finland has reached already 93 percent saturation. Sweden's decentralized storage facility CLAB is at 80 percent saturation. However, not all countries report on saturation levels of storage capacities, making a complete overview impossible.

Over its lifetime, the European nuclear reactor fleet is estimated to produce around 6.6 million m^3 of nuclear waste (excluding Russia and Slovakia). If stacked in one place, this would fill up a football field 919 meters high, 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai. The calculation includes waste from operation, spent nuclear fuel, and reactor decommissioning. This estimate and the ones above are based on conservative assumptions. The actual quantities of nuclear waste in Europe are likely higher. With a share of 30 percent, France would be Europe's greatest producer of nuclear waste, followed by the UK (20 percent), the Ukraine (18 percent), and Germany (8 percent). These four countries account for more than 75 percent of the European nuclear waste.

Apart from Russia, which is still an active producer of uranium, Germany and France have the largest inventory of nuclear waste from uranium mining in Europe. Officially, the former French uranium mining industry generated 50 million tons of mining residues, but independent experts estimate that it is much higher. The former German Democratic Republic (GDR) mined much larger quantities of uranium ore than France. The mining legacies comprise some 32 km^2 of facility areas, 48 heaps with a volume of low active rocks of 311 million m^3 and four tailing ponds holding a total of 160 million m^3 of radioactive sludge. Today, the EU imports most uranium, creating large amounts of nuclear waste outside of Europe.

4 RISKS FOR THE ENVIRONMENT AND HUMAN HEALTH

Radioactive waste poses risks to the environment and human health. “Risk” is defined here as a function of both hazard and exposure: the most likely consequence of a hazard, combined with the probability of exposure to it. This chapter will focus on higher activity nuclear wastes (see chapter on classifications) and highlight potential unresolved dangers and problems. Although nuclear waste poses both radiological and chemical risks, it will concentrate on the former, as these are generally more serious.

Although risks arise from every step in the lengthy nuclear fuel chain, this chapter will focus on the hazards and risks of nuclear waste arising from the following:

- uranium mining, milling, enrichment, and fuel fabrication
- operation of nuclear power plants
- spent nuclear fuel
- reprocessing of spent nuclear fuel, and
- reactor decommissioning.

4.1 RADIATION RISKS OF NUCLEAR WASTE

Nuclear waste can give off several types of radiation: alpha particles, beta particles, and gamma rays. While alpha particles are most easily stopped, even by thin barriers such as paper, their effects are particularly damaging. They are very detrimental when inhaled or ingested and have a radiation weighting factor 20 times greater than gamma rays per unit of exposure. Beta particles are more penetrating than alpha particles, but can still be attenuated by denser materials such as plastic and aluminum. Gamma rays are highly penetrating; dense materials such as lead and thick concrete are required to attenuate them.

Radiation from radioactive waste is carcinogenic, mutagenic, and teratogenic (a teratogenic substance is one that can damage a fetus or embryo). Radiogenic[65] cancer risks depend on the type of cancer, the tissues exposed, the dose, dose rate, and type of radiation. The final risk to individuals will also depend on their gender, age, and the time that has passed since exposure. Radiation is also increasingly implicated in a wide range of other diseases including cardiovascular diseases, strokes, eye cataracts, and mental effects.

According to the International Commission on Radiological Protection (ICRP), an external whole-body radiation dose of one sievert (Sv) results in an approximately ten percent risk of fatal cancer in adults. However, the ICRP later reduced its estimate by half to five percent through its use of a dose and dose-rate effectiveness factor (DDREF) of two for solid cancers.[66] DDREFs were formerly used to reduce risks derived from the Japanese bomb survivors’ exposures to low dose and low dose-rate radiation. Older cell and animal studies had indicated these exposures were less harmful than those to higher doses

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[65] Radiogenic means produced by or determined from radioactivity.

[66] International Commission on Radiological Protection 2007, “The 2007 Recommendations of the International Commission on Radiological Protection”, ICRP publication 103.37

at higher dose rates. More recent human studies have now shown the use of DDREFs is incorrect.[67, 68] Since 2013, most international agencies have ceased using DDREFs, so the real risk of fatal cancer has increased to at least 10 percent per Sv. Unfortunately, the ICRP has not stopped using DDREFs.[69] Thus, governments and the ICRP have not recognized the perceived increased risks of radiation, nor tightened radiation limits. There is still no international consensus on the risks of radiation. What is clear, however, is that the ICRP's recommendations are conservative.

Radioactive waste can contain a wide range of radionuclides, whose atoms are unstable. When their nuclei disintegrate, they give off various forms of radiation. Many of these atoms have a high radiotoxicity, which is the degree to which a radionuclide can damage an organism. Their half-lives, the amount of time it takes for half the original amount present to decay, are often extremely long, they can be thousands or even millions of years.

In order to estimate the risk of a radionuclide to an organism, the following factors are important:

- radioactive decay modes: the emission of alpha particles, beta particles and gamma rays
- chemical compounds which contain the radioisotope
- solubility in water
- transport modes through the environment
- relative biological effectiveness: the ratio of damage from one type of radiation relative to another, given the same amount of absorbed energy
- radiotoxicity: usually based on specific activity, stated as radioactivity in bequerel (Bq) per gram
- dose conversion factor, which converts becquerel to sieverts.
- In most instances, exposures will be internal rather than external, so doses and risks will also depend on their uptake rates, metabolisms and excretion rates in humans.

No proper hazard classification scheme has yet taken the above factors into account for radionuclides. Such schemes already exist for chemicals and biocides, and calls have been made for such a scheme to be established for radioactive waste.[70]

4.2 RISKS FROM URANIUM MINING, MINE TAILINGS, ENRICHMENT, AND FUEL FABRICATION

Uranium mining, mine tailings, enrichment, and fuel fabrication are collectively termed the 'front end' of the nuclear fuel chain. Health risks arise at each of these stages. Uranium is a radioactive substance naturally existing in the earth's crust. Its deposits are more concentrated in areas of the world where

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[67] United Nations Scientific Committee on the Effects of Atomic Radiation 2014, "Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami." New York: United Nations Scientific Committee on the Effects of Atomic Radiation.

[68] World Health Organization 2013. Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami, based on a preliminary dose estimation.

[69] Valentin, J. 2005, Low-dose extrapolation of radiation-related cancer risk. Annals of the ICRP, 35(4), pp.1-140.

[70] Kirchner, G. 1990, A New Hazard Index for the Determination of Risk Potentials of Radioactive Waste Journal of Environmental Radioactivity, 11, pp. 71-95.

the ore is mined and processed. The resulting mining waste and slurries are the first nuclear waste in the nuclear fuel chain. It is widely recognized that exposures to uranium and its decay products are responsible for a major fraction of the total health and environmental impact from the nuclear fuel chain.[71] The industry states that global uranium mining has decreased by four percent from 2013-16, but the decline in global uranium mining has accelerated since.[72]

Practically no uranium mining occurs in the European Union at present, but clean-up and remediation continue at former mines in France, Germany, Portugal, the Czech Republic, and Romania. During mine rehabilitation efforts in the Czech Republic, Germany and Hungary, small quantities of uranium are recovered; it is unclear whether there is still a small quantity being mined (a few dozen tons per year) in Romania at present.

HEALTH RISKS FROM EXPOSURES TO URANIUM

The health risks associated with exposures to uranium (including depleted uranium[73]) include kidney disease, respiratory disorders, DNA damage, endocrine disruption, cancers, and neurological defects.[74, 75] Populations exposed to environmental uranium should be monitored for increased risk of fertility problems and reproductive cancers.[76]

Animal and cell studies have indicated that uranium's health detriments are due to its affinity for DNA[77] and to the potential combination of its chemical and radioactive properties, as uranium as a heavy metal has both chemical and radiological effects. It is theorized that these might play tumor-initiating and tumor-promoting roles respectively.[78] The report focuses on U-238, which makes up 99.27 percent of natural uranium.

The rest is comprised of U-235 (0.72 percent) and U-234, a decay product of U-238 (0.0055 percent). Uranium in ore is invariably accompanied by U-238's decay progeny.[79] Each of the above nuclides individually is estimated to be more dangerous than the parent U-238. Together, these decay products in uranium ore contain about [14] times more radioactivity than the parent U-238.

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[71] IAEA 2004, "Environmental Contamination from Uranium Production Facilities and Their Remediation." Proceedings Of An International Workshop On Environmental Contamination From Uranium Production Facilities And Their Remediation Organized By The International Atomic Energy Agency And Held In Lisbon, 11–13 February 2004.

[72] NEA and IAEA 2016, Uranium 2016: Resources, Production and Demand. NEA Report No. 7301.A, viewed 24 May 2019, https://www.oecd-nea.org/ndd/pubs/2016/7301-uranium-2016.pdf

[73] Depleted uranium (DU) is a by-product of uranium enrichment. It is controversial: in some countries it is used for radiation shielding and ammunition by military forces, while in others it is banned. Information about DU and its risks from a 2008 UN Institute for Disarmament Research report is available here: http://www.unidir.org/files/publications/pdfs/uranium-weapons-en-328.pdf

[74] Keith, S., Faroon, O., Roney, N., Scinicariello, F., Wilbur, S., Ingerman, L., Llados, F., Plewak, D., Wohlers, D. and Diamond, G. 2013, "Toxicological profile for uranium," public statement by the US Agency for Toxic Substances and Disease Registry.

[75] Wilson, J. and Thorne, M. 2015, "An assessment and comparison of the chemotoxic and radiotoxic properties of uranium compounds," ASSIST report to RWM

[76] Raymond-Whish, S., Mayer, L.P., O'Neal, T., Martinez, A., Sellers, M.A., Christian, P.J., Marion, S.L., Begay, C., Propper, C.R., Hoyer, P.B. and Dyer, C.A., 2007. Drinking water with uranium below the US EPA water standard causes estrogen receptor–dependent responses in female mice, Environmental health perspectives, 115(12), pp. 1711-1716.

[77] Miller, A.C., Stewart, M., Brooks, K., Shi, L. and Page, N. 2002, Depleted uranium-catalyzed oxidative DNA damage: absence of significant alpha particle decay, Journal of inorganic biochemistry, 91(1), pp. 246-252.

[78] Miller, A.C., Brooks, K., Smith, J. and Page, N. 2004, Effect of the militarily-relevant heavy metals, depleted uranium and heavy metal tungsten-alloy on gene expression in human liver carcinoma cells (HepG2), Molecular and cellular biochemistry, 255(1-2), pp. 247-256.

[79] Includes thorium-234, protactinium-234m, protactinium-234, thorium-230, radium-226, radon-222, polonium-218, actinium-218, radon-218, lead-214, bismuth-214, polonium-214, thallium-210, lead-210, bismuth-210, polonium-210, thallium-206, and finally lead-206, which is stable.

The most problematic decay product is radium-226 for three reasons: its salts are mainly soluble; it has a long half-life (1,760 years); and it emits gamma rays. Another dangerous nuclide is radon-222 (half-life 3.8 days). Because it is an odourless, colourless gas, it and its progeny, although invisible, are readily distributed in the environment. Exposures to radon gas are considered to be the second leading cause of lung cancer worldwide after smoking tobacco.[80] The US Environmental Protection Agency (EPA) has estimated that indoor radon exposure causes or contributes to about 21,000 lung-cancer deaths in the United States annually.[81]

Partly for these reasons, the ICRP estimated that a lifetime excess absolute risk of 5×10^{-4} per Working Level Month (WLM)[82] should be used as the risk coefficient for radon-induced lung cancer, doubling its previous estimate.[83] These cancer risks are expressed using either the Excess Relative Risk (ERR) model or the Excess Absolute Risk (EAR) model. ERR is the proportional increase in risk over the background rate (i.e. where people are not exposed). EAR is the additional risk above the background rate. However, several ICRP authors later added that the risk would have actually increased to 7 × 10-4 per WLM if lung cancer rates among Euro-American males had been used instead of inappropriate ICRP reference rates (namely males and females and Euro-American and Asian populations).[84] In other words, the estimated risk rates for most uranium mine workers have approximately tripled rather than doubled since 1993. This increased awareness of uranium mining's risks has not been reflected in tighter safety standards for uranium workers.

URANIUM MINING

Although many uranium mines are now closed, the past history of uranium mining throughout the world remains bleak, with many accidents and reports of ill health among uranium miners. Older epidemiology studies indicated significant excesses of lung cancer among uranium mining workers.[85]

Perhaps the best-documented example in Europe is the Wismut mine complex in former East Germany. The Soviet-run uranium mine complex was in operation until 1996. 59,000 of these miners employed between 1946 and 1989 were examined. Researchers found a significant increase in lung cancer risk with increasing radon exposure (ERR/WLM = 0.0019).[86] An update of this study found that the lung-cancer risk actually increased threefold (to ERR/WLM = 0.006) with the extended observation period to 2013.[87] Also, the authors found 3,942 miners from the cohort had died from lung cancer during their increased observation period from 1946 to 2013. Unfortunately, the new study omits the number of deaths from extra-pulmonary cancers, heart diseases and cerebro-vascular diseases which had been observed in the earlier cohort study.

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[80] Darby, S., Hill, D., Auvinen, A., Barros-Dios, J.M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M. and Heid, I. 2005, Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies, Bmj, 330(7485), pp. 223.

[81] Pawel, D.J. and Puskin, J.S. 2004, The US Environmental Protection Agency's assessment of risks from indoor radon, Health physics, 87(1), pp. 68-74.

[82] One working level (WL) refers to the concentration of short-lived decay products of radon in equilibrium of 3,700 Bq/m³ (100 pCi/L) in air. A working level month (WLM) is the exposure to one working level for 170 hours per month. It is conventionally assumed that 1 WLM = ~10 mSv.

[83] Tirmarche, M., Harrison, J.D., Laurier, D., Paquet, F., Blanchardon, E. and Marsh, J. 2010, Lung cancer risk from radon and progeny and statement on radon, Annals of the ICRP, 40(1), pp.1-64.

[84] Tirmarche, M., Harrison, J., Laurier, D., Blanchardon, E., Paquet, F. and Marsh, J. 2012, Risk of lung cancer from radon exposure: contribution of recently published studies of uranium miners, Annals of the ICRP, 41(3-4), pp.368-377.

[85] Grosche, B., Kreuzer, M., Kreisheimer, M., Schnelzer, M. and Tschense, A. 2006, Lung cancer risk among German male uranium miners: a cohort study, 1946–1998, British journal of cancer, 95(9), pp. 1280.

[86] Kreuzer, M., Grosche, B., Schnelzer, M., Tschense, A., Dufey, F. and Walsh, L. 2010, Radon and risk of death from cancer and cardiovascular diseases in the German uranium miners cohort study: follow-up 1946–2003, Radiation and environmental biophysics, 49(2), pp.177-185.

[87] Kreuzer, M., Sobotzki, C., Schnelzer, M. and Fenske, N. 2017, Factors modifying the radon-related lung cancer risk at low exposures and exposure rates among German uranium miners, Radiation research, 189(2), pp.165-176.

URANIUM MINE TAILINGS

After mining, milling and the removal of uranium from its ore, the residues are pumped to tailing piles or pools. Since the average uranium content in ore is typically about 0.1 percent to 0.15 percent, almost all of the ore winds up in the tailings. The result is very large amounts of tailings at uranium mines. For example, by 2016, Canadian mining companies had accumulated about 200 million tons of uranium mine tailings at closed mines and another 17 million tons at operating mines (excluding waste rock and contaminated water).[88]

Because of the large volumes of sulphuric acid used, high levels of heavy metals such as copper, zinc, nickel, and lead are mobilized, which are toxic to wildlife. Severe contamination of ground water constitutes a permanent risk. Health Canada, a department of the Canadian government, has warned that "the food chain can be contaminated unless appropriate mitigation is instituted. Fish, wildlife, vegetation, country foods, and drinking water are all at risk should spills or leakages occur. The need to manage the water from waste management areas is important, particularly if there are drinking water sources in the vicinity."[89]

Undisturbed ore contains all the radioactive daughter isotopes of uranium listed above in this section in secular equilibrium; its Becquerel amount thus remains constant. Uranium mill tailings contain all the products of the U-238 decay chain. The total radioactivity of these nuclides is approximately 80 percent of the radioactivity in the original ore, although the exact percentage depends on how long the ore has been exposed to air. Tailings can also contain significant quantities of hazardous chemicals such as copper, zinc, nickel, lead, arsenic, molybdenum, and selenium, depending upon the ore source and the reagents in the milling process.

Uranium tailings remain problematic because their radionuclides have multiple routes to living beings. Radon gas and the radioactive decay products of radon can be inhaled. Radioactive and toxic chemicals can be ingested with food and water, and external gamma radiation is emitted by the tailings. Contrary to popular belief, inhalation is the most important route as its collective doses are considerably larger than those from other exposure paths.

The existence of tailings piles and pools remains problematic because one of the decay products (thorium-230, which has a half-life 80,000 years) continues to generate the many nuclides in its decay chain for millennia. These accumulate under waste containers or they may penetrate or permeate them depending on the soil depths and the permeability of the types of containers currently in use. Such permeation means that radioactive lead-210 or polonium-210 can reach surface soils on top of tailings in high concentrations via plant uptakes (these materials have half-lives of 22.3 years and 138 days respectively).[90]

Few studies have quantified the risks from uranium mill tailings. In a 1983 report, the US Environmental Protection Agency estimated the lifetime excess lung cancer risk of residents living near a bare tailings pile of 80 hectares (0.8 $km^{2)}$) at two cases per hundred residents.[91] Radon gas from mill tailings can

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[88] Government of Canada 2016, Inventory of Radioactive Waste in Canada 2016, viewed 24 May 2019, https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/uranium-nuclear/17-0467%20Canada%20Radioactive%20Waste%20Report_access_e.pdf

[89] Government of Canada 2008, Canadian Handbook on Health Impact Assessment — Volume 4: Health Impacts By Industry Sector, viewed 24 May 2019, http://publications.gc.ca/collections/Collection/H46-2-04-363E.pdf

[90] Pérez-Sánchez, D. and Thorne, M.C. 2014, An investigation into the upward transport of uranium-series radionuclides in soils and uptake by plants, Journal of Radiological Protection, 34(3), pp. 545.

[91] US Environmental Protection Agency (EPA) 1983, "40 CFR Part 192 Environmental Standards for Uranium and Thorium Mill Tailings at Licensed Commercial Processing Sites," in: Federal Register Vol.48, No.196, Washington D.C. October 7 1983, pp. 45940. https://www.gpo.gov/fdsys/pkg/FR-1983-10-07/content-detail.html

spread with wind and rain, so that there is also a danger that people further away will also be exposed. While the risks to these individuals are expected to be small, they cannot be neglected as radiation risks extend down to zero dose. As potentially large numbers of people may be exposed, their collective doses and risks must be estimated.[92]

The health risks associated with uranium conversion and enrichment are mostly due to the inhalation and/or ingestion of uranium in its different chemical forms. In the U-235 enrichment process, uranium concentrate from milling (U3O8), which is also called yellowcake, is converted into uranium hexafluoride (UF6), a highly volatile gas that is extremely chemically reactive and radiologically toxic. In addition, UF6 gas immediately reacts with water vapor in air to form hydrofluoric acid (HF), which is even more reactive and highly toxic, causing pulmonary irritation, oedema, and corrosion of the lining of lungs at low concentrations. It also causes seizures and death in people exposed to high concentrations.[93]

4.3 RISKS FROM OPERATION

RISKS FROM GASES, LIQUIDS AND SOLID WASTE

During normal operation, nuclear power plants routinely produce a significant amount of solid waste as well as liquid and gaseous discharges.

Risks from routinely storing solid waste arise from limited storage space and insufficient safety on-site; they drastically increase if the nuclear waste is involved in malfunctions of, or accidents within, nuclear facilities. Given the planned lifetime extensions of nuclear power plants in many countries around the world,[94] the accumulation of hazardous operational waste in older nuclear power plants could induce additional exposure to radiation.

> *Given the planned lifetime extensions of nuclear power plants in many countries, the accumulation of hazardous operational waste in older nuclear power plants could induce additional exposure to radiation.*

In addition to solid waste, nuclear power plants also emit radioactive gases and liquids to the surroundings. The main radioactive releases are tritium (hydrogen-3, half-life of 12.3 years), carbon-14 (5,730 years), krypton-85 (10.8 years), argon-41 (1.8 hours), and a number of iodine isotopes including iodine-129 (16 million years). The majority of annual air emissions (about 70 to 80 percent) are released during annual refueling. These increase the estimated doses to residents nearby by a factor of at least 20 compared to releases averaged over a year.[95] The main risk drivers are the emissions of tritium and carbon-14. Although the emissions of radioactive noble gases are slightly greater than those of tritium, these inert gases are not thought to contribute significantly to overall doses from reactor emissions.

Gaseous emissions result in greater individual and collective doses than liquid discharges do. They may contribute to a higher risk to develop leukemia near nuclear power plants. The first recorded leukemia

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[92] Fairlie, I. and Sumner, D. 2000, In Defence of Collective Dose, Journal of Radiological Protection, 20(1), pp. 9.

[93] US National Library of Medicine (NLM), undated, Uranium Hexafluoride. CASRN: 7783-81-5, viewed 29 May 2019, https://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+4501

[94] Schneider et al. 2018

[95] UK Health Protection Agency 2011, “Short-Term Releases to the Atmosphere” National Dose Assessment Working Group, viewed 29 May 2019, https://srp-uk.org/resources/national-dose-assessment

cluster near nuclear facilities in Europe was in 1984 in the UK near the Sellafield nuclear facility. In subsequent years, increased incidences of childhood leukemia occurred near other nuclear facilities in the UK,[96,97] in France,[98] and in Germany.[99]

In 2008, the German government published a major epidemiology study called Childhood Cancer in the Vicinity of Nuclear Power Plants. This report found a 120 percent increase in leukemia and a 60 percent increase in all cancers among infants and children under five years old living within five kilometers of all German reactors.[100, 101] The increase of risk with proximity to the reactor site was statistically significant for all cancers. The study reignited the international debate on childhood leukemia near nuclear power plants. Researchers undertook similar studies in the UK,[102] France,[103] and Switzerland.[104] Taken together, the research provides strong statistical evidence that leukemia increases near nuclear reactors.

Various studies have identified several possible causes for the phenomenon, including pre-paternal exposures to occupational doses received by fathers,[105] a postulated virus from population-mixing,[106] an unusual response to infectious diseases in children,[107] a genetic pre-disposition to cancer, high labelling of the embryos/fetuses of pregnant women near nuclear power plants,[108] or a combination of these factors. Whatever the final explanation, the evidence worldwide shows that living near nuclear reactors entails serious health risks for babies and young children.[109] While the evidence of association strongly suggests living near nuclear power presents serious health risks the causes cannot be definitively determined and so the issue remains controversial.

RISKS TO NUCLEAR WORKERS

Over the past two decades, the average exposures of nuclear workers in European countries have generally declined. Much of the collective dose continues to be received by temporary workers, nuclear

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[96] Forman, D., Cook-Mozaffari, P., Darby, S., Davey, G., Stratton, I., Doll, R., and Pike, M. 1987, Cancer near nuclear installations, Nature, 329(6139), pp. 499-505.

[97] Gardner, M.J. 1991, Father's occupational exposure to radiation and the raised level of childhood leukemia near the Sellafield nuclear plant, Environmental health perspectives, 94, pp.5-7.

[98] Pobel, D. and Viel, J.F. 1997, Case-control study of leukemia among young people near La Hague nuclear reprocessing plant: the environmental hypothesis revisited, Bmj, 314(7074), pp. 101.

[99] Baker, P.J. and Hoel, D.G. 2007, Meta-analysis of standardized incidence and mortality rates of childhood leukaemia in proximity to nuclear facilities, European Journal of cancer care, 16(4), pp. 355-363.

[100] Kaatsch, P., Spix, C., Schulze-Rath, R., Schmiedel, S. and Blettner, M. 2008, Leukemia in young children living in the vicinity of German nuclear power plants. International Journal of Cancer, 122(4), pp. 721-726

[101] Spix, C., Schmiedel, S., Kaatsch, P., Schulze-Rath, R. and Blettner, M. 2008, Case–control study on childhood cancer in the vicinity of nuclear power plants in Germany 1980–2003, European Journal of Cancer, 44(2), pp. 275-284.

[102] UK Committee on Medical Aspects of Radiation in the Environment 2011, "Further Consideration of the Incidence of Childhood Leukemia Around Nuclear Power Plants in Great Britain, 14th Report," COMARE

[103] Sermage-Faure, C., Laurier, D., Goujon-Bellec, S., Chartier, M., Guyot-Goubin, A., Rudant, J., Hémon, D. and Clavel, J. 2012, Childhood leukemia around French nuclear power plants—the Geocap study, 2002–2007, International journal of cancer, 131(5), pp. E769-E780.

[104] Spycher, B.D., Feller, M., Zwahlen, M., Röösli, M., von der Weid, N.X., Hengartner, H., Egger, M., Kuehni, C.E., Swiss Paediatric Oncology Group and Swiss National Cohort Study Group 2011, Childhood cancer and nuclear power plants in Switzerland: a census-based cohort study, International journal of epidemiology, 40(5), pp.1247-1260.

[105] Gardner, M.J., Snee, M.P., Hall, A.J., Powell, C.A., Downes, S. and Terrell, J.D. 1990, Results of case-control study of leukemia and lymphoma among young people near Sellafield nuclear plant in West Cumbria. Bmj, 300(6722), pp. 423-429.

[106] Kinlen, L.J. 2004, Childhood leukemia and population mixing, Pediatrics, 114(1), pp. 330-331.

[107] Greaves, M. 2006, Infection, immune responses and the aetiology of childhood leukemia, Nature Reviews Cancer, 6(3), pp.193.

[108] Fairlie, I. 2014, A hypothesis to explain childhood cancers near nuclear power plants, Journal of environmental radioactivity, 133, pp. 10-17.

[109] Laurier, D., Jacob, S., Bernier, M.O., Leuraud, K., Metz, C., Samson, E. and Laloi, P. 2008, Epidemiological studies of leukemia in children and young adults around nuclear facilities: a critical review, Radiation Protection Dosimetry, 132(2), pp. 182-190.

sub-contractor workers, and the operators of fuel chain facilities. Although exposures may be declining, the perceived risks from them are increasing. In 2015, a large epidemiology study[110] by scientists from national health institutes in the US, UK, and France of over 300,000 nuclear workers found that their leukemia risks were more than double those found in an earlier study.[111] A few months later a second study– this time for all solid cancers[112] — done by largely the same team of scientists found large absolute risks of solid cancers, with 47 percent per Gray (Gy)[113] much higher than researchers had expected. These risks are considerably larger than the ICRP's estimate of 5 percent per Gy.

4.4 RISKS FROM SPENT NUCLEAR FUEL

After nuclear fuel has undergone fission for three to four years, it is termed 'spent' and is placed in cooling pools. However, the adjective 'spent' is misleading as the fuel continues to emit large amounts of radiation for tens of thousands of years. For example, even after ten years' cooling, radiation dose rates from unshielded used fuel assemblies range from 1 to 100 Gy per hour depending on the type of fuel, its burnup, and how long it has been out of the reactor. A dose of 4 to 5 Gy is usually considered lethal.[114] An unshielded, freshly unloaded spent fuel element delivers a lethal dose at one-meter distance in less than one minute.

For this reason, spent fuel is either transferred under water, transported in heavily shielded casks to fuel ponds at reactor sites, or transferred into equally shielded dry store casks. Exposure rates near these casks vary considerably according to the type of fuel (uranium oxide or uranium-plutonium mixed oxide) fuel utilization or 'burnups' and the age of the spent fuel. Dose rates are estimated at 1 meter from German Castor dry store casks to be about 0.1 mSv/hour, for French TN28 flasks 0.04 mSv/hour.[115]

Countries have different regulations for how high dose-rates workers can be exposed to. In Canada, maximum allowable exposures to workers near dry store flasks are 2 mSv/hour at contact with the flask surface and 0.1 mSv/hour at one meter away. In the US, NRC regulations limit exposures to 10 mSv/hour at contact and 0.1 mSv/hour two meters away. Spent nuclear fuel contains most of the radioactivity in the world's nuclear waste, and consists of fission and activation products.[116]

RISKS OF SPENT FUEL IN POOLS

The continued practise of storing spent nuclear fuel for long periods in pools at most nuclear power plants worldwide constitutes a major risk to the public and to the environment.[117] Spent fuel pools must

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[110] Leuraud, K., Richardson, D.B., Cardis, E., Daniels, R.D., Gillies, M., O'hagan, J.A., Hamra, G.B., Haylock, R., Laurier, D., Moissonnier, M. and Schubauer-Berigan, M.K. 2015, Ionising radiation and risk of death from leukaemia and lymphoma in radiation-monitored workers (INWORKS): an international cohort study, The Lancet Haematology, 2(7), pp. e276-e281

[111] Cardis, E., Vrijheid, M., Blettner, M., Gilbert, E., Hakama, M., Hill, C., Howe, G., Kaldor, J., Muirhead, C.R., Schubauer-Berigan, M. and Yoshimura, T. 2005, Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries, Bmj, 331(7508), pp. 77

[112] Richardson, D.B., Cardis, E., Daniels, R.D., Gillies, M., O'Hagan, J.A., Hamra, G.B., Haylock, R., Laurier, D., Leuraud, K., Moissonnier, M. and Schubauer-Berigan, M.K. 2015, Risk of cancer from occupational exposure to ionising radiation: retrospective cohort study of workers in France, the United Kingdom, and the United States (INWORKS), bmj, 351, pp. h5359

[113] The gray is a derived unit of ionizing radiation dose. It is defined as the absorption of one joule of radiation energy per kilogram of matter

[114] US Nuclear Regulatory Commission 2019, "Legal Dose", Online glossary entry, viewed 29 May 2019, https://www.nrc.gov/reading-rm/basic-ref/glossary/lethal-dose-ld.html

[115] Wilkinson, W. 2006, Radiation Dose Assessment for the Transport of Nuclear Fuel Cycle Materials, World Nuclear Transport Institute, viewed 24 May 2019, https://www.wnti.co.uk/media/31656/IP8_EN_MAR13_V2.pdf

[116] The major activation products are plutonium-239, plutonium-240, plutonium-241, plutonium-242 and tritium. A series of 'minor' actinides are also formed: neptunium-237, curium-242, curium-244, americium-241, and americium-243. In addition, approximately 700 fission products are formed in spent fuel, most of them short-lived. The main risk drivers include caesium-134, caesium-137, strontium-90, technecium-99 and cobalt-60 as these have longer half-lives and emit powerful gamma rays. Tritium (H-3), the radioactive isotope of hydrogen, is also formed as a tertiary fission product.

[117] Alvarez, R. 2011, Spent Nuclear Fuel Pools in the US, Institute for Policy Studies.

be constantly monitored, continually cooled to remove decay heat, and chemically adjusted to ensure correct alkalinity levels. If cooling were to fail for any reason, the pools would fully evaporate within a few days and the fuel assemblies could ignite as their zirconium cladding would react strongly with oxygen in air.[118] The same would occur if the pond waters were emptied for any reason, such as a breach of the walls of the pools caused by a terrorist attack. These problems grow worse over time by the fact that the lengths of time spent fuel stays in pools has been increasing and now routinely extend for several decades.

> *The continued practise of storing spent nuclear fuel for long periods in pools at most nuclear power plants worldwide constitutes a major risk to the public and to the environment. Spent nuclear fuel contains most of the radioactivity in the world's nuclear waste, and consists of fission and activation products.*

In 2014, the US Nuclear Regulatory Commission (NRC) examined whether to require most spent fuel currently held in pools at nuclear power plants to be moved into dry casks and storage vaults. Such a move would reduce the likelihood and consequences of a spent fuel pool fire. It concluded that the projected benefits did not justify the estimated US$4 billion cost of a wholesale transfer.[119]

However, the NRC report was criticized for seriously underestimating the risk and consequences of a spent fuel fire: models of a potential accident at US nuclear fuel storage sites estimated very serious effects of hypothetical radionuclide releases.[120] They contained maps illustrating the radioactive plumes across large areas of northeastern United States. The lead author, Professor Frank von Hippel, Princeton University, warned of drastic economic consequences: "We're talking about trillion-dollar consequences."[121] This risk not just affects the US but most countries that operate nuclear power plants, where increasing amounts of spent fuel are being left in cooling pools for increasingly long periods of time.

The absence of robust proven technical solutions and the existence of political opposition to plans for nuclear waste facilities make this difficult situation even more problematic. The present situation poses considerable challenges for current governments and future generations.

In the meantime, it is widely accepted that spent nuclear fuel requires well-designed storage for long periods to minimize the risks of releases of the contained radioactivity to the environment. Safeguards are also required to ensure that neither plutonium nor highly enriched uranium is diverted to weapons use.

4.5 RISKS FROM THE REPROCESSING OF SPENT NUCLEAR FUEL

Two main means exist for managing spent nuclear fuel: long-term storage with the ultimate aim of direct disposal and reprocessing. This section discusses the latter method. In the 1950s and 1960s, during the Cold War, countries constructed reprocessing plants in order to create weapons with plutonium separated from spent fuel.

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[118] von Hippel, F.N. and Schoeppner, M. 2016, Reducing the danger from fires in spent fuel pools, Science & Global Security, 24(3), pp. 141-173.

[119] Barto, A. 2014, Consequence study of a beyond-design-basis earthquake affecting the spent fuel pool for a US Mark I boiling water reactor, United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

[120] von Hippel, F.N. and Schoeppner, M. 2017, Economic Losses from a Fire in a Dense-Packed US Spent Fuel Pool, Science & Global Security, 25(2), pp.80-92.

[121] Stone, R. 2016, "Spent fuel fire on US soil could dwarf impact of Fukushima", Science, May 24, viewed 25 May 2019, https://www.sciencemag.org/news/2016/05/spent-fuel-fire-us-soil-could-dwarf-impact-fukushima

Reprocessing involves the dissolution of spent fuel in boiling concentrated nitric acid followed by the physico-chemical separation of plutonium and uranium from the dissolved fuel. This difficult, complex, expensive and dangerous process results in numerous nuclear waste streams, very large releases of nuclide waste to air and sea, and large radiation exposures to workers and to the public.

Only about 15 percent of the world's spent nuclear fuel is reprocessed. Most countries have abandoned the reprocessing option and currently only France and Russia practice plutonium separation on a commercial scale. These countries that have historically carried out the work for a range of other countries now mainly process their own fuel. Reprocessing creates large quantities of highly active liquid (HAL) waste, which are heat-producing and extremely radioactive. As described below, liquid waste presents severe problems for current waste management. Originally, liquid waste was to be glassified and stored in a more manageable solid form called vitrified waste. However, such processes, though implemented rather successfully in France, have proved difficult in the UK and the US, and much of this waste may remain in liquid form for the immediate future. In addition to HAL waste, reprocessing also results in the following waste streams:

- Emissions of radionuclides in the air
- Discharge of radionuclides into the sea
- Large stockpiles of separated plutonium
- Tens of thousands of drums with separated reprocessed uranium
- Thousands of steel canisters containing vitrified waste
- Radioactive graphite from AGR fuel sleeves and decommissioned reactors
- Concrete silos filled with fuel claddings stripped from spent fuel, and
- Many other radioactive waste, including sludges, resins, and filters.

The collective doses to the world's population from the long-lived gaseous nuclides C-14, and I-129, and from medium-lived Kr-85 and H-3 (tritium) emitted at Sellafield and La Hague are very large, much higher than for nuclear power plants. While any discharge of alpha emitters is prohibited at reactor sites, it is authorized at La Hague within the limits of 0.01 GBq in gaseous and 140 GBq in liquid effluents.[122]

The global collective dose, truncated at 100,000 years, resulting from the discharges of the La Hague reprocessing facility alone has been calculated to be 3,600 person sieverts per year.[123] Continuing discharges at similar levels for the years of La Hague's operational life until 2025 would cause over 3,000 additional cancer deaths globally, if the linear no-threshold theory of radiation is applied.

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[122] Schneider, M., and Marignac, Y. 2008, "Reprocessing of Spent Nuclear Fuel in France", International Panel on Fissile Materials, Research Report #4, viewed 24 May 2018, http://fissilematerials.org/publications/2008/05/spent_nuclear_fuel_reprocessin.html

[123] Smith, R., Bexon, A., Sihra, K., Simmonds, J.2007, "The calculation, presentation and use of collective doses for routine discharges," In Proceedings of IRPA12: 12. Congress of the International Radiation Protection Association: Strengthening Radiation Protection Worldwide-Highlights, Global Perspective and Future Trends.

FISSILE MATERIALS

The original purpose of reprocessing was to obtain fissile plutonium for nuclear weapons. This rationale has changed over the years, at least since the mid-1990s, when the major nuclear weapon states ceased the separation of plutonium for military purposes. Moreover, in 2017, the UN General Assembly agreed the Treaty on the Prohibition of Nuclear Weapons, a legally binding international agreement to comprehensively prohibit nuclear weapons. Countries that persist with reprocessing face particular challenges of proliferation and security risks, such as the vulnerability to terrorist attacks.

In 2007, the UK's prestigious Royal Society warned that the potential consequences of a major security breach or accident involving the UK's stockpile of separated plutonium "are so severe that the Government should urgently develop and implement a strategy for its long term use or disposal."[124] These stocks amounted to 100 tons in 2007. By 2017, they had increased to 140 tons.[125] In the past 10 years, successive UK Governments have failed to develop a policy for this fissile waste. Japan faces a similar dilemma with a large stock of separated plutonium, a commercial reprocessing plant under construction, and only a small plutonium absorption capacity. France, however, remains the only country legally committed to large-scale reprocessing.

MIXED OXIDE FUEL (MOX)

A later justification for reprocessing was the goal to use the separated plutonium oxide in plutonium-uranium mixed oxide (MOX) nuclear fuel, first for Fast Breeder Reactors (FBRs), then as substitute for uranium fuel for Light Water Reactors (LWRs). FBR programs have been terminated in most countries and MOX fuel has proved to be several times more expensive than uranium fuel because of indispensable additional safety and security measures. Spent MOX fuel is not reprocessed anywhere, as the plutonium quality is degraded, and it is significantly more radioactive and hotter when it exits reactors. Compared to uranium fuel, MOX requires either over a century longer cooling periods in intermediate storage, or at least three times more space in a final repository. This has serious economic consequences as the inventory of a waste repository is generally limited by the thermal load.

4.6 DECOMMISSIONING RISKS

Once a nuclear power plant is closed, the spent fuel has to be removed, cooling systems and moderators drained. The process of defueling, deconstruction, and dismantling of a nuclear power plant is called decommissioning. In 2018, 154 nuclear reactors worldwide were awaiting, or are in various stages of decommissioning. Another 19 had been fully decommissioned, mostly in the US (13) and Germany (5). The average duration of reactor decommissioning is around 19 years, in most cases longer than the construction and operational period of the reactor combined.[126]

A reactor is considered "fully decommissioned", when the reactor building has been entirely emptied and can be put to other use or when every building has been removed but the spent fuel is still on-site. The decommission state is considered "greenfield" if all buildings and waste have been removed and the site can be freely used for other purposes. Only 10 of the 19 reactors fully decommissioned so far have reached the greenfield status. In some cases graphite reactor cores remain in situ in shielded buildings for later dismantlement.

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[124] The Royal Society 2007, Strategy options for the UK's separated Plutonium, Policy document 24/07, viewed 29 May 2019, https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2007/8018.pdf

[125] Department for Business, Energy and Industrial Strategy (DBEIS) 2017, The United Kingdom's Sixth National Report on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel and Radioactive Waste Management, viewed 25 May 2019, https://www.gov.uk/government/publications/the-uks-sixth-national-report-on-compliance-with-the-obligations-of-the-joint-convention-on-the-safety-of-spent-fuel-and-radioactive-waste-management

[126] Schneider et al. 2018

These two basic strategies for decommissioning are Immediate Dismantling (ID) and Long-Term Enclosure (LTE, termed “SAFSTOR” in the US). In general, ID is preferable as the skills and experiences of operating staff can be used, a clear line of responsibilities still exists, public interest is continuing, and the finance set aside is more likely to match the necessary work. Some large nuclear countries like France and Germany have made ID their principle policy. LTE usually runs the risk of losing human competences, clear lines of responsibility, corporate continuity and public interest, thus dragging out decommissioning for decades.

CONTINUED RADIONUCLIDE EMISSIONS FROM DECOMMISSIONED REACTORS

A variety of radionuclides are released not only from operating reactors but also from closed ones, especially gaseous emissions of tritium and carbon-14. Nuclide emissions data in the UK Government’s annual Radioactivity in Food and the Environment (RIFE) publication reveal that the Winfrith reactors which closed in 1995 still emitted two trillion (2 x 1012) becquerels per year of tritium in 2016, more than 20 years later.[127] Similar patterns are observed at the long-closed reactors at Trawsfynydd, Dounreay, Chapelcross and all closed Magnox stations. In Canada, the small experimental reactors at Whiteshell and Rolphton, which were closed over 30 years ago, are still reported as emitting large quantities of tritium each year. The available data so far only concern Magnox and heavy water reactors. During their operations, high concentrations of tritium and C-14 are absorbed into the concrete and steel structures of Magnox and HWR reactors and their containment structures. After the cessation of fission, these nuclides continue to seep out over decades-long time scales.

DECOMMISSIONING VS OPERATIONAL EXPOSURES

It has been claimed that worker exposures from reactor decommissioning will be significant and that decommissioning should be postponed for as long as possible. However, the European Commission (EC) has calculated that the dose reduction from the closure of a nuclear plant is considerably greater than the impact of its decommissioning. The EC estimated that the collective dose from atmospheric emissions during decommissioning of a nuclear facility in the EU in 2004 was about 2 person-sieverts per year, compared to about 150 person-sieverts per year from the operation of each nuclear facility in the EU.[128]

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[127] Scottish Environment Protection Agency (SEPA) 2017, Radioactivity in Food and the Environment. RIFE Report 22, viewed 24 May 2019, https://www.sepa.org.uk/media/328601/rife-22.pdf

[128] European Commission 2007, Guidance on the calculation, presentation and use of collective doses for routine discharges, Radiation Protection Report 144. Directorate-General for Energy Directorate D— Nuclear Energy Unit D.4 — Radiation Protection.

4.7 SUMMARY

Nuclear waste constitutes a health hazard for several reasons. First are the reported health impacts from routine gaseous and liquid waste emissions from nuclear facilities. Second are the very large global collective doses from nuclear reprocessing. And third is the unsatisfactory and unstable condition of much of the nuclear waste already created. High-level waste (HLW) in the form of spent nuclear fuel and vitrified waste from reprocessing contains more than 90 percent of the radioactivity in nuclear waste. However, there is no fully operational HLW final disposal site in the world. The continued practise of storing spent nuclear fuel for long periods in pools at most nuclear power plants worldwide constitutes a major risk to the public and to the environment. Spent nuclear fuel contains most of the radioactivity in the world's nuclear waste, and consists of fission and activation products.

Estimates of the impacts of an operational HLW disposal remain speculative, but HLW still poses key questions of intergenerational liability and justice. The very long time-frames involved—the half life of Pu-239 is over 24,000 years—remains the single most important factor distinguishing nuclear waste from other kinds of waste.

Reprocessing of nuclear fuel creates more accessible forms of highly dangerous radioactive wastes, proliferation problems, high exposures to workers and the public, and radioactive contamination of the air and seas.

Only few countries do publish information, for example, on nuclide inventories in wastes. Such data collection and dissemination are primarily the responsibility of national governments. The data is needed to properly assess risks from nuclear waste and develop hazard rankings which tie observed health effects to exposures. So far, no comprehensive hazard scheme exists for the radionuclides in nuclear waste.

Risks may be derived from epidemiological studies, but the few that exist are of limited quality. Some studies suggest increased cancer rates, for example, but are individually too small to give statistically significant results. Meta-analyses could combine smaller studies to generate larger datasets which do produce statistically significant findings. However, meta-analyses on nuclear waste are notable for their virtual absence. The result is that many small studies continue to be criticized for their lack of statistical significance.

Finally, in order to assess risks, it is also necessary to have accurate doses, but these are often not measured in epidemiology studies. Even if they do exist they can often be unreliable due to the large uncertainties which surround them.

5 WASTE MANAGEMENT CONCEPTS

5.1 HISTORICAL BACKGROUND

The management of nuclear waste over the past seven and a half decades requires a brief historical introduction. Nuclear technology is a child of war[129] and the ensuing conflict between the Western and Eastern power blocs.[130] Only the "Atoms for Peace" program announced by US President Dwight Eisenhower on the occasion of the UN General Assembly on December 8, 1953 opened the way for the use of nuclear energy for energy production.[131] But the two programs remained from the outset as "Siamese twins", the then-chairman of the US Atomic Energy Commission (AEC), Gordon Dean, stated in 1950.[132] Under the post-war conditions prevailing at the time, the nuclear waste produced primarily in the large military production facilities was transferred to the environment at nearly zero costs.[133] The standard disposal practices at the time included direct discharge of cooling water from military reactors into the Columbia River,[134] the burial and seepage of solid and liquid low-, medium- and even diluted high-level waste on the premises of military laboratories,[135] the dumping of solid waste in the sea,[136] as in the case of Farallon Island west of San Francisco,[137] or the discharge of liquid waste from the Sellafield reprocessing plant into the Irish Sea.[138]

From the 1950s onwards, corrections were made to this practice and the first orderly program ideas for nuclear waste disposal were defined. The risks of diluting nuclear waste in water were addressed more openly. The containment of radioactive substances was assumed to be mandatory by the turn of the century in view of the expected strong worldwide growth in nuclear waste: "Even ignoring the problems of inadequate mixing and reconcentration by marine life, it is clear that dispersal alone cannot be the long-term answer to the waste storage problem. Even the oceans are not big enough to hold the activity which conceivably may be produced. One is forced to turn, then, to some form of containment."[139] The search for containment techniques and disposal options was intensified. Initial proposals were made for

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[129] Rhodes, R. 1986, The Making of the atomic bomb, Simon & Schuster New York

[130] Stöver, B. 2017, Der kalte Krieg, Geschichte eines radikalen Zeitalters, 1947-1991 (The Cold War: History of a Radical Age), C.-H. Beck.

[131] Krige, J. 2010, Techno-Utopian Dreams, Techno-Political Realities: The Education of Desire for the Peaceful Atom, in Gordin, Michael D., Tilley, Helen, Prakash, Gyan (Edts.), Utopia/Dystopia, Conditions of Historical Possibility, Princeton University Press, pp. 151-175. http://www.geosociety.org/documents/gsa/memorials/v16/Goodman-C.pdf

[132] Dean, G. 1950, Problems of Atomic Energy Commission, Nucleonics, 6(5), May 1950, pp. 5-10.

[133] Western, F. 1948, Problems of Radioactive Waste Disposal, Nucleonics, August 1948, pp. 43-49.

[134] Honstead, J. F., Foster, R. F., Bierschenk, W. H. 1959, Movement of Radioactive Effluents in Natural Waters at Hanford in International Atomic Energy Agency, Disposal of Radioactive Wastes, Vol. 2, Conference Proceedings, Monaco, 16-21 November 1959

[135] Pearce, D. W., Linderoth, C. E., Nelson, J.L., Ames, L.L. 1959, A Review of Radioactive Waste Disposal to the Ground at Hanford, pp. 347-363, in International Atomic Energy Agency, Disposal of Radioactive Wastes, Vol. 2, Conference Proceedings, Monaco, 16-21 November 1959

[136] Scott, K.G. 1950, Radioactive Waste Disposal – How Will It Affect Man's Economy? Nucleonics, 6:1, January 1950, pp. 18-25.

[137] Jones, D.G. et al. 2001, Measurement of Seafloor Radioactivity at the Farallon Islands Radioactive Waste Dump Site, California, Open-File Report 01-62, USGS, BGS, EPA, NOAA, viewed 31 July 2019, https://pubs.usgs.gov/of/2001/of01-062/

[138] Fair, D. R. R., McLean, A. S. 1956 Décharge de déchets radioactifs dans la mer d'Irlande, Troisième partie: Evacuation expérimentale d'effluents radioactifs (Discharge of radioactive waste in the Irish Sea, Part III: Experimental disposal of radioactive waste), Actes de la Conférence internationale sur l'utilisation de l'énergie atomique à des fins pacifiques, Geneva 8-10 August 1955, Volume IX.

[139] Rodger, W. A. 1954, Radioactive Wastes – Treatment, Use, Disposal, Chemical Engineering Progress, 50(5), pp. 263-266.

the introduction or melting of nuclear waste into cements,[140] glass, or ceramic matrixes,[141] and their final disposal in geological subsoil,[142] in desert areas,[143] or in disused mines or deep wells.[144] These proposals were put into concrete terms over the years, although implementation is still to come.

In the late 1940s, the AEC and the various laboratories involved raised the issue of disposal in expert discussions.[145] Cooperation with experts, universities and industry became increasingly institutionalized from the 1950s onwards. In September 1955, a meeting on the questions of storage and disposal took place at Princeton University[146], which was followed by further exchanges,[147] partly in connection with the international conferences that took place beginning in August 1955 under the auspices of the United Nations.[148] From 1955, the AEC also called on the American National Academy of Sciences (NAS), which in 1957 published a much-acclaimed report on the disposal of nuclear waste, outlining the current state of knowledge and the current disposal strategies.[149] It describes mines as particularly interesting disposal facilities and salt formations as particularly suitable host rocks. Parallel to this, the NAS published a second report of its committee "on the effects of atomic radiation on oceanography and fisheries", which signaled a certain caution in the implementation of the strategy for the disposal of radioactive waste in the seas.[150]

The first specific research projects in disused salt mines started in the US.[151] This research was carried out at the Carey Salt Mine in Hutchinson, Kansas, where field-experiments with small amounts of high-level reprocessing waste were performed as early as the end of the 1950s.[152] These experiments served to understand the temperature development in the salt cavities and in the deposited waste as well as reactions between waste and salt. At the end of the 1960s, the Oak Ridge National Laboratory (ORNL), the supporting organization of these experiments, proposed the mine as a repository[153] Over the next years, a severe conflict took place between the ORNL and federal government agencies on one side and the affected state of Kansas on the other. The project was eventually abandoned after a geologist discovered 29 former gas and oil drillholes in the mining area and the hydraulic hazards became manifest.[154] In addition there were major uncertainties regarding "solution mining" in an adjacent mine as well regarding the risk of mine collapse of a near area to the planned repository.[155]

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[140] Hatch, L.P. 1953, Ultimate disposal of Radioactive Waste, American Scientist, 41(3), pp. 410-421.

[141] Herrington, A.C., Shaver, R.G., Sorenson, C.W., 1953, Permanent Disposal of Radioactive Wastes, Economic Evaluation, Nucleonics, 11(9), September 1953, pp. 34-37.

[142] Morton, Roy J., Struxness, Edward G. 1956, Ground Disposal of Radioactive Wastes, American Journal of Public Health, February 1956, pp. 156-163.

[143] Glueckauf, E. 1955, The Long-Term Aspects of Fission Product Disposal, Atomics, pp. 274.

[144] Theis, Charles V. 1956, Problèmes relatifs à l'enfouissement des déchets nucléaires (Problems related to the disposal of nuclear waste), Actes de la Conférence Internationale sur l'Utilisation de l'Energie Atomique à des Fins Pacifiques, Geneva 8-20 August 1955, Vol. IX, pp. 774-779.

[145] Waste Disposal Symposium, Nucleonics, March 1949, pp. 9-23.

[146] US National Academy of Sciences (NAS) 1957a, The Disposal of Radioactive Wastes on Land, Report of the Committee on Waste Disposal of the Division of the Earth Sciences, National Research Council, pp.2, and Appendix B. pp. 12-81.

[147] Carter, L.J. 1987. Nuclear imperatives and public trust: Dealing with radioactive waste. Issues in Science and Technology, 3(2), pp. 46-61.

[148] United Nations 1956, Proceedings of the First International Conference on the Peaceful Uses of Atomic Energy, Geneva 8-20 August 1955.

[149] NAS, 1957a, pp. 8.

[150] NAS, 1957b, Report of the Committee on the effects of atomic radiation on oceanography and fisheries.

[151] Parker, F.L. et al. 1959, Disposal of Radioactive Wastes in Natural Salt, pp. 368-384, in International Atomic Energy Agency, Disposal of Radioactive Wastes, Vol. 2, Conference Proceedings, Monaco 16-21 November 1959.

[152] Two times 25 gallons of neutralized respectively synthetic PUREX waste (PUREX = Plutonium Uranium Redox Extraction), see Parker, F.L. et al., 1959, pp. 377-381.

[153] Walker, J.S. 2009, The Road to Yucca Mountain, University of California Press, pp. 51-75.

[154] Alley, W. and Alley, R. 2013, Too Hot To Touch. The Problem of High-Level Nuclear Waste, Cambridge University Press, pp. 15.

[155] Boffey, P. 1975, The Brain Bank of America, McGraw Hill, pp.104-105.

The Lyons project in Kansas became the first major failure of disposal in deep geological strata and revealed for the first time the problems of planning and governance of such projects. All planned and implemented projects to this day face these two fundamental problems: the underestimation of planning complexity and the difficulties in the governance of megaprojects.[156] The Lyons project is also interesting because it considered the possibility of retrieval of stored waste at a very early stage.[157]

> *All planned and implemented projects to this day face two fundamental problems: the underestimation of planning complexity and the difficulties in the governance of megaprojects.*

In the 1960s, West Germany started considering former salt mines as potential sites, thus following the recommendation by the NAS.[158] Germany has extensive salt deposits, and at the time already around 150 years of experience in operating rock salt and potash mines. In addition, West German geologists and mining engineers regarded salt as “de facto” dry (despite early experiences to the contrary).[159] The developments in the Asse II experimental repository mine in Wolfenbüttel, Lower Saxony, appeared so promising that they were presented at that time in publications of the IAEA[160] and national waste management organizations[161] as the repository model of the future. With the water inflows that were recorded from 1988 onwards and became publicly known in 2008, the Asse II project, characterized by secrecy and mismanagement, also came to an inglorious end (*see Section* 7.3).[162]

In the meantime, disposal methods continued to be implemented, aimed primarily at diluting nuclear waste and liquids in sea- or groundwater at minimal costs. This included dumping operations in the different oceans of the world, in which all major nuclear–weapon states participated and which also become the model for the disposal of civil nuclear waste of various European countries.[163] In addition, nuclear wastes were disposed of by injection of liquid nuclear waste of various activities into old exploration wells, which was practiced in both the United States and Soviet Union (later Russia) for years and even decades.[164]

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[156] Hodge, G., and Greve, C. 2013, Public-private partnership in developing and governing megaprojects, in: Priemus, H. and van Wee, B. Edts., International Hand-book on Mega-Projects, Edward Elgar.

[157] Parker, F.L. et al. 1959, p. 371.

[158] Radkau, J. 1983, Aufstieg und Krise der deutschen Atomwirtschaft 1945–1970 (The rise and crisis of the German nuclear industry 1945-1970), Rowohlt Taschenbuch; Möller, Detlev, 2007, Endlagerung radioaktiver Abfälle in der Bundesrepublik (Final disposal of radioactive waste in the Federal Republic of Germany), Peter Lang.

[159] Buser, M., and Wildi, W. 2018, Du stockage de déchets toxiques dans des dépôts géologiques profonds (Storage of toxic waste in deep geological repositories), Sciences & Pseudosciences, June, viewed 31 July 2019, https://www.pseudo-sciences.org/Du-stockage-des-dechets-toxiques-dans-des-depots-geologiques-profonds;

[160] IAEA 1977, Radioaktive Abfälle: Woher – Wohin? (Radioactive waste: Where from — Where to?) Internationale Atomenergieagentur Wien

[161] Verband Schweizerischer Elektrizitätswerke, Gruppe der Kernkraftwerkbetreiber und -projektanten (Federation of Swiss Electricity Utilities, nuclear power plant operators and developers) 1978, Die nukleare Entsorgung in der Schweiz (Nuclear waste disposal in Switzerland), Konferenz der Überlandwerke (UeW), Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Conference of regional utilities, National Cooperative for Nuclear Waste Storage), 9 February.

[162] Möller, D. 2015, Zur Geschichte des Endlagers Asse II [1964-2009] und ihrer heutigen Relevanz (The history of the Asse II repository [1964-2009] and its relevance today), Rückholung der Nuklearabfälle aus dem früheren Forschungsbergwerk Asse II bei Wolfenbüttel, Vortragsreihe am Institut für Technikfolgenabschätzung und Systemanalyse (ITAS), 1 December, pp. 9-24, viewed 31 July 2019, http://www.itas.kit.edu/pub/v/2016/houa16a.pdf

[163] Calmet, D. 1989, Ocean Disposal of Radioactive Waste: A Status Report, IAEA-Bulletin 4/1989, pp. 47-50, viewed 2 August 2019, https://www.iaea.org/sites/default/files/31404684750.pdf; IAEA, 1999, Inventory of radioactive waste disposals at sea, August 1999, viewed 2. August 2019, https://www-pub.iaea.org/MTCD/Publications/PDF/te_1105_prn.pdf

[164] NDC 1977, Radioactive Waste Disposal, Low- and High-Level, Pollution Technology Review 38; Spitsyn, V. I., Balukoda, V.D. 1978, The Scientific Basis For, and Experience With, Underground Storage of Liquid Radioactive Wastes in the USSR, in Scientific Basis for Nuclear Waste Management, Springer, pp. 237-248.

From the 1970s onwards, research and development in the field of nuclear waste management was greatly intensified. The management structures were fundamentally reorganized (as in the case of the US Department of Energy) and the concepts of final disposal were further developed. Exotic concepts of final disposal were dropped one by one, from canister emplacement in the Antarctic ice shield[165] to space disposal[166] or to the self-melting of nuclear waste in thermonuclear created caverns (DUMP project).[167] At the time, either international projects such as the sub-seabed-disposal project, which investigated the introduction of highly active waste canisters into deep-sea sediments,[168] or repository projects in the continental subsoil were pursued. The possibility of disposing of high-level waste in deep boreholes, which was envisaged as early as 1957 in the NAS report,[169] was increasingly relegated to the background. However, it is still discussed as a possible option today.[170]

The focus remained on disposal in specially constructed mines at depths of several hundred (to one thousand) meters, which were essentially determined by the construction techniques of the time. A new quality standard was set with the Swedish KBS project for the final disposal of vitrified high-level waste and spent fuel elements at the end of the 1970s.[171] The Swedish approach is based on the so-called multibarrier concept, which was planning standard of the time. Various barriers nested into each other according to the Russian doll principle are meant to ensure the containment of the radioactive material over the long storage periods of hundreds of thousands of years. Barriers include the solidification of the waste in a leach-resistant matrix (borosilicate glass, ceramic materials, etc.), its packaging in special storage containers made of steel or/and copper, its encapsulation by swelling volcanic ashes ("bentonites") and buffer materials in the storage galleries and its introduction into a dense rock in a propitious geological environment.[172]

Future repositories are planned to be built with storage galleries, some of which are kilometers long, in which the packaged waste would be introduced vertically or horizontally, connected to the surface by shafts and sometimes by transport ramps. From this point on, all repository concepts worldwide in the last four decades have been based on this concept. By contrast, the strategies of final disposal in sediments or the subsoil of the deep sea were abandoned. Research into final disposal in kilometer-deep boreholes is being pushed forward only sporadically.

A number of cases illustrates that even all these innovations could not guarantee the safe implementation of nuclear waste disposal in continental repositories. For example, the Waste Isolation Pilot Plant (WIPP) repository project, located in New Mexico, which was implemented on the basis of the planning principles mentioned above, experienced various minor or more serious incidents and accidents be-

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[165] Philbert, B. 1961, Beseitigung radioaktiver Abfallsubstanzen in den Eiskappen der Erde (Disposal of radioactive waste substances in the ice caps of the earth), Schweizerische Zeitschrift für Hydrologie, Vol. XXIII, Birkhäuser

[166] Burns, R.E. et al. 1978, Nuclear Waste Disposal in Space, NASA Technical Paper 1225, May 1978, viewed 31 July 2019, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780015628.pdf

[167] Milnes, A.G 1985, Geology and Radwaste, London:Academic press, pp. 46-48.

[168] Sub-seabed disposal is prohibited under the 1996 Protocol to the 1972 London Dumping Convention, see Holt, M. 2009, Nuclear Waste Disposal, Alternatives to Yucca Mountain, CRS Report for Congress, 6 February 2009

[169] NAS 1957a

[170] Schwartz, F., Kim, Y., Chae, B.-G. 2017, Deep Borehole Disposal of Nuclear Wastes: Opportunities and Challenges, Journal of Nuclear Fuel Cycle Waste Technologies 15(4), pp. 301-312.

[171] KBS 1978a, Handling of spent nuclear fuel and final storage of vitrified high-level reprocessing waste, Kärnbränslesäkerhet, Stockholm; KBS, 1978b, Handling and final storage of unreprocessed spent nuclear fuel, Kärnbränslesäkerhet, Stockholm

[172] Milnes, A.G., Buser, M., and Wildi, W. 1980, Endlagerungskonzepte im Überblick (Overview of final disposal concepts), Zeitschrift Deutschen Geologischen Gesellschaft 131(2), pp. 359-385.

tween 2014 and 2017.[173] This reveals a further risk dimension in the concrete realization for repositories: in addition to technical and geological safety problems, fundamental questions arise about structural and organizational deficits, particularly quality assurance, safety culture and the governance of repository programs.[174]

The Swiss repository concept of the Commission for Nuclear Waste Disposal Concepts (EKRA) took up these questions at the turn of the millennium.[175] EKRA, like no other commission before it, dealt with all possible options for storing and disposing of nuclear waste. The EKRA concept set out fundamental innovations in the planning and implementation of disposal projects in deep geological repositories. These included the distinction between active programs of measures and passive safety systems and the need for systematic implementation of programs. This also included concepts for long-term monitoring of repositories, as already requested by some previous authors.[176] The feasibility was to be demonstrated via a pilot repository and corresponding monitoring programs. Other fundamental elements concerned the principle of reversibility of decisions and the recoverability of stored waste, but also the organization of the program, the structural framework conditions and the process guidance embedded therein, quality assurance programs or a long-term oriented research policy. The EKRA concept formed the basis for the 2003 Nuclear Energy Act. The Swiss program and law thus went far beyond what France had already envisaged with its 1991 Waste Act ("Loi Bataille")[177], and the formulated obligation to study reversibility options.[178]

Requirements for the governance of nuclear waste programs are increasingly the subject of clarification and regulation today, as the examples of French practice[179] or the German Repository Site Selection Act (StandAG) show. The latter understands the site selection procedure as a learning system that "is in a position to take into account new findings and influences arising in the course of the procedure and to integrate and implement these into the process where necessary."[180] Governance issues are increasingly being addressed in research and practice.[181]

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[173] Klaus, D. 2019, What really went wrong at WIPP: An insider's view on two accidents at the only underground nuclear waste repository, Bulletin of the Atomic Scientists, 75(4), pp. 197-204.

[174] Buser, M. 2019, Wohin mit dem Atommüll? (Where to put the nuclear waste?), Rotpunkt, pp. 204-206.

[175] Expert Group on Disposal Concepts for Radioactive Waste (EKRA) 2000, Disposal Concepts for Radioactive Waste, Final Report, Federal Office of Energy, Bern

[176] Hammond, R. P. 1979, Views: Nuclear Wastes and Public Acceptance: Monitored containers in a controlled tunnel environment may prove more widely acceptable than the uncertainties of an uncontrolled geologic structure. American Scientist, 67(2), pp.146-150; Roseboom Jr, E.H., 1983. Disposal of high-level nuclear waste above the water table in arid regions (No. USGS-CIRC--903). Geological Survey, Alexandria, VA (United States).

[177] Government of France 1991, Loi n° 91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs (Law on research of radioactive waste management).

[178] Lehtonen, M. 2010, Opening Up or Closing Down Radioactive Waste Management Policy? Debates on Reversibility and Retrievability in Finland, France, and the United Kingdom, Risk, Hazards & Crisis in Public Policy 1(4).

[179] Levers, P. 2018, La réversibilité dans le projet de stockage profond (Reversibility in the deep storage project), Science & Pseudoscience, n° 324, April-June 2018, viewed July 31 2019, https://www.afis.org/La-reversibilite-dans-le-projet-de-stockage-profond

[180] Kommission Lagerung hoch radioaktiver Abfallstoffe (German commission for highly radioactive waste storage) 2014, Aspekte eines Standortauswahlverfahrens für ein Endlager für Wärme entwickelnde Abfälle (Aspects of a site selection procedure for a repository for heat-generating waste), Deutsche Arbeitsgemeinschaft Endlagerforschung; Brochure, pp. 13, viewed July 31 2019, https://www.bundestag.de/endlager-archiv/blob/352790/fbe1c31a22e4ca2c30345c46bc36bed0/drs_081-data.pdf

[181] Brunnengräber, A. et al 2015, Nuclear Waste Governance, Springer VS; Kuppler, S. and Hocke, P. 2018, The role of long-term planning in nuclear waste governance. Journal of Risk Research pp. 1-14.

The brief review of the more than 70-year history of nuclear waste management allows four conclusions to be drawn regarding program management and the success or failure of previous nuclear waste management projects:

- No single deep underground waste disposal program worldwide has been successfully implemented to date.
- The complexity and risks of nuclear waste management have been massively underestimated.
- The history of nuclear waste management shows an ongoing shift in concepts and programs in terms of objectives, implementation, safety and planning of measures in the direction of more manageable long-term projects (governance and long-term stewardship).
- The history of nuclear waste management reveals that a purely scientific and technical handling of such programs is not able of meeting the challenges posed by such a high-risk program. Questions such as the governance of a project, co-construction of management and disposal policies and the role of the affected communities have been often neglected by governments in the past.

5.2 THE CONTEXT OF NUCLEAR WASTE MANAGEMENT

Past experience suggests that five basic dimensions should be taken into account in the continuation and development of waste management programs:

HISTORICAL FRAMEWORK: societies will have to live with both the radioactive legacy left behind so far and the legacy that is likely to remain. This task represents a particular social, technical, political and financial challenge for future generations. The predicted costs of US$490 billion estimated for the remediation of nuclear contaminated sites in the United States show the magnitude of the problem.[182] Modern societies will not be able to avoid taking over the radioactive legacy and providing it with some far-sighted and safer solutions than today. Nevertheless, lessons should be learned from history in order not to repeat mistakes in the management of nuclear waste. This applies to the processes initiated in the search for, and implementation of, solutions and social control over them. It also implies that during the planning and implementation of programs, a safety culture is applied with a sincere commitment to best practices.

SOCIAL FRAMEWORK CONDITIONS AND TIME REQUIREMENTS: The historical examples show that the time requirements for the implementation of waste disposal programs have been massively underestimated worldwide. Nuclear disposal and the planning and implementation of the strategies for deep geological disposal of nuclear waste under consideration today will extend over at least three further generations. If one considers the requirements for monitoring and long-term monitoring of the targeted "repositories", one can also assume periods of five to ten generations (150 to 300 years). These long periods place special demands on the stability of societies and inevitably lead to considerations as to how the radioactive inventory already stored in extended interim storage facilities can be safely stored, managed and maintained over these periods. This also poses particular challenges to the quality of planning, specific long-term management and the technical design of such longer-term extended storage facilities. There may also be a need to establish extended underground storage facilities for longer storage periods.

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[182] Klaus 2019, pp. 201.

COMPLEXITY: The complexity of the disposal of the nuclear legacy is still massively underestimated today. The physical-chemical aging of waste materials and the resulting hazards are still largely unexplored. Similarly, the heterogeneity of the waste inventory and the carrier and consolidation materials involved lead to completely new problems in the introduction of these waste mixtures into underground repositories. For example, a large number of organic substances have been used in cleaning, maintenance or solidification processes for low- and intermediate-level waste. Certain of these mixtures are to be regarded as ignition sources (e.g. bituminized ion exchange resins) and as such represent a particular source of danger when a repository is operated openly.[183] In addition, organic waste will play a decisive role in gas formation in closed underground storage facilities. The risks concern not only the planned high-level nuclear waste repositories, but also those for low- and intermediate-level waste. Fire risks and fires are known in underground repositories for chemotoxic waste.[184]

Another example of new problems from waste mixtures is the large number of stored materials, ranging from radioactive materials, metals and heavy metals, organic materials and degradation products, to corrodible container materials and products (alkali aggregate reactions in concrete), represents a particularly reactive environment in contact with deep waters, pore waters[185] or brines of the corresponding host rocks. The resulting chemical milieu of such an underground waste deposit has so far only been the subject of very limited investigations and research and should therefore be examined in greater depth. This also applies to gas formation by bacterial or chemical degradation processes.

The complexity of the planning can be illustrated by a large number of questions for which there is no or only very limited experience today. Questions will also have to be answered as to how underground facilities extending over many square kilometers will behave in the longer term in tension-sensitive underground and to what extent such facilities can be sealed tightly at all. A further question relates to the development of fuel elements during the storage process underground, their long-term development and the potential effects on their possible recoverability. Finally, scientific findings or technical developments and leaps may fundamentally call into question a planned repository system that is currently being implemented. In such a case, too, reference should be made to the above-mentioned considerations on the complexity of a repository system. Many of these fundamental questions require comprehensive and urgent clarification.

POLITICAL FRAMEWORK CONDITIONS: This concerns the proliferation of fissile materials and the recognition that a repository can also be regarded as a 'plutonium and recyclables mine' in the long term. This naturally raises far-reaching questions about the intrusion respectively the protection of such repositories. In this sense, the disposal of irradiated highly active fuel elements represents a particular challenge with regard to future socio-political decisions.

GOVERNANCE AND SOCIETY: Finally, two further central factors are to be addressed in waste management projects. Firstly, there are the questions of governance of programs, the central importance of which decision-makers are only slowly becoming aware of (examples of WIPP in the US and Asse II in Germany) and which are indispensable for further confidence-building. Secondly, civil society (especially the affected regions) cannot only be involved in the sense of accompanying participation, but has to be involved in a broader participation and co-determination process for the long-term acceptance of such projects.

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[183] Buser, M., Wildi, W. 2018, "Abfallkonditionierung in Bitumen: ASN sagt nein!" (Waste conditioning in Bitument: ASN says no). Viewed 2 August 2019, https://www.nuclearwaste.info/abfallkonditionierung-in-bitumen-asn-sagt-nein/

[184] Comité de pilotage Stocamine (Stocamine's steering group) 2011, Rapport d'expertise (Expert report), viewed 1 August 2019, http://www.stocamine.com/media/1061/Conclusions%20COPIL.pdf

[185] Pore water is groundwater or deep water that is stored in the open spaces in sediments between grains or minerals.

These considerations on the context of nuclear waste management precede the further explanations of deep geological disposal of nuclear waste respectively the associated necessity of an interim extended storage until an underground solution can be implemented.

5.3 MANAGEMENT CONCEPTS FOR NUCLEAR WASTE

Every waste management solution must protect the population and the environment in the best possible way, be feasible and tolerated, and not impose unreasonable burdens on future generations. This common understanding of the requirements for waste storage is articulated in the 2001 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Article 11 of the Joint Convention states that "each Contracting Party shall take the appropriate steps to ensure that at all stages of nuclear waste management individuals, society and the environment are adequately protected against radiological and other hazards."[186] The long-term protection of a repository against intrusion must be guaranteed as well. This goal is particularly challenging, because of the tremendous advances in today's and future drilling technologies. This reversal and the simultaneous enlargement of the protection objectives must lead to a fundamental rethinking of the roles and responsibilities in the planning and design of waste management programs. Ultimately it also has to reconsider the current vision of a deep geological disposal exempt without of societal monitoring.[187]

DISPOSAL CONCEPTS

The IAEA describes disposal as an emplacement with no retrieving intention (which does not mean retrieval is not possible). The IAEA differentiates in its safety requirements for radioactive waste which range between:[188]

- Specific landfill disposal: similar to conventional landfill for very low-level waste (VLLW), for example from dismantling
- Near-surface disposal: in engineered trenches or vaults on the ground or tens of meters below ground level for low-level waste (LLW)
- Belowground facilities: consisting of constructed caverns and vaults, or built of mines in tens of meters up to hundreds of meters below ground for intermediate-level waste (ILW)
- Geological disposal: as described above mainly spent fuel and other high-level waste (HLW)
- Borehole disposal: a few hundred meters up to a few kilometers deep for HLW-canister respectively plutonium disposal.[189]

In this categorization, the IAEA assigns certain waste categories to certain disposal facility concepts in a graded approach. The decision about the facility system lies with the respective country. Most countries have at least disposal concepts, and many have disposal facilities under construction or in use for low- and intermediate-level wastes (*see section 2.3.1*).

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[186] IAEA 2001, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, viewed 11 June 2019, https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste

[187] Buser, M. 2017a, "Nuclear Waste — How to Handle our Legacy to Future Generations: The dual approach," Lecture held in the international Congress "Human rights, future generations & crimes in the nuclear age", University of Basel, 14-17 September 2017.

[188] IAEA 2011, Disposal of Radioactive Waste, Specific Safety Requirements No. SSR-5, International Atomic Energy Agency, viewed 1 August 2019, https://www-pub.iaea.org/MTCD/publications/PDF/Pub1449_web.pdf

[189] NAS 1994, Management and Disposition of Excess Weapons Plutonium, Committee on International Security and Arms Control, Washington D.C., Appendix C p. 247.

HOST ROCKS

As the historical analysis shows, today's repository concepts have developed relatively specifically in the direction of the disposal of nuclear waste in the continental crust (*see chapter* 5.1). From the very beginning, mainly salt rocks but also montmorillonites, such as clay minerals and clays, were regarded as particularly interesting host rocks due to their very low permeability and high sorption capacity. The search for siting areas for high-level waste focused particularly on these two types of rock. However, the options had to be extended relatively quickly to other host rocks because some countries did not have such formations in their subsoil. Especially the choice of crystalline rocks of the Baltic Shield by the two Nordic states using nuclear power (Sweden, Finland) is due to this circumstance. However, the Nordic programs in particular were forced to massively reinforce the artificial barriers (copper canisters) at the expense of geological isolation in order to counter the groundwater inflows through the fissured and permeable crystalline rock. Japan, too, resorted to the rocks found in the subsoil of the circum pacific fire belt: crystalline rocks and pelagic or hemipelagic sediments.[190]

There are also other exotics among the host rocks: volcanic tuffs, which were intended for example primarily for Yucca Mountain, Nevada[191]—the site of the US repository program that has been abandoned in the meantime (*see section* 7.8)—and which raise fundamental questions of suitability because of their permeability. Equally problematic are the generally relatively thin layers of anhydrite, which appear as rocks accompanying rock salt deposits. They were an early specialty of the Swiss disposal programs.[192] Other rocks selected in the course of the site search were, for example, basalts in the US Hanford Program lying below the quaternary cover[193] or alpine marls of Wellenberg in Switzerland.[194]

Historically, "exotic" host rocks often occurred in the immediate vicinity of nuclear facilities or mines such as the iron ore mine of Schacht Konrad near Salzgitter in Germany[195] or the uranium mine "Beta" in the pegmatites of El Cabril in Spain.[196] Regardless of the fact that only limited experience is available in the implementation of geological repositories, salt and clay rocks or crystalline rocks are usually considered to be particularly suitable host rock formations.

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[190] NEA 2016, Japan's Siting Process for the Geological Disposal of High-Level Radioactive Waste, Nuclear Energy Agency / OECD, viewed 1 August 2019, pp. 15, https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/chiso_shobun/pdf/018_s01_00.pdf

[191] Walker, S. 2009, The Road to Yucca Mountain, University of California Press

[192] Buser, M. 2017b, Short-term und Long-term Governance als Spannungsfeld bei der Entsorgung chemo-toxischer Abfälle (Short-term and long-term governance as a field of tension in the disposal of chemotoxic waste), Vergleichende Fallstudie zu Entsorgungsprojekten in der Schweiz und Frankreich: DMS St-Ursanne und das Bergwerk Felsenau (beide Schweiz) und Stocamine (Frankreich), ITAS-ENTRIA-Arbeitsbericht 2017-02, viewed 1 August 2019, http://www.itas.kit.edu/pub/v/2017/buse17a.pdf

[193] Milnes 1985, pp. 154-155.

[194] Mosar, J. 2010, Beurteilung der Tektonik im Standortgebiet Wellenberg (Kt. NW/OW) hinsichtlich eines Tiefenlagers für schwach- und mittelradioaktive Abfälle (Assessment of tectonics in the Wellenberg siting area (NW/OW) with regard to a deep geological repository for low- and intermediate-level radioactive waste), Sachplan geologische Tiefenlager, z. Hd. Baudirektion Nidwalden, pp. 4-6, viewed 1 August 2019, https://www.nw.ch/_docn/30814/gutachten_tektonik_prof._mosar.pdf

[195] Physikalisch-Technische-Bundesanstalt Braunschweig 2012, Schachtanlage Konrad (Shaft Konrad), viewed 1 August 2019, https://epic.awi.de/id/eprint/37594/1/schacht-konrad.pdf

[196] Hernando-Fernández, J. L., Hernando Luna, R. 2002, Descubrimiento, explotación y tratamiento de los minerales radioactivos de Sierra Albarrana, El Cabril, Córdoba (Discovery, exploitation and treatment of the radioactive minerals of Sierra Albarrana), viewed 1 August 2019, https://helvia.uco.es/xmlui/bitstream/handle/10396/6947/braco143_2002_1.pdf?sequence=1&isAllowed=y

LILW-REPOSITORIES

The first three facility types listed by the IAEA (specific landfill disposal, near surface disposal and belowground facilities) have been implemented for decades in many countries. However, the degree of maturity of the implementations varies considerably and corresponds to the conceptual perspectives and the technical means of the time. The early landfills for commercial low-level waste in the United States, such as Maxey Flats or West Valley, New York, showed relatively quickly that radioactivity was discharged from the landfills. They were leaking, as later confirmed by monitoring programs at many other sites. In Maxey Flats it was already proven in the 1970s that LILWs deposited in large quantities were washed out and that plutonium complexes could also be found outside the landfill.[197] At the Beatty landfill in Nevada, where both nuclear and chemotoxic waste was dumped in trenches, incidents accumulated from the start of operation until very recently, when disposed metallic natrium reacted and was partially ejected.[198] Many other such landfills followed the same course, as can be seen from the US Environmental Protection Agency's list of superfund sites. In summary, conventional landfills and trenches, the first of the plants named by the previously mentioned IAEA report, cannot be reliably sealed hydraulically. Therefore, these plants are to be regarded as more or less controlled permanent dilution 'facilities'.

The second type of disposal facility consists of reinforcing the protective functions already achieved with the first type of landfill with the additional help of concreted components and structures. This type of construction contributes above all to the creation of a basic environment, which creates a geochemical barrier, especially for leachates containing heavy metals. This design is used for both LLW and LILW sites. One plant of this type is the one for LLW-waste opened 1971 in Barnley, South Carolina, which was designed as trenches, which has a clay seal and in which the waste is stored in prefabricated conditioned concrete cylinders.[199] Other plants of this type include the two French Sites "Centre de Stockage de la Manche" (CSM), Digulleville, Normandy, operated between 1969 and 1994,[200] and the successor landfill "Centre de Stockage de l'Aube" (CSA), Soulaines-Dyus, Aube.[201] Here the pre-conditioned and packaged LILW were sunk into trenches in the early days before there were deposited into engineered concrete disposal vaults. The shallow landfills are covered using conventional sealing techniques. The sites are equipped with drainage systems and corresponding monitoring. The LLW deposit in Dessel, Campine Area, Belgium, is also constituted as monolithic blocks cast in concrete.[202]

Although these facilities are better protected against infiltration than the original trenches, rainwater penetrates into the concrete blocks over time and can wash out small amounts of soluble radioactive substances (especially tritium).[203] Even these plants cannot do without dilution. The plants for LILW in

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[197] Shrader-Frechette, K. 1993, Burying Uncertainty, Risk and the Case Against Geological Disposal of Nuclear Waste, University of California Press, p.p 103-104; Cleveland, J. M., and Rees, T. F. 1981, Characterization of Plutonium in Maxey Flats Radioactive Trench Leachates, Science, 212(4502), pp.1506.

[198] Alley and Alley 2013, pp. 139-148.

[199] South Carolina Department of Health and Environment Control 2007, Commercial Low-Level Radioactive Waste Disposal in South Carolina, Bureau of Land and Waste Management, Division of Waste Management, Columbia, South Carolina, viewed 5 August 2019, https://www.scdhec.gov/sites/default/files/docs/HomeAndEnvironment/Docs/commercial_low_level.pdf

[200] IAEA 2005, Upgrading of Near-Surface Repositories for Radioactive, Technical Report Series N° 433, pp. 63-70, viewed 5 August 2019, https://www-pub.iaea.org/MTCD/Publications/PDF/TRS433_web.pdf

[201] Andra 2008, Rapport annuel (annual report), Centre de stockage de déchets radioactifs de faible et moyenne activité, viewed 5 August 2019, https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/034/49034330.pdf

[202] Wacquier, W. 2013, The safety case in support of the license application of the surface repository of low-level waste in Dessel, Belgium, NEA/OECD, NEA/NWR/R(2013)9

[203] IAEA 2005, pp. 65.

El Cabril, Córdoba, Spain,[204] or those for LLW in Drigg, Cumbria, UK,[205] are built according to similar principles.[206]

In contrast to many HLW repository programs, active measures such as planning quality, long-term monitoring (hundreds of years) and maintenance of installations are often taken for granted in the case of LILW repositories.

Belowground facilities were implemented relatively early in Sweden[207] and Finland[208]. Both repositories contain LILW waste. These are silo or storage caverns in which various types of LILW wastes are stored some 60 meters underground. Significantly, bituminized ion exchange resins are also stored in these storage facilities. Neither plant has a monitoring system (with drill holes, water and gas sampling outside of the disposal area), quite in contrast to today's landfills for municipal or other wastes. Other belowground facilities use mines for the disposal of LILW-waste, as already mentioned in respect to the meanwhile remediated Mina Beta in El Cabril. This is also the case in the Czech Republic. The former Richard limestone mine with a depth of 70-90 meters below surface has been refurbished for disposal of institutional waste. The disposal facility Bratrství in a former uranium mine was used for waste with naturally-occurring radionuclides and shall be closed, beginning in 2025. The Hostim Repository with a volume of around 1,700 m^3 in an abandoned limestone mine was permanently sealed in 1997.

HLW-REPOSITORIES

The HLW-repositories are assigned based on the inventory of high-level or long-lived, transuranics bearing wastes. In this sense, the WIPP in New Mexico (US) is regarded as a HLW repository. It is the only such repository worldwide that has been constructed and operated to date. The US government started searching for a site in the early 1970s following the failure of the Lyons project. The site initially chosen had to be abandoned due to pressurized gas and brine inclusions[209] but the repository was built and operated at a second site in the 1990s. Originally, a reversible repository was planned.[210] The issued operating license was subject to the condition that the waste be retrievable in principle over several hundred years.[211] However, following the explosion/fire on February 14th, 2014, doubts are growing as to whether this is possible. It is extremely unlikely that the broad spectrum of the stored waste inventory with non-recyclable waste mixtures of the most diverse provenances will ever be retrieved.[212] After a storage break of more than three years, WIPP restarted operations in early 2017.

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[204] Zuloaga, A., Guerra-Librero, A. Morales, A. 1997, L/IL W disposal experience in Spain after the startup of El Cabril disposal facility, Planning and Operation of Low Level Waste Disposal Facilities, Proceedings Symposium Vienna, 1996, IAEA, pp. 261-274.

[205] IAEA 2005, pp. 11-18.

[206] Finster, M., Sunita, K. 2011, International Low-Level Waste Disposal Practices and Facilities, Fuel Cycle Research & Development, Argonne National Laboratory, prepared for US Department of Energy, viewed August 5, 2011, https://publications.anl.gov/anlpubs/2011/12/71232.pdf

[207] Finster et al. 2011, pp. 60-66.

[208] Bergström, U., Per, K., and Almén, Y. 2011, International Perspectives on repositories for low-level-waste, SKB, pp. 34-36, viewed 5 August 2019, http://www.skb.com/publication/2343713/R-11-16.pdf

[209] Mora, C. 1999, Sandia and the Waste Isolation Pilot Plant 1974 – 1999, Sandia National Laboratories Albuquerque SAND99-1482.

[210] Irby, H.H., and Segura, M. 1980, Retrievability of waste at WIPP, Transactions of the American Nuclear. Society 34.

[211] NEA 2011, Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel, Final Report of the NEA R&R Project (2007-2011), NEA/RWM/R(2011)4, 08.-Dec-2011; CFR 2014, Code of Federal Regulations, 40CFR194 – Criteria for the certification and recertification of the waste isolation pilot plants compliance with the 40CFR191 disposal regulations.

[212] Buser, M. 2016a, Endlagerung radio- und chemo-toxischer Abfälle im Tiefuntergrund: Wissenschaftlich-technische, planerisch-organisatorische und strukturelle Schwachstellen (Disposal of radio- and chemotoxic waste in deep underground repositories: Scientific-technical, planning-organizational and structural weak points), Eine Beurteilung vier ausgewählter Fallbeispiele, Greenpeace Germany

Choosing a site for a suitable repository for spent fuel and high-level waste remains challenging for every country. So far, and with exception of WIPP, no repository for high-level waste is in operation anywhere. All projects for final disposal or deep geological disposal of nuclear waste worldwide are mostly at an early planning stage. As *Table 5* shows, the status of these country projects varies considerably. So far, three countries (Finland, Sweden, and France) have de facto determined the location in an early confinement process. This group of countries is so advanced that the building permit for the HLW-repositories has already been granted or is expected in the next decade. However, questions remain regarding the corrosion of the copper storage canisters to be used,[213] which could delay the process in the Nordic countries.[214] In France, too, the regulator is progressing more slowly than originally planned.

TABLE 5 | Country programs for repositories for high-level waste as of August 2019

Country	Waste type	Host rock	Site selection status	Underground Research Laboratory	Construction permit	Time frame to repository license
BELGIUM	SNF, HLW, TRU	clay, unconsolidated	appointed	Hades		not scheduled
CANADA	SNF, HLW, TRU	crystalline	deferred*	none		not scheduled
CHINA	HLW, TRU	crystalline, clay	ongoing?	Beishan		not scheduled
CZECH REPUBLIC	HLW	crystalline	1990-2015 (est.)	none		2065 (est.)
FINLAND	SNF	Crystalline	appointed (1985-2000)	Onkalo RF	2018	2024 (est.)
FRANCE	HLW, TRU	clay, consolidated	appointed	Bure, Tournemire	2020 (est.)	not scheduled
GERMANY	SNF, HLW, TRU	salt, clay, Crystalline	2017-2031 (est.)	none		2050 (est.)
HUNGARY	SNF, TRU	clay	1995-2030 (est.)	Pécs		not scheduled
JAPAN	HLW, TRU	crystalline, sediments	2010-2030 (est.)	Honorobe Mizunami, others		not scheduled
THE NETHERLANDS	SNF, HLW	open	deferred	none		storage >100 years
SPAIN	SNF, HLW	salt, clay, Crystalline	deferred	none		not scheduled
SWEDEN	SNF (HLW)	crystalline	appointed (1980s-2009)	Äspö	ongoing (deposited 2011)	not scheduled
SWITZERLAND	SNF, HLW, TRU	clay, consolidated	2008-2030 (est.)	Mont-Terri		2060 (est.)
UNITED KINGDOM	HLW, TRU	not specified, different UK-country policies	2008	none		not scheduled
USA	TRU-wastes	salt	appointed (1972-1988)	none	repository in operation (1998/2000)	
	SNF, HLW	tuff (other)	deferred	none		not scheduled

Source: Own compilation based on official country reports
Notes: *on voluntary basis. est. = estimated; HLW = high-level waste; SNF = spent nuclear fuel; TRU = transuranic waste

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[213] Ottosson, M. et al. 2017, Copper in ultrapure water, a scientific issue under debate, Corrosion Science, 122, pp. 53-60; King, F. 2010, Critical review of the literature on the corrosion of copper by water, in: Technical Report SKB TR-10-69, Svensk kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co), December 2010, viewed 6 August 2019, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/42/093/42093282.pdf;

[214] Swahn, J. 2019, Comments on the ongoing licensing review of the repository for used nuclear fuel in Forsmark, mkg, viewed 6 August 2019, http://mkg.se/uploads/Swahn_MKG_presentation_Stockholm_May_24_2019.pdf

A second group of countries such as Switzerland[215] and Germany[216] have launched actual site search programs, which are expected to be completed within the next good decade. The other countries have programs on a different level. The blurredness of the projects is visible. Small countries, in particular, find it difficult to cope with such a program. Status and progress in China is difficult to assess.[217] Little is known about progress of the program in Russia, which has a peculiar disposal concept in underground repositories in crystalline rocks in Siberia with specific waste forms and packages that should be disposed of into 75 meter long drillholes with no intention of retrieving them again.[218] Finally, it should be mentioned that the international programs that were the subject of repeated debate until a decade ago (e.g. Pangea, Arius) are apparently not considered to be feasible.[219] It should also be noted that Russia has already offered to take over high-level waste from third countries and has accepted to take back spent nuclear fuel.[220]

As already stated, project planning is in progress. The repository design projects, which are based on the original Swedish KBS project, have varied somewhat over the years, as for example the development of the Belgian supercontainer shows.[221] Whether such strategies can ultimately be implemented, however, can only be determined in the context of industrial development and maturity. The same applies to the whole complex of retrievability and retrieval techniques that have to be developed for high-radiation waste and tested on an industrial scale. The relevant research, development and demonstration programs (RD&D) must be adapted accordingly. Finally, the central role of process management and governance such as structures, organization, and oversight needs to be adapted and developed to the necessities of far-sighted transparent projects.

DEEP BOREHOLE DISPOSAL

As already mentioned, various new projects concerning deep borehole disposal have been under discussion in last ten years. But as in the case of the mine concept, extensive in-situ feasibility tests and demonstration facilities are required in order to bring the concept to industrial maturity. The time frame is likely to be in the range of decades.

Overall the management of LILW programs in many countries using nuclear energy today is a routine task that is carried out under controlled conditions. However, a number of fundamental issues still need to be addressed and resolved such as bituminized waste, organic waste, diversity of medical, industrial and research waste and associated treatment and storage problems. Today, two main basic concepts exist for high-level waste: mined repository in 500-1000 meters depth and the deep borehole concept. They need to be specified in many essential questions and their functionality has to be tested on an industrial scale under controlled process conditions. It is assumed that the proof of feasibility will take several decades at least.

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[215] Swiss Federal Office of Energy, Deep Geological Repository sectoral plan (SDGR), viewed 6 August 2019, https://www.uvek-gis.admin.ch/BFE/storymaps/EA_SachplanGeologischeTiefenlager/?lang=en

[216] Öko-Institut e.V. 2017, Standortsuche Atommüll-Endlager (Site search for nuclear waste repositories), pp. 13, viewed 6 August 2019, https://www.oeko.de/uploads/oeko/das_institut/institutsbereiche/nukleartechnik-anlagensicherheit/Lehrerhandreichung.pdf

[217] Shu, J., Liu, Z., Lin, X., Wang, R. 2016, A Review of the Development of Nuclear Waste Treatment for China's Nuclear Power Industry, International Conference on Sustainable Development (ICSD 2016). Atlantis Press.

[218] Laverov, N. et al. 2016, The Russian Strategy of Using Crystalline Rocks as a Repository for Nuclear Waste, Elements 12(4) pp. 253-256; NEA 2014, Radioactive Waste Management and Decommissioning in the Russian Federation, viewed 6 August 2019, https://www.oecd-nea.org/rwm/profiles/Russian_Federation_report_web.pdf

[219] World Information Service on Energy (WISE) 2012, "Multinational approaches", viewed 6 August 2019, https://www.wiseinternational.org/nuclear-monitor/746-747-748/multinational-approaches

[220] Encyclopedia, 2001, Russia Agrees To Take The World's Nuclear Waste, Encyclopedia.com, viewed 6. August 2019, https://www.encyclopedia.com/history/energy-government-and-defense-magazines/russia-agrees-take-worlds-nuclear-waste-where-put-it

[221] Lavasseur, S., van Geet, M., Sillen, X. 2018, The Belgian Supercontainer Concept, ONDRAF/NIRAS, viewed 6 August 2019, https://igdtp.eu/wp-content/uploads/2018/12/2.T2.1155-Levasseur-ONDRAF-Supercontainer-IGDTP.pdf

Finally, a fundamental observation concerns the shift in concepts, particularly for high-level waste, towards a less definitive basis based on forecasts of safety cases. As the Swiss EKRA concept 20 years ago recognized, today's concepts are increasingly developing in the direction of monitored programs. The organizational setting of such processes and the guarantee of the independence of the supervising institutions are of paramount importance for the future development of these programs.

5.4 INTERIM STRATEGIES: STORAGE

For decades there have been massive delays in the concrete implementation of projects for all nuclear waste disposal programs worldwide. This applies in particular to programs for the disposal of high-level waste, for which there is still not a single geological repository available.

INTERIM STORAGE

With the approval of the national supervisory authorities, the responsible national project executing agencies have continuously adapted the implementation plans in the past and built up additional interim storage capacities accordingly. Today, interim storage takes place either directly in the nuclear power plants or in special central storage facilities, either in pools (wet storage) or in special containers (dry storage). In addition, as in the case of Fukushima, decommissioning work and improvised interim storage systems for fuel elements as well as for contaminated water or other waste must be considered.[222]

In terms of historical development and for safety and security reasons, there has generally been a rapid increase in efforts towards dry storage.

WET STORAGE: Spent fuel pools are common to nuclear power plants in order to provide cooling following discharge from the reactor. There is a lot of experience with wet storage. Off-site wet storage, located at reprocessing plants, is used in France, the UK and Russia. Since 1985, Sweden operates an underground central wet storage facility (CLAB). The facilities consist of one or more pools for underwater storage of the spent fuel in storage racks. The pool fluid ensures heat removal and shielding. Subcriticality[223] has to be maintained by spacing and/or neutron absorbing-materials. In addition, wet storage facilities need systems with continuous power supply for cask reception, decontamination, unloading, maintenance, and re-circulation systems for water-cooling, and purification. Furthermore, wet storage entails nuclear waste handling (from water purification), radiation and water chemistry monitoring, leakage monitoring, and other auxiliary systems.[224]

DRY STORAGE: Dry storage systems can be single purpose (such as vaults or casks) and dual purpose (special casks used for both transport and storage). Today, many different dual-purpose cask types are used, such as CASTOR in Germany, TN 24 in Belgium, and NAC-STC in the US. Vaults are modular reinforced concrete buildings with storage spaces for spent fuel.[225] For storage, spent fuel has to be removed from a transportation cask and placed into a metal tube or cylinder which is later sealed. Other vault systems contain already sealed canisters including spent fuel. Systems for canister or fuel handling are necessary. Active ventilation also requires components and systems. Vault systems are used in Canada (ANSTOR/MACSTOR), Hungary (MVDS facilities at Paks), the UK (Wylfa facility), and the Netherlands (HABOG). Some dry storage facilities have one or dual-purpose casks, which are generally single and

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[222] Yamaguchi, A. et al. 2017, Risk assessment strategy for Decommissioning of Fukushima Daiichi Nuclear Power Station, Nuclear Engineering Technology 49(2), pp. 442-449.

[223] Subcriticality is a state where a chain reaction cannot be set in motion by technical measures.

[224] IAEA 1999, Survey of wet and dry spent fuel storage, IAEA Tecdoc 1100

[225] IAEA 2012, Storage of Spent Nuclear Fuel, No. SSG-15

sealed systems. They are made of a metal body with baskets or a concrete body with a metal liner or canister inside, which are then closed with welded or sealed lids. These dual-purpose casks are loaded and unloaded at the nuclear power plant. Transfer casks may also be used for transport to the storage site. Dual-purpose metal casks are used in Switzerland (ZWILAG)[226] and Germany (Gorleben, Ahaus and others)[227], while concrete casks are mainly used in the US.

In 2010, IAEA researchers estimated the quantities of generated spent nuclear fuel to be at 340,000 t HM worldwide, up from 255,000 t HM just seven years earlier. However, the global storage capacity at the beginning of 2002 was only about 243,000 t HM, "with the bulk of storage capacity at reactor pools with 163,000 t HM."[228] For 2020 the researchers estimated around 445,000 t HM. The increase in the quantities of spent fuel elements leads to a permanent expansion of interim storage capacities. In other words, stockpiling is constantly increasing, while the implementation schedules for repositories are regularly being postponed into the future.

Historical developments in the United States are exemplary for the problems of interim storage of nuclear waste elsewhere. The United States initially saw an increasing need for dry storage capacities to bridge the gap until the Yucca Mountain repository was ready for operation. With the looming failure of the repository project due to problems with the demonstration of long-term safety, the desired storage periods became longer. In 2010, the supervisory authority developed its policies to ensure that spent fuel elements can be safely stored for up to 60 years after a reactor's operating life. As the aim for reactor operation including possible extensions up to 60 years, the arising interim storage period will extend to 120 years.[229] However, the actual time requirement is completely open after the failure of the only repository option. There is neither an alternative nor strategies for finding a site at present. Instead, the Trump administration supports a restart of the licensing procedure of Yucca Mountain, against continuous strong opposition of the Nevada state government.[230] In its report published in 2012, the American Blue Ribbon Commission on America's Nuclear Future came to the conclusion that program delays can be measured "in decades" and cause additional costs of billions and billions.[231]

This development applies to all countries using nuclear energy. In Switzerland, in about the same period (2011), the Federal Commission for Nuclear Safety called for a compilation of the time developments of the Swiss programs. They fully confirm the conclusions regarding the many decades-long delays of the Swiss program.[232] The impact on cost development in Switzerland is also in the double-digit

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[226] Zwilag Website, "Casks for highly active waste and spent fuel elements," viewed 2 August 2019, https://www.zwilag.ch/en/casks-for-highly-active-waste-and-spent-fuel-elements-_content---1--1049.html

[227] Oldiges, O., Boniface, J.M. 2008, TGC36 A Dual Purpose Cask for the Transport and Interim Storage of Compacted Waste (CSD-C) -8349, Waste Management Conference 2008, February 2008, Phoenix, Arizona, viewed 2 August 2019, https://pdfs.semanticscholar.org/21f1/76354b78eb9a241eb16072e7652b565ddcb9.pdf

[228] Fukuda, K. et al. 2010, IAEA Overview of Global Spent Fuel Storage, IAEA-CN-102/60, pp. 4-6, viewed 2 August 2019, http://www.efn-uk.org/l-street/politics-lib/nuclear-reports/index_files/IAEASpentfuel.pdf

[229] According to the 2014 Act 10 Continued Storage of Spent Nuclear Fuel CFR 51.23.

[230] World Nuclear News 2019, "US budget request supports Yucca Mountain", 12 March, viewed 29 May 2019, http://world-nuclear-news.org/Articles/US-budget-request-supports-Yucca-Mountain

[231] Blue Ribbon Commission 2012, Report to the Secretary of Energy, January 2012, viewed 2 August 2019, pp. 48, https://www.energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf

[232] Institute for Sustainable Waste Management 2011, Erfahrungswerte bei der Planung und Umsetzung des Sachplans und des Realisierungsplans geologische Tiefenlager und Planungsgrundlagen für das weitere Vorgehen (Experience in the planning and implementation of the Sectoral Plan and the implementation plan for deep geological repositories and planning bases for further action), viewed 29 May 2019, https://www.umweltbundesamt.at/fileadmin/site/umweltthemen/kernenergie/Schweizer_Endlager/Entsorgungsprogramm/File_F.pdf

billion range.[233] Today, most countries expect implementation periods for their repository programs of at least four to six decades. In Finland, Sweden and France, implementation schedules are expected to be shorter because the sites for the disposal programs have already been selected. However, even in these countries, neither timetables nor effective costs are set in stone. Thus, interim storage of spent fuel and HLW will continue for many decades up to more than 100 years and even longer.

EXTENDED STORAGE

This approach across countries will result in the further construction of extended interim storage capacities and their operation for a very long time (from many decades to 100 years or more). This discussion already took place in the 1980s and 1990s, above all in the US in connection with Negotiated Monitoring Retrievable Storage (NMRS) or the concepts of the Away From Reactor AFR[234] and in Great Britain with extended storage over periods of 100 to 300 years.[235] The strategy of "Away-from-Reactor-Storage" was also brought up again by the Blue Ribbon Commission (2012) in the US.[236] The integrity and retrievability of spent fuel (and HLW) over such storage periods is thus a growing challenge, as is the task of monitoring and maintenance. The goal is to keep options open for further waste management paths and their requirements such as transport, conditioning, and packaging. In consequence, there is a great need for research, for example on the long-term behavior of fuel, degradation mechanisms, and other knowledge gaps.

> *The integrity and retrievability of spent nuclear fuel and other high-level waste over long storage periods is a growing challenge, as is the task of monitoring and maintenance. The goal is to keep options open for further waste management paths and their requirements such as transport, conditioning, and packaging.*

The international subcommittee of the Electric Power Research Institute (EPRI) Extended Storage Collaboration Program (ESCP) identifies in a report technical data gaps for dry storage facilities, especially concerning the degradation of cladding and welded canisters.[237] The EPRI report also shows that countries have specific problems depending on their respective dry storage system and the overall situation. Other topics concerning spent fuel management in the long term are data provision and documentation, the handling of damaged spent fuel, and the influence of burn-up and fuel type (uranium or MOX). Solutions are needed for questions like: Which safety requirements for long-term storage are needed? How long is high-level waste safely manageable? Which type of infrastructure (incl. hot cells) is needed in the long term? How and how long can or should expertise be preserved?

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[233] Buser, M. 2016b "Kosten nukleare Entsorgung Schweiz: eine erste Evaluation des Systems der Kostenberechnung," (Costs of Nuclear Waste for Switzerland: A primary evaluation of the system of calculating costs) Report for Greenpeace Switzerland, January 2016, viewed 2 August 2019, http://m.greenpeace.org/switzerland/Global/switzerland/publications/ce_various/2016/Buser_Sammelmappe.pdf.

[234] Shrader-Frechette, K. 1993, Burying Uncertainty, Risk and the Case Against Geological Disposal of Nuclear Waste, University of California Press, pp. 218.ff.

[235] Nirex Ltd. 2004, Literature Review of Approaches to Long-Term Storage of Radioactive Waste and Materials, Nirex Report N/107, July 2004

[236] Blue Ribbon Commission 2012, Report to the Secretary of Energy, January 2012

[237] Electric Power Research Institute 2012, "International Perspectives on Technical Data Gaps Associated With Extended Storage and Transportation of Used Nuclear Fuel" International Subcommittee Report, Extended Storage Collaboration Program

KEY CHALLENGES OF EXTENDED STORAGE

The growing inventories and risks puts pressure on governments in countries that use nuclear energy to better manage the gap between interim storage and the realization of underground repositories or equivalent solutions.[238] A number of key issues for storage management are up for discussion in the future. They concern for instance a general safety analysis of the worldwide storage policies in respect to wet-storage in ponds and dry storage in vaults or other sites as well as a general risk assessment on the worldwide spread of interim storage facilities and over storage periods exceeding 100 years. For wet storage subcriticality over such storage times must be addressed, as well as the whole range of ageing and degradation mechanisms of the stored spent fuel (also in dry casks). In view of the long storage periods, particular attention must be paid to socio-political and economic factors that would increase "the risk that adequate maintenance and security at storage sites" could end before the waste is removed.[239]

Finally, the longer-term storage of low- and intermediate-level (LILW) waste is to be addressed. While fewer safety problems emerge during the interim storage of LILW, individual waste categories pose special challenges here as well, both in terms of their handling and the associated risks in closed facilities. The IAEA requires that "under conditions of long term storage awaiting disposal, the package must successfully maintain its characteristics under two very different environments"; if this cannot be guaranteed, further problems may arise, for instance when the repository operator refuses to receive waste that does not comply with the requirements of the Waste Acceptance Criteria (WAC) "as directed by the operator's license conditions."[240] Therefore, safety authorities such as the French ASN have recently been advising the repository operator to look into and provide a solution for these questions.[241]

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[238] Buser, M. 2019, Wohin mit dem Atommüll? (Where to put the nuclear waste?), Rotpunkt, pp. 204-206.

[239] Holt, M. 2009, pp. 23

[240] IAEA 1998, Interim Storage of Radioactive Waste Packages, Technical Report Series N° 390, International Atomic Energy Agency, pp. 11-13, viewed 24 August 2019, https://www-pub.iaea.org/MTCD/Publications/PDF/TRS390_scr.pdf

[241] Autorité de sûreté nucléaire (French nuclear safety authority) 2017, French National Plan for the Management of Radioactive Materials and Wastes 2016-2018, 30 December, viewed 2 August 2019, http://www.french-nuclear-safety.fr/Information/Publications/Others-ASN-reports/French-National-Plan-for-the-Management-of-Radioactive-Materials-and-Waste-for-2016-2018

5.5 SUMMARY

Nuclear waste management concepts have evolved slowly over the past decades. First, governments practiced the strategy of diluting and dumping radioactive materials in the environment in the early days of nuclear power. It was gradually followed by a rethinking towards the containment of waste and the search for suitable sites above or in geologically suitable layers of the continental crust. However, the projects realized from the 1960s onwards were only able to meet the high safety expectations to a very limited extent, if at all.

More than 70 years after the start of the nuclear age, no country in the world has a deep geological repository for spent nuclear fuel in operation. Finland is the only country that is currently constructing a permanent repository for this most dangerous type of nuclear waste. Besides Finland, only Sweden and France have de facto determined the location for a high-level waste repository in an early confinement process. The US is operating the Waste Isolation Pilot Project (WIPP). However, this repository is only used for long-lived transuranic waste from nuclear weapons, not for spent nuclear fuel from commercial reactors.

Despite multiple examples of failed selection procedures and abandoned repositories, current national and international governance show a preference for geological disposal. This requires clear and ambitious conditions for the site selection, exploration, and approval processes. Still, there is no guarantee for the feasibility of deep geological disposal. This is why the process of searching for such repositories must be implemented with extraordinary care on the basis of industrial feasibility and accompanied by appropriate monitoring. Some scientists consider that monitored, long-term storage in a protected environment is more responsible, much faster to achieve and should therefore be implemented. Overall there is a strong consensus that the current state of research and scientific debate and exchange with politicians and involved citizens is not adequate for the magnitude of the challenge.

The conditioning, transport, storage and disposal of nuclear waste constitute significant and growing challenges for all nuclear countries. These developments show that governments and authorities are under pressure to improve the management of interim storage and disposal programs. Accordingly, standards must be implemented for the governance of the programs, including planning quality and safety, quality assurance, citizen participation and safety culture.

Interim storage of spent nuclear fuel and high-level waste will continue for a century or more. With deep geological repositories not available for decades to come, the risks are increasingly shifting to interim storage. The current storage practices for spent nuclear fuel and other easily dispersible intermediate- and high-level waste forms were not planned for the long-term. These practices thus represent a growing and particularly high risk, especially when other options are available (solidification, dry storage) in hardened facilities. Extended storage of nuclear waste increases risks today, adds billions in costs, and shifts these burdens to future generations.

6 COSTS AND FINANCING

All European countries have signed the IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, the first legal instrument to address the issue of spent fuel and radioactive waste management safety on a global scale.[242] With this, they are obliged to provide adequate financial resources for decommissioning (Article 26), spent fuel, and radioactive waste management (Article 22), and commit "to avoid imposing undue burdens on future generations" (Article 3). However, countries neither always separate these tasks clearly in their waste management policies nor do they define exactly what decommissioning includes. There are strong technological and organizational interdependences between decommissioning, storage, and disposal.

It is thus difficult to compare nuclear waste management costs among different countries. For example, the United States includes low-level waste management as part of decommissioning to be funded by decommissioning money.[243] In Germany, in contrast, the utilities are only liable for the conditioning of waste with their decommissioning funds, while storage and disposal are paid by a separate public fund.

6.1 THE NATURE OF THE FUNDING SYSTEMS FOR DECOMMISSIONING, STORAGE, AND DISPOSAL

BASIC LIABILITY FOR DECOMMISSIONING AND WASTE MANAGEMENT

In general, the owners or licensees of nuclear power plants are liable for the processing, conditioning, storage, and eventual disposal of the waste generated during operation and decommissioning of the reactor and for the long-term management of spent fuel. These obligations and liabilities arise with the start of operation. In order "to avoid imposing undue burdens on future generations" (Article 3 of the Joint Convention), one unifying concept, observed in nearly every country, is the polluter-pays-principle, which makes the operator liable for the costs of these activities.

In some countries, some additional grants or subsidies are available to reduce the polluter's liability, or the liability is taken into public ownership and taxpayers' money is used to cope with the costs.[244] Due to its high capital intensity, long-term nature and health and safety risks, reactor decommissioning and especially radioactive waste management are heavily regulated. The regulatory authority is in some cases a dedicated institution and sometimes directly a state institution (such as a ministry). But sooner or later states often become directly involved at some point, including financially. The latter principle holds especially true for waste management; the polluter-pays-principle applies in most cases only for the decommissioning and dismantling of the reactors. For the long-term storage of radioactive waste, a variety of organizational models has evolved in which the national authorities–not the operator of the nuclear facility–more or less assume technical and financial liability for the very long-term issues of waste management (such as in the US, Germany, and France).

Many countries embed the polluter-pays-principle in domestic legislation, but do not apply it rigorously. The long-term costs and risks are instead socialized and passed on to future generations; the operators may only be required to contribute to the financing of the long-term costs.[245] Even in countries in which the polluter-pays-principle is a legal requirement, an operator of a nuclear power plant will not be held

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[242] IAEA 2001

[243] Album, K., Braend T., and Randen Johnson A. 2017, "How to pay? Financing decommissioning of nuclear power plants", Naturvernforbundet (Friends of the Earth Norway)

[244] IAEA 2015, Policy and Strategies for Environmental Remediation

[245] Von Hirschhausen, C. 2017, "Nuclear Power in the 21st Century – An Assessment (Part I)", DIW Berlin.

financially liable for any problems arising during the long-term storage of the waste. Yet, high costs can still arise after the disposal facility is closed. For instance, at the Asse II site in Germany, low- and intermediate-level waste needs to be recovered from an abandoned salt mine at an estimated cost of €4-6 billion (US$4.5-6.6 billion) covered by taxpayers; while the fees collected for the disposal of radioactive waste during operation of the mine amount to only €8.25 million (US$9.3 million).[246]

OVERVIEW AND NATURE OF THE FUNDS

Crucial for every funding system is the management and control of the funds, which can be done internally or externally. Financing decommissioning and waste management can take the following forms:[247]

- External segregated fund: The operators pay their financial obligation into an external fund. Here, private or state-owned independent bodies manage the funds. One fund can cover the whole industry or there can be one for each operator. An external fund can exist with or without transfer of the liabilities and with or without a short-fall guarantee by the operator.

- Internal non-segregated fund: The operator pays into a self-administrated fund and manages the financial resources, which are held within its own assets.

- Internal segregated fund: The operator is obliged to form and manage funds autonomously. The assets must be segregated from other businesses or earmarked for decommissioning and waste management purposes.

- Public budget: State authorities take over the financial responsibility including the accumulation of financial resources (for instance via taxes and levies). This option is typically used for legacy nuclear power plant fleets and orphan sites (sites where the former operator has declared bankruptcy or simply does not exist anymore, such as the former East German reactors).

The segregation of the funds does not ensure their correct use, however. The funds can be restricted, so that the liable organization is not fully free in using the accumulated money. Legal requirements beyond standard accounting principles and general tax law can be applied and restrictions imposed on the funds with respect to accumulation, management, and investment.[248] A restriction could limit the use of the funds, so that earmarked assets can only be used for decommissioning or waste management. External segregation of the funds does not automatically mean that the funds are restricted and earmarked. For instance, in Italy the external segregated fund CCSE (La Cassa conguaglio per il settore elettrico) pays all decommissioning costs of the public body Sogin responsible for decommissioning and waste management. But the funds have been partly used for other purposes of public interest than decommissioning, as the state is free to use the money for any purposes.[249]

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[246] Kirbach, R. 2009, “Das Lügengrab,” (The grave of lies) Die Zeit, 10 September, viewed 14 July 2019, http://www.zeit.de/2009/38/DOS-Asse/komplettansicht

[247] Wealer, B., von Hirschhausen, C., and Seidel, J.P. 2019, “Decommissioning of Nuclear Power Plants and Storage of Nuclear Waste: Experiences from Germany, France, and the UK”, in R Haas et al The Technological and Economic Future of Nuclear Power, Springer VS, Wiesbaden, pp. 261-286.

[248] Irrek et al. 2007, “Comparison among different decommissioning funds methodologies for nuclear installations,” Final Report on behalf of the European Commission Directorate-General Energy and Transport, viewed 1 July 2019, https://epub.wupperinst.org/frontdoor/deliver/index/docId/2609/file/2609_EUDecommFunds_FinalReport.pdf

[249] Irrek et al. 2007, “Comparison among different decommissioning funds methodologies for nuclear installations — Final Country Report (WP 1/ WP 3) Italy”, Wuppertal Institute.

There are arguable advantages for the external management of funds: a higher degree of transparency, protection against a shortfall of financial resources caused by the bankruptcy of operators, and improved public confidence. Beside the high costs for taxpayers, problems with competition policies of the EU could also arise, as financial support for the operators by the respective government could be seen as state aid.[250]

ACCUMULATION OF THE FUNDS

After the costs have been estimated (*see section* 6.2), the necessary funds need to be accumulated. Here, one crucial factor is timing, as the funds have to be available when they are needed. The main scenario is to build up a fund over the entire expected lifetime of a nuclear power plant or facility. However, shorter periods of time are also conceivable (for instance, 25 years in Germany). More and more reactors are shutting down before they reach the end of their license, for instance in the US, where many reactors have already or will prematurely close due to unfavorable economic conditions. In some rare cases, funds for decommissioning and decontamination of a nuclear power plant have to be fully collected by the start of operation, such as in France since 2006 (so it does not apply to the entire past and currently operating fleet).[251] However, no reactor has gone into operation in France since that date.

The accumulation of the funds can either be achieved by a fee, a levy set on the sale of electricity, "internally" by the operators who set aside funds from the revenue obtained from the sale of electricity, or by the investment of the funds. As most of the costs only occur in the future, a crucial aspect is whether funds or future provisions are based on discounted or undiscounted costs.[252] If the costs are not discounted, the operators have to set aside the full amount of the estimated costs. Only a few nuclear funding systems use undiscounted costs. If costs are discounted, the funds are expected to grow over time. Here the provisions are determined using the inflation rate until the due date and then discounted with an interest rate, which is supposed to represent the expected rate of return. The employed discount rates range widely (for example, 5.5 percent in Germany versus 1.5 percent in Spain). A cost escalation rate is not always assumed, in France decommissioning and waste management expenses are expected to grow with the general inflation rate, while in Germany a "nuclear-specific inflation rate" of 1.97 percent is calculated on top of the inflation rate. Applying only the general inflation rate could eventually lead to an underestimation of the costs and hence the amount of the funds.

Depending on the fund's nature, a major source of resource accumulation is the investment of the fund. Here a conflict of interest arises between the operator and the regulator in choosing the investment strategy. The former will typically prefer riskier investment strategies with higher rates of return, while the latter will ideally prefer a more secure investment strategy and accept lower rates of return. In Sweden, for instance, following the financial crisis of 2008, the rate of return on long-term bonds was lower than expected, and concerns of underfunding grew, leading to a change of the investment strategy. Since 2017, the funds can now be put into less secure investments than government bonds. Small changes in the assumptions of the rates have tangible effects on the present value of the financial resources and hence the amount of funds that need to be set aside; in particular, when the rate of return (discount rate) is prone to overestimation and the cost escalation rate to underestimation.

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[250] Neri, E., French, A., Urso, M.E., Deffrennes, M., Rothwell, G., Rehak, I., Weber, I., Carroll, S. and Daniska, V. 2016, Costs of Decommissioning Nuclear Power Plants (No. NEA-7201). Organisation for Economic Co-Operation and Development (OECD).

[251] Ibid.

[252] A provision is an account in the balance sheet of an operator but represents only liability; this does not mean that these funds are invested to finance decommissioning or waste management.

Accumulation also depends on the scope of the fund. One option is the integrated coverage of liabilities for decommissioning and waste management in only one fund. In Sweden, the utilities pay a fee on the price of electricity, which accumulates in an integrated fund for decommissioning and waste management. In some countries, different accumulation methods are simultaneously in place for the two processes, for instance in the US where operators are obliged to set aside funds for decommissioning but also pay a fee on the sale of electricity for high-level waste management (although the accumulation is currently stopped). In Italy, operators contributed to a fund, but decommissioning and waste management costs are covered by a general levy on the sales of electricity when all nuclear power plants were closed after a referendum.

6.2 COST ESTIMATIONS AND EXPERIENCES

COST ESTIMATION METHODOLOGIES

In order to accumulate funds, costs need to be estimated. This is a critical aspect of funding, especially for unknown projects like a deep geological facility for high-level waste. Different cost estimation methods are conceivable:[253]

- the "order-of-magnitude estimate" is a rough calculation without detailed engineering data (for example by taking some cost figures in international literature for granted and only slightly adapting them to the situation in the country, by scaling up or down factors and approximate ratios).

- The "budgetary estimate" is based on the use of flow sheets, layouts and equipment details, where the scope has been defined but the detailed engineering has not been performed (for example, modelling based on reference cases or differentiated modelling for every individual facility).

- In the "definitive estimate", the details of the project have been prepared and its scope and depth are well defined.

In reality, most cost estimates are budgetary estimates based on studies and estimates from the 1970s and 1980s, which are then extrapolated. In France, for example, until 2013, estimates of future decommissioning costs were based on a 1991 study by the French Ministry of Trade and Industry, confirming assumptions defined in 1979 by the PEON commission (commission pour la Production d'Électricité d'Origine Nucléaire). EDF then confirmed these estimates in a representative study for decommissioning of the Dampierre site (four 900 MW units). Between 2014 and 2015, an audit of the estimated dismantling costs for EDF's operational nuclear fleet was conducted at the request of the French Department for Energy and Climate, which made a number of recommendations to EDF following this audit. However, these recommendations only led to limited changes in the cost estimate and associated provisions although the estimates should now be reviewed annually.[254] In a recent report on the technical and financial feasibility of the decommissioning process, the French National Assembly alleged that EDF shows "excessive optimism".[255] The report concluded that decommissioning will take more time and that the process will cost overall much more than EDF anticipates.

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[253] Irrek et al. 2007

[254] Electricité de France (EDF) 2019, "Consolidated financial statements at 31 December 2018"

[255] Commission for Sustainable Development and Regional Planning of the French National Assembly 2017, Rapport d'Information déposé en application de l'article 145 du règlement par la mission d'Information relative à la faisabilité technique et financière du démantèlement des installations nucléaires de base (Report on the technical and financial feasibility of dismantling nuclear plants) 1 February, N°4428

In the US, a 2016 audit by the US Office of the Inspector General concluded that the cost estimates should be based on the best available knowledge from research and operational experience. Yet, the Nuclear Regulatory Commission (NRC) formula for estimating decommissioning costs is based on studies conducted between 1978 and 1980. The audit recommended that the funding formula be revaluated to determine whether a site-specific cost estimate would be more efficient. During the audit, an operator stated that the NRC's minimum formula estimated decommissioning costs of US$600 million, while the site-specific decommissioning cost estimate done by the operator was around US$2.2 billion.[256]

In Germany, the cost of both decommissioning and long-term waste management is based on expert opinions. On behalf of the operators, the private company NIS (Siempelkamp) uses cost models for both types of light water reactors to estimate decommissioning cost by adjusting the strategy and the reactors in question. On behalf of the utilities, the private and utility-owned GNS estimated the costs for waste management based on schedules and cost estimates produced by the German Federal Office for Radiation Protection (BfS, now BfE) for the disposal facilities. The cost estimates produced by the private companies for the utilities are not public.[257]

DECOMMISSIONING COSTS

As of today, only a few reactors have been decommissioned, while hundreds of plants worldwide are preparing to be decommissioned in the coming decades. In early 2018, 154 units were awaiting or are in various stages of decommissioning, while only 19 reactors (with a capacity of only around 6 GW) had been fully decommissioned (*see Table 1*).[258] This poor outcome and a lack of country-specific decommissioning experience also leads to generally underestimated decommissioning costs. Nuclear power plants were built with operation in mind, and until now, most plants currently in the decommissioning process or entering it were built at a time when the idea of decommissioning was not yet fully conceptualized. As a result, countries have to approach decommissioning using trial-and-error methods.

> *A lack of country-specific experience leads to generally underestimated decommissioning costs. Nuclear power plants were built with operation in mind and at a time when the idea of decommissioning was not yet fully conceptualized. As a result, countries approach decommissioning using trial-and-error methods.*

In order to make different estimates between different countries comparable, the Nuclear Energy Agency (NEA) developed the International Structure for Decommissioning Costing (ISDC), which recommends categorizing decommissioning costs into eleven distinct categories. However, most cost estimation methodologies do not use this classification. The cost estimations for decommissioning also heavily depend on the reactor technology and the decommissioning strategy. For example, at some plants in the US, large components such as the reactor pressure vessel and the steam generators were removed and disposed of in one piece, a strategy that heavily reduces costs. However, in Germany, large components must by law be taken apart on site. In general, the owners or licensees are responsible for developing cost estimates for decommissioning, which they submit periodically to the competent authority for review or approval (for example, every three years in Finland, and every five years in Switzerland).

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[256] US Office of the Inspector General 2016, Audit of NRC's Decommissioning Funds Program, US Nuclear Regulatory Commission, Defense Nuclear Facilities Safety Board.

[257] Irrek, W., and Vorfeld, M. 2015, "Liquidity and valuation of assets in unrestricted funds from provisions set up for nuclear decommissioning, dismantling and disposal — Brief study", Alliance 90/The Greens parliamentary group in the German Bundestag.

[258] Schneider et al. 2018

Data on actual decommissioning costs are scarce, with only three countries having completed decommissioning projects to full dismantling. In the US, where the most reactors were completely decommissioned (13 of 34 closed nuclear power plants as of mid-2018) decommissioning costs show a high variance, from US$280/kW to US$1,500/kW.[259] In Germany, only two commercial reactors have finished decommissioning: Gundremmingen-A was completed after 23 years of dismantling work with a latest estimate of around €2.2 billion in 2013 (US$2.5 billion) or €9,300/kW (US$10,500/kW). At Würgassen, decommissioning costs were around €1.1 billion (US$1.2 billion) or €1,700/kW (US$1,900/kW).[260] All German decommissioning projects experienced cost increases up to six percent per year, which were much higher than the general inflation rate and the assumed nuclear-specific inflation rate. Despite the cost increases, the estimated costs for future decommissioning (without casks, transport etc.) of around €19.7 billion[261] (US$22.2 billion) or €830/kW (US$940/kW) are still based on the above mentioned and not publically available cost models.

In the Czech Republic, the estimates for decommissioning its six VVER reactors are between US$412-532/kW (or around US$1.8 billion). VVER reactors, a series of pressurized water reactor designs originally developed in the Soviet Union, have not yet been decommissioned anywhere in the world. The most advanced decommissioning project is Greifswald in Germany, where the latest cost estimate for the five units and the smaller Rheinsberg unit is also around €6.5 billion (US$7.3 billion) or €3,090/kW (US$3,490/kW), which is about eight times higher per kW than the estimate for the same type of reactors in the Czech Republic.

In France and the UK, not one nuclear power plant has been fully decommissioned. In 2018, EDF estimated total costs of around €31.7 billion EUR (US$35.8 billion) for decommissioning for its entire fleet. For the 58 operational reactors the figure was €25 billion (US$28 billion) or around €400/kW (US$450/kW)[262]. This is very low by international standards. The combined costs for the legacy fleet consisting of six Uranium Naturel Graphite Gaz (UNGG) reactors, one PWR, one heavy water gas-cooled reactor (EL-4), and the fast breeder reactor Super-Phenix have increased steadily and doubled since 2001, when they were estimated to be around €3.3 billion (at that time around US$3.1 billion).[263] In a recent audit, the French National Assembly concluded that it cannot share EDF's overly optimistic view on decommissioning and expects a much more expensive and technologically challenging process. In the UK, the Nuclear Decommissioning Authority expects decommissioning costs for the 26 Magnox reactors alone of around £15.3 billion (US$19.4 billion) or 3,500 £/kW (US$3,950/kW).[264] In 2018, EDF Energy estimated the costs for decommissioning its 14 GCRs and 1 PWR to be around €15.7 billion (US$17.7 billion) or around €1,800/kW, which is very low for GCRs, especially if one considers the technological problems EDF encounters at home with its GCRs, the costs are steadily increasing, and the proposal to delay full decommissioning until the beginning of the 22nd century.[265] The European Commission aggregates the various decommissioning costs estimates of the Member States (excluding the Netherlands and Italy) to around €123 billion (US$139 billion).[266]

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[259] Ibid.

[260] Wealer, B., et al. 2015, Stand und Perspektiven des Rückbaus von Kernkraftwerken in Deutschland (Status and Perspectives on the Decommissioning of Nuclear Power Plants in Germany), DIW Berlin and TU Berlin.

[261] Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015, Gutachtliche Stellungnahme zur Bewertung der Rückstellungen im Kernenergiebereich (Evaluation on the Assessment of Provisions in the Nuclear Power Sector).

[262] EDF 2019

[263] Government of France Cour des Comptes (Accounting Office) 2014, "Le coût de production de l'électricité nucléaire — Actualisation 2014" (The cost of production of nuclear energy, updated 2014).

[264] Nuclear Decommissioning Authority 2015, Annual Report and Accounts — Financial Year April 2014 to March 2015

[265] Schneider et al. 2018

[266] European Commission 2016, Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty for the opinion of the European Economic and Social Committee.

DISPOSAL COSTS

For waste management, costs depend heavily on the disposal technologies, clearance levels of the waste, the waste quantities, or in some cases compensation schemes for the local communities who agreed to host the repositories. Naturally, the costs for disposing radioactive waste depend on the level of radioactivity (LILW or HLW). For the former, a variety of disposal options exist, which influence the disposal costs. For instance, disposing of waste in near-surface trenches as in France is cheaper than disposing all waste of these categories in deep geological facilities as in Germany. Other important factors that influence disposal costs are the inventory type and size, conditioning and packaging assumptions, design concepts, site characterizations and the selection process; the licensing process can also have huge effects on costs.

In most cases, the waste management organization is responsible for developing cost estimates for the long-term management of radioactive waste.[267] This organization can be state-owned (such as in Germany, Spain and the UK) or in some cases utility-owned, as in Sweden and Switzerland. In France, state-owned ANDRA projected the cost for the disposal of 12,000 m^3 of HLW and 72,000 m^3 of long-lived intermediate-level waste (ILW-LL) in CIGEO at €31 billion (US$34.6 billion). In the US, disposing of HLW is the scope of the Department of Energy (DOE). In 2008, the DOE estimated costs of around US$96 billion for the HLW disposal facility at Yucca Mountain. In Germany, the discounted costs are estimated to be €8.3 billion (US$9.3 billion) for a disposal facility for 27,000 m^3 of mostly spent nuclear fuel, undiscounted costs amount to €51 billion (US$ 56.4 billion).

For HLW disposal, it is important to keep in mind that all published figures are estimates, as no country has yet opened or even constructed a deep geological disposal facility for HLW. In addition, it is impossible to compare the cost estimates as the underlying factors are different. For instance, France mainly stores vitrified waste from reprocessing, while the amounts of spent nuclear fuel to dispose of in the US are much higher than in Germany. In addition, countries vary on which costs they list under storage and which under disposal. As is the case for cost estimates for decommissioning, they are often based on outdated studies. The German cost estimate for HLW, for instance, is still partly based on an extremely rough estimate from 1997 by the German regulatory authority, the Bundesamt für Strahlenschutz (BfS), at that time, for the previously considered site Gorleben.

6.3 FINANCING SCHEMES

FINANCING SCHEMES FOR DECOMMISSIONING

The polluter-pays-principle is applied to decommissioning in most nuclear countries. However, there are some cases where the state takes over the liability for decommissioning (for example, for the former East German reactors). The organization that is principally liable is not always the organization that fully pays for decommissioning activities, however. Bulgaria, Lithuania, and the Slovak Republic get EU support for decommissioning in exchange for having closed their older Soviet nuclear power plants.[268] In Spain, after the operator has defueled the facility and conditioned the waste from operation, the liability for decommissioning and the facility are both transferred to the state-governed radioactive waste management agency ENRESA.[269] After this transfer of liabilities, the former operators do not have to further contribute to the decommissioning fund, even if decommissioning costs exceed the provisions made.

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[267] IAEA 2007, Cost Considerations and Financing Mechanisms for the Disposal of Low and Intermediate Level Radioactive Waste

[268] European Court of Auditors 2016, EU nuclear decommissioning assistance programmes in Lithuania, Bulgaria, and Slovakia: some progress made since 2011, but critical challenges ahead. Luxembourg.

[269] Government of Spain 2017, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management — 6th Spanish National Report

Not all nuclear countries require that decommissioning funds be managed externally and segregated from the operator or licensee. Decommissioning is in some cases still financed through internal segregated and restricted funds, such as in France and the Czech Republic. Internal non-segregated funds were abandoned in nearly all countries, except for Germany (and South-Korea, although here the operator is publicly owned). In Germany, the utilities are still responsible for setting aside provisions for decommissioning in unrestricted non-segregated internal funds. The companies set up the provisions according to international accounting standards and are free to choose where to invest it. This financial system is a singular case and was criticized harshly against the backdrop of the utilities' dire financial situations; in the case of a bankruptcy of the utility, the funds would be lost.[270] In more and more countries, external bodies take over the funds for decommissioning. In Switzerland and Sweden for instance, the decommissioning expenses will be paid by the external, restricted decommissioning funds. The UK has also introduced the Nuclear Liabilities Fund, an independent trust, which currently amounts to £9.26 billion (US$12 billion) and will be used for decommissioning (and waste management) for the operational Advanced Gas-cooled Reactors (AGRs) run by EDF Energy.

The decommissioning funds can be fed by a charge or fee, included in the electricity price or a compulsory government charge. Some countries have both mechanisms, for example for different generations of nuclear power plants. In France, EDF accumulates the funds for decommissioning with a rate on the electricity price, but the company itself sets the level of the rate.[271] In Switzerland and Sweden, on the other hand, detailed cost studies are the basis for adequate provisions to the fund. In other countries such as Germany, where two or more financing schemes are in place, the financing scheme for decommissioning differs between purely public facilities, facilities with mixed ownership and facilities in private ownership. The costs for the decommissioning of the former GDR nuclear facilities are financed from the current public budget.

In addition to a lack of preparedness and technical expertise, countries decommissioning nuclear facilities are also struggling with and predicting potential further financial shortfalls in decommissioning funding. It is unclear whether enough money has been accumulated to pay for complete decommissioning, or if the taxpayers will have to step in. Early shutdowns, shortfalls in decommissioning funds, and rising decommissioning costs are forcing some plants to delay decommissioning in order to build up additional funds. Countries are also considering ways to enable facilities to recover their costs through higher fees, subsidized prices, and longer operation times, for instance in the US and Japan.[272] In most countries, the funds already set aside do not cover the cost estimates.

> *In most countries, the funds already set aside do not cover the cost estimates. This risk of underfunding seems to be an issue in nearly all countries facing decommissioning.*

This risk of underfunding seems to be an issue in nearly all countries facing decommissioning. EDF has only set aside around €18.5 billion (US$20.9 billion) or 58 percent of the estimated costs for decommissioning. In the Czech Republic, only 15 percent of the funds for Temelín and 28 percent of the funds for Dukovany have been accumulated. In 2016, in the US, the balance in the Nuclear Decommissioning Trust Fund (NDT) was around US$64 billion with specific decommission cost per reactor of around

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[270] von Hirschhausen, C. and Reitz, F. 2014. Nuclear power: phase-out model yet to address final disposal issue. DIW Economic Bulletin, 4(8), pp.27-35.

[271] Neri et al. 2016

[272] Album, Braend, and Johnson 2017.

US$700/kW for public power utilities and US$850/kW for investor-owned utilities.[273] Two recent cases in the US highlight the inherent risks of insufficient financing. Exelon reported shortfalls in the decommissioning fund for three reactors ranging from US$6 million to US$83 million. Although, the NRC granted Exelon a 20-year license extension with the idea of allowing additional time to increase the decommissioning fund.[274] In 2017, the German utilities have provisions of around €24.2 billion (US$26.7 billion) for scrapping up the 23 commercial reactors. This amount tops the cost estimate of €19.7 billion (US$22.2 billion). However, set aside provisions and cost estimates vary in scope. The provisions are to cover also costs for casks, conditioning the operational waste and transport, which were excluded from the estimate. So it remains open if the provisions are sufficient to cover the costs. In addition, due to the lack of transparency of the German decommissioning funding systems, the funds might not be invested in decommissioning, and tangible assets may continue to decline in value in the coming years.[275]

Table 6 compares the funding systems for decommissioning in the Czech Republic, France, and Germany. The table includes the funding system, the accumulation method, a total cost estimate for decommissioning, and the value of the set aside funds.

TABLE 6: Funding systems for decommissioning in the Czech Republic, France, and Germany as of December 2018

	CZECH REPUBLIC	FRANCE*	GERMANY
FUNDING SYSTEM	internal segregated and restricted fund	internal segregated and restricted fund	internal non-segregated and unrestricted
CONTROLLED BY	operators	operator	operators
ACCUMULATED BY	fee on generated electricity	levy on electricity price	provisions by operators
COST ESTIMATES	Temelín: US$ 847 million Dukovany: US$ 1 billion US$410/kW to US$530/kW	US$ 35.7 billion for entire fleet US$450/kW for operational; US$1,350/kW for legacy	US$ 22.2 billion for 23 commercial reactors** US$940/kW
SET ASIDE FUNDS, (IN % OF COST ESTIMATE)	Temelín: US$ 129 million (15%) Dukovany: US$ 276 million (28%)	US$ 20.8 billion (58%)	US$ 26.7 billion*** (n.a.)

Source: Own depiction.
Notes: * only applies to EDF
** excluding costs for casks, transport, and conditioning
*** including provisions for casks, transport, and conditioning (also of operational waste); in 2017

FINANCING SCHEMES FOR INTERIM STORAGE

The costs and the financing schemes for interim storage of nuclear waste, from both operation and decommissioning, depend heavily on the available waste management infrastructure and the existence of a disposal path for the waste. As there is currently no disposal solution for high-level waste and spent nuclear fuel, all nuclear countries are faced with both technological, organizational, and financial interim storage issues. Countries with no disposal solution for LILW increasingly face financing of storage for LILW with a growing number of reactor shutdowns.

The costs for interim storage of waste can be paid from operational revenues (as at CEZ in the Czech Republic). In Switzerland, the operator has to pay directly for the expenses to handle the nuclear waste arising during the operation of a nuclear power plant and during the post-operational phase. In Germany,

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[273] Moriarty, J. 2017, “2017 Nuclear Decommissioning Funding Study”, Callan Institute.

[274] Schneider et al. 2018.

[275] Irrek and Vorfeld 2015.

the utilities set aside provisions for interim storage of their waste; the estimated discounted costs were around €5.8 billion in 2014.[276] After the financing reform, this amount was transferred to an external segregated fund and all interim storage costs, including for spent nuclear fuel that will arise from continued operation, will be paid by the public fund. In Sweden, the costs for the centralized interim storage facility CLAB are paid by the Nuclear Waste Fund.

The most complex financing situation for interim storage of spent nuclear fuel is in the US. The Nuclear Waste Policy Act required the Department of Energy (DOE) to take over spent nuclear fuel in 1998. This created a significant liability for the DOE. The absence of a high-level waste repository forces local utilities to store spent fuel on their own sites, including already decommissioned sites. For this interim storage, the utilities request substantial financial compensation from the DOE, which has spent over US$10 billion in legal penalties so far. DOE estimates that total damages could amount to US$20.8 billion, if it begins accepting fuel in 2020. With further delays, the liabilities could increase by hundreds of millions of dollars annually.[277] The US Department of Justice manages a Judgment Fund of taxpayer money, about US$2 million per day, on all nuclear power plants, operating or shut down, to help manage their spent nuclear fuel.

In France, EDF estimates an additional €18.7 billion (US$21.1 billion) for spent fuel management (for example storage, reprocessing), and another €1.2 billion (US$1.4 billion) for waste removal and conditioning.[278] This amounts to €51 billion (US$57.5 billion) only for handling and storing the waste generated from operation.

FINANCING SCHEMES FOR DISPOSAL

The polluters are not always financially liable for disposal (and partly waste management, too); in some cases, liability is transferred to a state-governed organization that is also responsible for radioactive waste.[279] Most countries require funds for the long-term management of radioactive waste to be managed externally and segregated from the operator or licensee. In France, for instance, the operators of nuclear power plants must bear all costs related to waste management, but an external fund for the construction and operation, final closure, maintenance, and monitoring of the intermediate- and high-level waste disposal installations was created. ANDRA, the state-owned waste management agency, holds and manages the fund (Article 16 of the 2006 Waste Law).[280] In addition, there is also an internal, restricted ANDRA fund for research for future storage facilities. The two funds are fed by payments from the operator's internal funds at the time they are needed. However, the only fund fed right now is the research fund, as there is still no construction license. Instead, the operators make payments from their internal fund (for waste management) to ANDRA's general budget to finance operations related to the storage facilities for short-lived, medium-level waste.[281] Due to the 2006 Waste Law, the assets in the funds of EDF and Areva have to be reported separately, and the market value has to be at least as high as the liabilities to be covered. If EDF goes bankrupt, the state can claim right over the assets. An administrative authority supervises the internal funds; it can impose corrective measures, including the right to impose payments to ANDRA's budget.

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[276] Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft, 2015.

[277] US Department of Energy 2012, "Blue Ribbon Commission on America's nuclear future".

[278] EDF 2019, "Consolidated Financial Statements at 31 December 2018".

[279] Wuppertal Institut 2007.

[280] Government of France 2006, The 2006 programme act on the sustainable management of radioactive materials and wastes, Office parlementaire — Assemblée nationale.

[281] Wealer, Hirschhausen, and Seidel 2019.

In Germany, in the old financing system, private companies managed the financial resources to cover waste disposal by internal non-segregated funds without public authority controlling. A 2016 law led to a fundamental change in the German funding system with the implementation of an external segregated fund, which will have to finance all aspects related to final disposal.[282] The fund was fed with the amount of the former provisions for waste management of €24.1 billion (US$27.2 billion), including a risk premium, into an external segregated public fund. The Fund for the Financing of Nuclear Waste Management was set-up in mid-2017 to ensure that the money is invested "securely and profitably." Yet, responsibility and future risks will have to be borne by the public, infringing the polluter-pays-principle.[283] In its first financial year, the fund only invested a fraction of its assets, most of which are still held at the Bundesbank (Federal Bank) at an interest rate of 0.4 percent. The result was around €39 million (US$44.1 million) of interest expenses during the fund's first six months of existence.[284] In the US, HLW disposal is financed by the Nuclear Waste Fund, with revenue from a levy of US$0.001 per kWh on the electricity price. Over time, the fund has accumulated over US$34.3 billion. Money is no longer collected in the fund as a result of a federal lawsuit against the Department of Energy in 2013, because the DOE failed to accept spent nuclear fuel for disposal (*see section* 7.8).

The UK provides another approach to financing decommissioning. The state is responsible through the Nuclear Decommissioning Authority for the management and financing of legacy wastes and decommissioning cost of the first generation of nuclear (mostly Magnox) reactors. For the later reactors and new build decommissioning and waste management costs are funded through a Funded Decommissioning Programme and are based on a fixed unit price that is, in principle, funded by the operators. It is intended to fund a deep disposal repository which will be developed and managed by the state.

Table 7 gives an overview of the funding systems, the total cost estimate, and set aside funds in selected countries. The data indicates that countries fall short of setting aside enough funds to cover expected costs for disposal. For instance, France and the US have set aside funds for disposal which would cover only around a third of the estimated costs.

TABLE 7: Funding systems for disposal in France, Germany, and the US as of December 2018

	FRANCE*	GERMANY	US
FINANCING SCHEME	internal segregated and restricted fund, then moved to waste management agency (ANDRA) at construction start	external segregated fund	external
ACCUMULATED BY	levy on electricity price	investment of the funds	previously levy on electricity price but no longer collected
TOTAL COST ESTIMATES	US$ 34.9 billion	US$ 19.8 billion**	US$ 96 billion
SET ASIDE FUNDS, (IN % OF COST ESTIMATE)	US$ 11 billion (32%)	US$ 27.2 billion (>100%)**	US$ 34.3 billion (36%)

Source: Own depiction
Notes: *only applies to EDF ** including interim storage, LILW and HLW disposal.

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[282] Government of Germany, Act on the reorganization of responsibility in nuclear waste management (Gesetz zur Neuordnung der Organisationsstruktur im Bereich der Endlagerung (BGBl., I, S. 1843 768/16).

[283] Jänsch, E., Brunnengräber, A., von Hirschhausen, C. and Möckel, C. 2017, Wer soll die Zeche zahlen? Diskussion alternativer Organisationsmodelle zur Finanzierung von Rückbau und Endlagerung (Who should pay? Discussion about alternative organizational models for the finance for decommissioning and storage) GAIA-Ecological Perspectives for Science and Society, 26(2), pp. 118-120.

[284] Fonds zur Finanzierung der kerntechnischen Entsorgung (German Fund for the Financing of Nuclear Waste Management) 2018, Geschäftsbericht 2017 (Status Report 2017).

INTEGRATED FINANCING SCHEMES

Due to the great interdependences between decommissioning, storage, and disposal, an integrated, external, segregated, and restricted ("ringfenced") fund seems to be the most suitable approach to finance the future costs for these processes.[285] Integrated funding means the scope of the fund covers decommissioning and waste management. Countries with an integrated funding system include Sweden, Switzerland, and the UK (but only for the operational EDF Energy reactors).

In Sweden, the contributions (from a fee on the electricity price) to the Nuclear Waste Fund are based on cost estimations done by SKB, the utility-owned Swedish Nuclear Fuel and Waste Management Company, and reviewed by SSM, the Swedish Radiation Safety Authority. The cost estimates are based on detailed surveys and decommissioning plans interlinked to the openings of the disposal facilities. These surveys also include the planned decommissioning actions, including the planned timing and the sequence of actions, and the related costs in detail. A working group comprising members of the SKB, from the operators, and experts from the providers of technological systems of the facilities undertake these surveys. These publicly available decommissioning plans additionally increase transparency.

For the operational reactors of EDF Energy, the UK government introduced the Nuclear Liabilities Fund in 1996 with the only function of funding the costs stemming from waste management and decommissioning. The fund is fed from two sources: a small quarterly payment by EDF Energy and the return on investments from the fund. If EDF Energy wants to receive payments from the fund to meet liabilities, it can only be made by application to the NDA, which acts as an agent of the government. The NDA as the administrator of the Liabilities Management Agreements approves the NLF payments for decommissioning and waste management. However, the UK government can decide to transfer the decommissioning responsibility to the NDA at any point after the electricity generation at the power stations ends.[286]

The Swiss funding system is comparable to the Swedish (for example, cost estimates for specific nuclear reactors determine contributions to the fund), but Switzerland has created two funds: one to finance decommissioning and one to finance the disposal of waste. Operators of nuclear power plants have to pay fees to both funds, which are under the supervision of the Swiss Federal Council.[287] But, as in most countries, the cost studies are not public and done by the a private company, in this case the same company as for the German decommissioning cost estimates (NIS).

Table 8 gives an overview of the integrated financing schemes for decommissioning and waste management. Information is given on who controls the funds (i.e. external, internal, segregated) and on the cost estimates for decommissioning. The data reveals that countries fall short of setting aside enough funds for the estimated costs that will occur. Sweden has set aside funds for decommissioning and waste management of so far only two thirds of the estimated costs, the UK less than half (for its operational reactors), and Switzerland not even a third.

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[285] Wealer, Hirschhausen, and Seidel 2019.

[286] Neri et al. 2016.

[287] Swissnuclear 2011, Cost Study 2011 (CS11) Overview Report.

TABLE 8: Integrated funding systems for decommissioning and waste management in Sweden, Switzerland, and the UK as of December 2018

	SWEDEN	SWITZERLAND	UK*
FINANCING SCHEME	one external segregated and restricted fund	two external segregated funds (for waste management and for decommissioning)	one external segregated and restricted fund
ACCUMULATION	fee on electricity price (set individually for each plant)	payment by operator	payment by operator
TOTAL COST ESTIMATES	US$ 10.7-11.8 billion	US$ 24.6 billion***	US$ 26.5 billion**
SET ASIDE FUNDS, (IN % OF COST ESTIMATE)	US$ 7.2 billion**** (61-67%)	US$ 7.39 billion (30%)	US$ 12.1 billion (46%)

Source: Own depiction.
Notes: *EDF Energy reactors **as of 2018 ***Estimated total costs for a 50-year operating period as of 2019 ****as of 2017

6.4 SUMMARY

Nearly every government claims to apply the polluter-pays-principle, which makes operators liable for the costs of managing, storing, and disposing of nuclear waste. In reality, however, governments fail to apply the polluter-pays-principle consistently. Most countries enforce it only on decommissioning, although there are some cases where the government takes over the liability for decommissioning (for example, for the reactors in former East Germany). Bulgaria, Lithuania, and the Slovak Republic receive EU support for decommissioning in exchange for having closed their older Soviet-era nuclear power plants. Most countries do not enforce the polluter-pays-principle for the disposal costs of nuclear waste. For this, national authorities more or less end up assuming liability as well as the responsibilities for long-term waste management and disposal. The operator is, however, required to contribute to financing the long-term costs. Even in countries in which the polluter-pays-principle is a legal requirement, it is applied incompletely. For instance, a nuclear power plant operator will not be held financially liable for any problems arising once a final disposal facility is closed; this is the case for the German Asse II disposal facility, where the retrieval of large amounts of waste has to be paid for by taxpayers.

Governments fail to properly estimate the costs for decommissioning, storage, and disposal of nuclear waste. All cost estimates have underlying uncertainties due to long time-scales, cost increases, and estimated discounting (fund accumulation) rates. A major reason for the uncertainty is the lack of experience in decommissioning and waste disposal projects in particular. Only three countries, the US, Germany and Japan, have completed decommissioning projects including full dismantling and thus generated data. As of mid-2019, of 181 closed power reactors in the world, only 19 had been fully decommissioned, of which only 10 to “green field”. But even these limited experiences show a wide range of uncertainty, up to a factor of five. In the US, decommissioning costs varied between reactors from US$280/kW to US$1,500/kW. In Germany, one reactor was decommissioned for US$1,900/kW, another one for US$10,500/kW.

Many governments base their cost estimates on outdated data. Many countries reviewed here such as France, Germany, and the US base their estimates on studies from the 1970s and 1980s, rather than on the few existing real-data cases. Using outdated data, in most cases drawn up by operators, industry, or state agencies, likely leads to low-cost estimates and overly optimistic conclusions.

Many governments apply overly optimistic discount rates. One key factor leading to the underestimation of the costs for decommissioning and nuclear waste management is the systematic use of overly optimistic discount rates. A fundamental aspect of funding decommissioning and waste management is the expectation that the funds will grow over time. In Germany, for instance, the funds of €24 billion set aside for all waste management-related activities are expected to grow nearly fourfold to €86 billion by 2099. The discount rates employed range widely, and not all countries calculate cost increases, although it is likely that costs will increase faster than the general inflation rates.

In order to guarantee the availability of sufficient funding for decommissioning, waste management and disposal, the financing schemes need to create secure holding conditions for the funds ("ring-fencing"). They also need to make sure that the resources set aside are sufficient to cover the real costs. Some countries fulfill one condition but fail on the other.

Countries differ significantly on how they plan the financing of nuclear waste management, storage, and disposal. Not all nuclear countries require decommissioning funds to be managed externally and segregated from the operator or licensee. Decommissioning is in some cases still financed through internal segregated and restricted funds, although the money for long-term waste management is managed externally in most countries. Financing decommissioning and storage is complex; in most cases, multiple funding systems are in place in one country.

In light of different national approaches, governments do not always define what "decommissioning" includes. Nuclear waste management is an important aspect of decommissioning, as is spent fuel management. But both are not always defined under "decommissioning", making it hard to compare costs across different countries. The processes of decommissioning, storage, and disposal are heavily interlinked. That is why an integrated external segregated and restricted fund seems to be the most suitable approach to finance the future costs for these processes. Only a few countries have opted for this solution, notably Sweden, the UK, and Switzerland; although, Switzerland has two funds, one for decommissioning and one for waste management. No country has secured the complete financing of decommissioning, storage, and disposal of its nuclear waste. Doing so will be a challenge for all countries using nuclear power.

Today, no country has both estimated costs precisely and closed the gap between secured funds and cost estimates. In most cases, only a fraction of the funds needed has been set aside. For instance, Sweden has set aside funds for decommissioning and waste management of two thirds of the estimated costs so far, the United Kingdom less than half for its operational reactors, and Switzerland not even a third. The same can be observed of funding waste disposal. France and the US have set aside funds for disposal that would cover only around a third of the estimated costs. As an increasing number of reactors are closing ahead of schedule due to unfavorable economic conditions, the risk of insufficient funds is increasing. These early closures, shortfalls in funds, and rising costs are pushing some nuclear power plant operators to delay other closures and decommissioning in order to build up additional funds. Countries are also considering ways to enable facilities to recover their costs through higher fees, subsidized prices and lifetime extensions, for instance in the US and Japan.

7 COUNTRY STUDIES

7.1 CZECH REPUBLIC

OVERVIEW

The history of the Czech nuclear sector dates back to the 1940s. Due to its uranium ore deposits, Czechoslovakia was an important producer of uranium for the Eastern Bloc in communist times. Between 1946 and 2016, when the last mine closed, more than 112,000 tons of uranium were extracted.[288] There are still at least 119,000 tons of recoverable uranium resources in the country. Plans for renewing mining, if it were to become cost effective, exist.

At the time, Czechoslovakia processed uranium into yellowcake; further processing was conducted in the Soviet Union. The Uranium Ore Chemical Treatment Plant in Dolní Rožínka is still in operation today, although it only processes residual uranium contained in remediated areas.

The first nuclear power plant, Dukovany, went into operation in 1985–87. It consists of four Soviet VVER 440 pressurized water reactors (PWR) with a total output of 2,040 megawatts (MW). The plant is expected to operate until 2035–37, but an extension is being considered. The Temelín nuclear power plant has two VVER 1000 reactors that went into operation in 2000-02 with a total output of 1,055 MW. There are also two research reactors, LVR-15 and LR-0, at the Research Centre Řež and a university reactor, VR-1, at the Czech Technical University in Prague.

In 2018, Czech nuclear power plants generated 28.2 TWh of electricity, one-third of total power production.[289] The State Energy Policy of the Czech Republic aims to build at least another two nuclear reactors by 2040.[290]

WASTE CLASSIFICATION SYSTEM

The Czech waste classification system corresponds with the suggestions of the IAEA. Most recent legislation only deals with categorizing waste in a very general manner.[291] Solid waste is classified based on how it is disposed of:[292]

- temporary radioactive waste, which has radioactivity lower than clearance levels after storage for at most five years;
- very low-level waste (VLLW) with radioactivity higher than that of temporary radioactive waste, but which does not require any special measures during disposal;
- low-level waste (LLW) with radioactivity higher than that of temporary radioactive waste, but which at the same time contains a limited amount of long-lived radionuclides;

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[288] NEA and IAEA 2018, Uranium 2018: Resources, Production and Demand, viewed 29 May 2019, https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf

[289] Czech Republic Energy Regulatory Office 2019, Quarterly Report on the Operation of the Czech Republic's Electricity Grid for Q4, 2018, viewed 29 May 2019, http://www.eru.cz/documents/10540/4580207/Ctvrtletni_zprava_2018_IV_Q.pdf/f47bc2a0-05e3-4402-a1db-5b6e2b0a44a4

[290] Government of the Czech Republic 2015, State Energy Policy, viewed 29 May 2019, https://www.mpo.cz/assets/en/energy/state-energy-policy/2017/11/State-Energy-Policy-_2015__EN.pdf

[291] Government of the Czech Republic 2016, Decree No. 377/2016 Coll., on the requirements for the safe management of radioactive waste and on the decommissioning of nuclear installations or category III or IV workplaces, viewed 29 May 2019, https://www.sujb.cz/fileadmin/sujb/docs/legislativa/vyhlasky/377_Radioactive_Waste.pdf

[292] Government of the Czech Republic 2016, Decree No. 422/2016 Coll., on radiation protection and security of a radioactive source, viewed 29 May 2019, https://www.sujb.cz/fileadmin/sujb/docs/legislativa/vyhlasky/422_Radiation_safety_fin.pdf

- intermediate-level waste (ILW) that contains a significant amount of long-lived radionuclides and thus requires a higher degree of isolation from the surrounding environment than low-level waste; and

- high-level waste (HLW), whose heat generated by the decay of the radionuclides it contains must be taken into account during its storage and disposal; after this waste is processed and treated, it must meet waste acceptance criteria and be disposed of in deep geological repositories several hundred meters underground.

QUANTITIES OF WASTE

The Czech Republic has the largest volumes of nuclear waste of any of the more recent member states in the EU. In communist times, spent nuclear fuel was returned to the supplier, the Soviet Union. Since the early 1990s, however, Russia has no longer accepted returned nuclear waste. ČEZ, the operator of the Czech nuclear power plants, built dry cask storage facilities at its plants to store spent fuel after it had been removed from the spent fuel pool. There are two dry storage facilities the Dukovany plant and one at Temelín with a total capacity of 3,310 tons of spent fuel.

The Czech government regularly publishes a waste inventory. The data below comes from the most recent inventory, which records waste volumes and activity as of December 31, 2016.

TABLE 9: Nuclear waste in the Czech Republic as of December 31, 2016

Type of waste	Type of storage	Storage site	Quantity
SNF (HLW)	Interim storage (dry)	Dukovany and Temelín	1,174 tHM
	Interim storage (wet)	Dukovany and Temelín	654 tHM
LILW LIQUID	Reactor storage tanks	Dukovany and Temelín	1,439 m^3
LILW SOLID	Reactor storage facility	Dukovany and Temelín	351,3 t
	Near-Surface repository (disposed)	Dukovany	11,520 m^3
VLLW			n.a.

Source: Czech State Office for Nuclear Safety report to EURATOM 2018

Low- and intermediate-level waste produced by nuclear plants and research reactors is mostly treated on site; liquid waste is either bituminized or polymerized, whereas solid waste is either compacted or first incinerated before being compacted into 200 liter canisters. Intermediate-level waste unsuitable for deposition now is stored and will be deposited in the deep geological depository.

The government estimates that after 40 years of operation of the Dukovany and Temelín plants nearly 3,500 tons of spent fuel would be produced.[293] Every additional year of operation would produce another 35 tons of waste from Dukovany and 36 from Temelín. If three additional reactors were built, nearly 10,000 tons of spent fuel would need to be disposed of by mid-22nd century. In addition to spent fuel, this repository would also need to hold 4,200 tons of waste from decommissioned nuclear plants, 140 tons of operating waste, and 84 tons of other waste.

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[293] Government of the Czech Republic 2017, "Policy for Spent Nuclear Fuel and Radioactive Waste Management in the Czech Republic", 29 November, viewed 29 May 2019, https://www.mpo.cz/assets/cz/energetika/strategicke-a-koncepcni-dokumenty/2017/12/Koncepce-nakladani-s-RaO-a-VJP-v-CR.pdf

The shallow permanent waste repository at Dukovany is intended primarily for LLW and ILW from nuclear energy. The total capacity is about 55,000 m³ and by the end of 2016, around 11,500 m³ of waste had been deposited here.[294]

The estimated total amount of low-level and intermediate-level waste produced by both Czech nuclear power plants (during a 60-year lifetime) is 18,300 m³. Another 10,800 m³ will be produced during the decommissioning process of both plants.

In addition to nuclear waste from operation of power plants, the Czech Republic also has relevant amounts of waste from uranium mining. The state-owned DIAMO enterprise administers 18 tailings ponds filled with radioactive sludge covering an area of almost 600 hectares and with a total volume of 54 million m³. The firm is also responsible for 371 waste heaps with a total volume of 49 million m³ of materials containing residual uranium ore.[295]

WASTE MANAGEMENT POLICIES AND FACILITIES

The 1997 Act on Peaceful Utilization of Nuclear Energy and Ionizing Radiation (also known as the Atomic Act) serves as the legal framework for nuclear waste management in the Czech Republic. It established the Radioactive Waste Repository Authority (RAWRA), a government agency under the Ministry of Industry and Trade. RAWRA is responsible for managing nuclear waste including the safe storage of spent nuclear fuel.

The State Office for Nuclear Safety is responsible for supervising nuclear safety including repositories, as defined in the 2016 Atomic Act.[296] It maintains the main principles of the preceding act, but in addition requires a further law for selecting the site for a deep geological depository. No such law has yet been adopted.

In 2002, the Czech government adopted the Policy for Spent Nuclear Fuel and Radioactive Waste Management, despite objections from the Ministry of the Environment based on a Strategic Environmental Assessment. The policy defines the principles of nuclear waste management and establishes timeframes. The government updated the policy in 2017.[297] Public consultation was limited.

Spent nuclear fuel is stored in dry casks at nuclear power plants under the responsibility of ČEZ, the company that produced it. Once it is declared as waste, it falls under the authority of RAWRA. RAWRA operates the repositories at Dukovany, Litoměřice and Jáchymov (last two for non-power waste). Plans exist for a central subterranean spent nuclear fuel storage at the Skalka site, but they are considered outdated by now. Spent fuel is not expected to be reprocessed for both economic and technological reasons.

In 2002, RAWRA selected six granite sites potentially suitable for deep repositories as proposed by the Czech Geological Survey. Inspiration for this project was drawn from Swedish KBS-3 technology for disposal of spent nuclear fuel at a depth of 500 meters in encapsulated canisters buried in bentonite

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[294] Czech Radioactive Waste Repository Authority (RAWRA) Website n.d., "About repositories", viewed 29 May 2019, https://www.surao.cz/en/public/operational-repositories/about-repositories/

[295] DIAMO 2018, "Comprehensive Information about Monitoring Results and the State of the Environment", 20 April, viewed 18 May 2019, https://www.diamo.cz/en

[296] More information about the Atomic Act at https://www.sujb.cz/en/legal-framework/new-nuclear-law/

[297] Government of the Czech Republic 2017, Policy for Spent Nuclear Fuel and Radioactive Waste Management in the Czech Republic, adopted 29 November.

clay. RAWRA virtually ignored the concerns of the selected municipalities and their inhabitants, thus creating ongoing conflicts between local governments and central authorities. The Platform Against Deep Repository, whose members include thirty-two towns and villages and fourteen associations, opposes the plans.[298] Consequently, geological planning is years behind schedule. New sites are being considered, ones with less likely public resistance but possibly inferior geological conditions. As of 2019, RAWRA is considering nine potential sites.[299]

The suitability of the chosen site is to be confirmed by 2025, which seems optimistic. In 2030, construction of an underground laboratory should begin, and then after 2050 work on the repository should commence. The goal is to start operation by 2065.

COSTS AND FINANCING

The first Atomic Act stipulated the establishment of a state "nuclear account" administered by the Ministry of Finance. The funds it contains are earmarked for nuclear waste management, including the development, operation, and closure of a deep geological repository in the future. The main source of income comes from fees paid by nuclear waste producers. Thus, the polluter-pays-principle is applied. By 2018, the account held CZK26.9 billion (US$1.24 billion).[300] The Act sets a fee of CZK55 (around US$2.53) for every MWh of electricity generated at a nuclear power plant and CZK30 (around US$1.38) for every MWh of thermal energy produced by a research reactor. Other producers of nuclear waste must pay a one-time fee covering costs.[301]

The Czech government calculated the costs of storing low- and intermediate-level waste at CZK4.57 billion (US$210 million) and the costs for storing spent nuclear fuel and high-level waste at CZK111.4 billion (US$5.13 billion); storage is paid by ČEZ from operational expenditure. According to an analysis from the Czech Technical University, these fees will not be sufficient to cover actual future costs.[302]

Another financial mechanism addresses the decommissioning of nuclear facilities in the future. Those licensed to operate nuclear facilities must build up financial reserves for decommissioning and draft a schedule, both of which must be approved at least every five years by the State Office for Nuclear Safety. RAWRA must confirm that operators possess these reserves in a special segregated account.

Each year, ČEZ sets aside CZK209 million (US$9.6 million) for decommissioning the Dukovany plant. As of 31 December 2016, CZK6 billion (US$276 million) had been reserved; by the time the plant is shut down, this figure should be CZK22.4 billion (US$1 billion). The total reserve fund for decommissioning the Temelín plant should amount to CZK18.4 billion (US$847 million). As of December 31, 2016, ČEZ had reserved CZK2.8 billion (US$129 million) and annually sets aside CZK198.5 million (US$9.1 million).[303]

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[298] List of members of Platform Against Deep Repository: http://www.platformaprotiulozisti.cz/cs/clenove-platformy/

[299] Czech Radioactive Waste Repository Authority (RAWRA) Website, "DGR in Czech Republic", viewed 29 May 2019, https://www.surao.cz/en/public/deep-geological-repository/dgr-in-czech-republic/

[300] RAWRA 2018, Annual Report on the Activities of Radioactive Waste Repository Authority in 2017

[301] Government of the Czech Republic 2017, Decree No. 35/2017 Coll.

[302] Knápek, J.,et al. 2017, "Updated Economic Model and Fee Calculation for the Nuclear Account for LLW/ILW and HLW/SNF", Technical University study

[303] Czech State Office for Nuclear Safety 2018, National Report of The Czech Republic under Article 14.1 of the Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, viewed 29 May 2019, https://www.sujb.cz/fileadmin/sujb/docs/zpravy/narodni_zpravy/EuroNZ_VP_RAO_2_1A.pdf

SUMMARY

Nuclear waste management in the Czech Republic has several problems yet to be solved. The government has taken responsibility for the final disposal of waste; the producers of such waste are liable for disposal costs and thus pay fees into a state nuclear account that aims to ensure full funding in the future. The fees paid by waste producers, however, are insufficient to cover all expected post-decommissioning costs.

According to government plans, a deep geological repository for high-level waste should be operating by 2065. The site selection process is behind schedule, however, and opposition from potentially affected communities has grown. A long-promised law on the repository, which would better define the site selection process, is not yet available. Site selection criteria are vague, and therefore there is the real threat of a site being selected based not on long-term safety but on the willingness of a community to tolerate it. The long-term storage of spent fuel is a possibility that has not been debated.

In contrast, low- and intermediate-level waste is comparably well managed. A smaller repository which is practically full is soon to be closed. RAWRA will operate two repositories, the Richard repository for institutional radioactive waste and most importantly, the Dukovany repository for low- and intermediate-level waste from nuclear power plants.

7.2 FRANCE

OVERVIEW

French nuclear history began with the development of nuclear weapons in the aftermath of World War II. After a few small reactors dedicated to the production of military nuclear materials, France built six gas-cooled reactors (GCR) in the 1960s and early 1970s, dedicated to both plutonium and power production. Next, France built three other types of reactors. All these early reactors have been shut down and are now at various stages of decommissioning.

France next developed a fleet of 58 pressurized water reactors (PWR) at 19 sites, ranging from 900 to 1,450 MW, all operated by Électricité de France (EDF). They were brought into operation between 1977 and 1999, are still in operation and provide about 72 percent of the country's electricity.[304]

In 2007, EDF began construction on the European pressurized reactor (EPR) at Flamanville. Initially planned to cost €3.3 billion (US$3.7. billion) and to start operation in 2012, it is now expected to cost at least €10.9 billion (US$12.2 billion) and start at the earliest by the end of 2022.[305]

Uranium was mined in France until 2001, though even before France imported more uranium than it produced. France has developed large operational capacities at all stages of the nuclear fuel chain. It operates also nuclear facilities for military purposes.

The main producers of radioactive waste are EDF, Orano, the operator of nuclear fuel chain facilities, and the Commission for Alternative Energies and Atomic Energy (CEA). They each remain responsible until the waste is transferred to and managed and/or disposed of by ANDRA, the national agency for radioactive waste management. ANDRA is a public agency created in 1979 as a department of CEA and formed into an independent body in 1991.

Reprocessing of spent fuel is a national policy. Most uranium oxide (UOX) fuel is reprocessed at La Hague. While now virtually all of the fuel is French, significant quantities of foreign fuel were reprocessed at La Hague in the past. Most of the separated plutonium is reused together with depleted uranium as mixed oxide fuel (MOX) in 22 reactors, amongst the oldest of the fleet (the government has launched plans to use MOX in the more recent 1,300 MW reactors). Some reprocessed enriched uranium (REU fuel) had been used in French reactors until 2016, and EDF is preparing for using some again as of 2023.

A large and complex stock of radioactive waste has accumulated over time in France. While disposal facilities operate to deal with most of short-lived wastes, plans to develop a deep geological disposal (DGD) site for high- and intermediate-level long-lived waste is being delayed by technical problems and public resistance.

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[304] Réseau de Transport d›Electricité (RTE) (Electricity Transmission Network), 2018, Bilan électrique 2018 (Electricity Balance), February.

[305] World Nuclear News 2019, "Weld repairs to delay Flamanville EPR start-up," 20 June, viewed 22 August 2019, https://www.world-nuclear-news.org/Articles/Weld-repairs-to-delay-Flamanville-EPR-start-up

WASTE CLASSIFICATION SYSTEM

The French classification of nuclear waste is in line with the IAEA recommendations, although bringing in specific developments. It is based on two characteristics: its activity and lifetime. Indicative thresholds are based on mass activity, and the radioactive period of the most significant long-lived radionuclides in the waste. There are three lifetime categories and four activity categories, as shown in *Table 10*. Compared to IAEA guidelines, it introduces a distinction between long- and short-lived waste for intermediate-level waste (ILW). While most other countries allow for parts of very low-level waste (VLLW) to be disposed of in conventional landfills, there is no exemption threshold for VLLW in France. The categories are meant to relate to distinct, dedicated management solutions, of which some are already operational, while others remain subject to research.

TABLE 10: Categories of nuclear waste in France and management status as of 2018

		Long-lived	Short-lived	Very short-lived
	PERIOD HALF-LIFE	> 30 years	≤ 30 years > 100 days	≤ 100 days
HIGH-LEVEL WASTE (HLW)	> 109 Bq/g	Under study (Art. 3 of 2006 law) 1 laboratory for geological disposal (Bure)		Management by radioactive decay
INTERMEDIATE-LEVEL WASTE (ILW)	≤ 109 Bq/g > 106 Bq/g	Under study (Art. 3 of 2006 law)	Surface disposal 1 closed facility (CSM) 1 operating facility (CSA)	
LOW-LEVEL WASTE (LLW)	≤ 106 Bq/g > 102 Bq/g	Study of dedicated subsurface disposal (Art. 4 of 2006 law)		
VERY LOW-LEVEL WASTE (VLLW)	≤ 102 Bq/g	Dedicated surface disposal 1 operating facility (Morvilliers)		

Source: ANDRA national inventory of radioactive materials and waste 2019
Notes: ILW/LLW surface disposal does not include specific waste, e.g. contaminated with tritium, for which dedicated management is still being studied; CSA = Centre de stockage de l’Aube, CSM = Centre de stockage de la Manche.

OTHER RADIOACTIVE MATERIALS NOT CLASSIFIED AS WASTE

According to a 2006 law on radioactive waste management, nuclear substances “for which further use is planned or envisaged” are considered as nuclear materials and not defined as waste.[306] A statement of intent from the industry to use a substance is sufficient to classify it as a material, even if there is no precise or realistic plan to use it. Thus, all types of spent fuel, separated plutonium, reprocessed uranium, and depleted uranium are not considered as waste and are not included in the categories indicated above. The possibility that some of these materials will not be reused in the future led to the passing of a law in 2016.[307] It allows the French government to change the qualification of a nuclear ‘material’ to nuclear waste on the advice of the safety authority ASN. This option has not yet been used.

Radioactive gaseous and liquid effluents are not included in the waste classification system. Produced at various stages of nuclear facilities (in large part in the La Hague reprocessing plants), they are managed by dilution in the environment (after a period of storage for decay for some of them).

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306 Government of France 2006, Loi n° 2006-739 du 28 juin 2006 de programme relative à la gestion durable des matières et déchets radioactifs (Law for the sustainable management of radioactive waste and materials number 2006-739, June 28 2996)

307 Government of France 2016, Article 14 of Ordonnance n° 2016-128 du 10 février 2016 portant diverses dispositions en matière nucléaire (Article 14 of the Ordinance bearing various provisions about nuclear matters number 2016-128, February 10 2016)

QUANTITIES OF WASTE

ANDRA publishes an inventory of nuclear materials and waste every three years. The last comprehensive inventory was published in 2018, providing data for the end of 2016. A summary update published in 2019 provides data for the end of 2017 for some categories.

As of December 2017, ANDRA estimated 3,740 m³ of high-level waste (HLW), 42,800 m³ of intermediate-level long-lived waste (ILW-LL), 93,600 m³ of low-level long-lived waste (LLW-LL), 938,000 m³ of low- and intermediate-level short-lived waste (LILW-SL), and 537,000 m³ of very low-level waste (VLLW). In addition, 1,770 m³ of waste was not included in any category. Detailed information is provided in *Table 11*.

Data provided by ANDRA include foreign waste when it is stored on French territory. This mostly relates to spent fuel reprocessing contracts with foreign customers. Solid wastes stemming from that processing has to be returned to the countries of origin, since French law forbids the disposal of nuclear waste of foreign origin on the national territory. However, substitution occurs between different types of waste so as to minimize the volumes to be shipped. The substitution can also circumvent problematic waste forms (e.g. bituminized intermediate-level waste) that have not been accepted by foreign reprocessing customers. Moreover, past and current activities related to nuclear materials of foreign origin have generated waste (e.g. unirradiated breeder fuel), and “reusable materials” (e.g. reprocessed uranium) with no actual use that are now accounted for as French.

HLW almost entirely arises from spent fuel reprocessing. As of the end of 2018, more than 34,000 tHM of French and foreign fuel have been reprocessed at La Hague. Most of the resultant HLW, at least 95 percent, is conditioned as vitrified waste packages. A small fraction is stored for cooling in tanks, while awaiting vitrification.

For ILW-LL, the situation is quite heterogeneous: some waste is conditioned for final disposal, while some is pre-conditioned or even raw. This waste can be cemented in metal drums, in sludges or other raw forms, bituminized, vitrified or concreted. However, some old packages or sludges need characterization before reconditioning. A large quantity of bituminized, inflammable waste packages represent a particular reconditioning challenge.

TABLE 11: Nuclear waste in France as of December 2017

Type of waste	Type of storage	Storage site	Quantity
SNF (HLW)	Interim storage (wet)	Nuclear power plant sites (one pool per reactor)	4,040 tHM
	Interim storage (wet)	La Hague	9,788 tHM*
	Interim storage (wet)	Creys-Malville**	106 tHM
	Interim storage (partly wet, partly dry)	CEA sites	55 tHM
HLW	Interim storage	La Hague, Marcoule, CEA sites	3,740 m^3
ILW-LL (FROM SNF TREATMENT)	Interim storage	NPP sites, La Hague, Marcoule, CEA sites, research centers, Bouches-du-Rhone	42,800 m^3
LLW-LL	Interim storage	NPP sites, La Hague, Marcoule, CEA sites, research centers, Le Bouchet	93,600 m^3
TRITIUM-BEARING WASTE	Interim storage	Côte D'Or	5,640 m^3
LILW-SL	Interim storage	NPP sites, conditioning plants, Marcoule, research centers, uranium plants	85,400 m^3
	Disposed waste	Shut down above-ground repository (CSM)	527,000 m^3
	Disposed waste	Operational above-ground repository (CSA)	326,000 m^3
WASTE WITHOUT CLASSIFICATION		Site not named	1,770 m^3
VLLW	Interim storage	Conditioning plants	185,000 m^3
	Disposed waste	Operational above-ground repository (CIRES)	352,000 m^3
U-HOLDING WASTE	Tips and slurry settling facility		50 million tons
DISUSED RADIOACTIVE SOURCES* **			1,700,000 m^3
ESTIMATED FUTURE WASTES	**HLW:** 12,000 m^3; **ILW-LL:** 72,000 m^3; **LLW-LL:** 190,000 m^3; **LILW-SL:** 2,000,000 m^3; **VLLW:** 2,300,000 m^3		

Source: Own compilation based on ANDRA 2018 and République Francaise 2017
Notes: *includes 30 tHM of foreign SNF; **Creys-Malville also stores 70 t HM of unirradiated fuel initially for Superphénix; *** as of end of 2015; CEA = Commission for atomic energy and alternative energies.

The estimated future waste in *Table 11* is the amount that will be produced by the 58 operational reactors and associated plants, according to ANDRA, using the following assumptions:

- existing reactors will operate for 50 to 60 years,
- all spent fuel (including MOX) is reprocessed,
- all "reusable" nuclear material will be used in existing or future reactors, so there is no requalification (but waste arising from this hypothetical use is not included).
- In comparison to quantities so far, future quantities are much larger. HLW are expected to triple, ILW-LL would be multiplied by 1.7, LLW-LL and LILW-SL would double and VLLW would increase more than fourfold.

OTHER RADIOACTIVE MATERIALS NOT CLASSIFIED AS WASTE

The operation of fuel chain facilities and the reprocessing strategy are meanwhile generating stockpiles of materials that are declared reusable. According to ANDRA's inventory,[308] France stored at the end of 2017:

- 14,189 tHM of spent fuel mostly from PWRs, plus other types of reactors, now shut down (excluding spent fuel from national defense activities, which amounts to 194 tHM). This stockpile increases every year, because quantities discharged from reactors exceed those reprocessed at La Hague by around 20 percent (typically, on recent averages, 1,200 tHM vs. 1,000 tHM);
- 315,000 tHM of depleted uranium stored mostly at Tricastin and Bessines;
- 30,500 tHM of reprocessed uranium, stored at Tricastin and La Hague, of which 2,700 tHM belonged to foreign countries as of the end of 2016. In the past, France has assumed responsibility for large shares of foreign reprocessed uranium, with some of it sent to Russia for storage or re-enrichment;
- and 54 tHM of separated plutonium.

Although spent UOX fuel has increased in recent years, the increase in overall spent fuel was mostly due to MOX fuel and reprocessed enriched uranium (REU) fuel, both of which are not reprocessed. As of the end of 2017, the stockpile of spent MOX amounted to 1,910 tHM; that of spent REU to 578 tHM.

According to the government, the total French unirradiated plutonium stocks, including separated plutonium and unirradiated plutonium fuel and waste, amounted to 65.4 tons by the end of 2016.[309] This plutonium stockpile is increasing on average by more than one ton per year despite the government's pledge to follow a "balance of flows" policy, where no unirradiated plutonium should be accumulated. The main reason for the increase in recent years has been the storage of MOX fuel fabrication waste with high plutonium content. France also held 16.3 tons of plutonium belonging to foreign bodies as of the end of 2016.

Finally, the operation of uranium mines in France until 2001 led to the accumulation of around 50 million tons of uranium mill tailings. These were disposed of at 16 sites, plus around 200 million tons of waste rock at numerous mining sites.

WASTE MANAGEMENT POLICIES AND FACILITIES

For decades, reprocessing of spent fuel has shaped the country's waste and nuclear material management policy, resulting in a very complex system of facilities and regulation.

France's legal and regulatory framework for managing nuclear waste was developed decades after the waste generation started. An initial law on research on radioactive waste management came into force in 1991.[310] The first comprehensive approach came in 2006, with the Law on Sustainable Management

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[308] ANDRA 2019, Inventaire national des matières et déchets radioactifs 2019 – Les essentiels (National inventory of radioactive materials and waste 2018 — The essentials), January.

[309] IAEA 2017, Communication Received from France Concerning Its Policies Regarding the Management of Plutonium, INFCIRC/549/Add.5/21, 29 September.

[310] Government of France 1991, Loi n° 91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs (Law on research for the management of radioactive waste, number 91-1381, December 30th 1991)

of Radioactive Materials and Waste.[311] It set up a National Plan for the Management of Nuclear Materials and Radioactive Waste (PNGMDR), which includes the regular discussion of this strategy in a pluralistic working group, the periodic publication of a joint tri-annual report by ASN and the government, and the periodic update of a governmental order turning the recommendations of the report into legal requirements to the operators.[312]

The strategy of reprocessing resulted in the accumulation of spent nuclear fuel and various nuclear materials (such as separated plutonium and reprocessed uranium). While they release the pressure on waste disposal schemes thanks to their "reusable" status, these stocks put increasing pressure on dedicated storage capacities. About one-third of spent fuel from PWRs is stored in pools at reactor sites, while two-thirds is stored in La Hague's pools. These are projected to become full by 2030 at the latest, a situation that would challenge the operation of reactors. EDF is therefore planning to build a new centralized spent fuel pool with a capacity of 10,000 tHM on one of its nuclear sites. The pool would be designed to operate over a century. The option of dry cask storage for spent fuel has been abandoned.

Long-lived waste also accumulates in storage facilities, mostly at La Hague, where most HLW and ILW-LL are produced, and Marcoule, which holds the second largest inventory. Short-lived waste is the only type of nuclear waste for which final disposal already exists. LILW-SL were sent to the surface disposal site called Centre de stockage de la Manche (CSM) up to 1994. It is now closed with over 527,000 m^3 of waste, of which almost two thirds came from the nuclear power sector. LILW-SL is now directed to the surface disposal site called Centre de stockage de l'Aube (CSA). Its 1 million m^3 capacity was 33 percent full at the end of 2017. VLLW-SL has been sent to the industrial facility for grouping, sorting and disposal called Centre industriel de regroupement, d'entreposage et de stockage (CIRES) at Morvilliers since 2003, and 54 percent of its 650,000 m^3 capacity had been used as of the end of 2017.

For LLW-LL, the 2006 law on radioactive waste management introduced the principle of dedicated shallow disposal that was planned to start operation by 2013. Due to technical problems and local acceptance issues, the project has been shelved. Shallow disposal is under study, but the management strategy is not yet decided (number of sites, location, technological concept). Until a repository is available, LLW-LL is stored mainly at the production sites.

A deep geological disposal facility called CIGEO is planned for HLW and ILW-LL as the solution defined by the 2006 law for their disposal. Most HLW is stored at La Hague (85 percent); the rest at Marcoule. The ILW-LL is mainly stored at La Hague (44 percent), Marcoule (34 percent) and Cadarache (16 percent). CIGEO construction is planned to begin in 2022.

The siting area was selected in the 1990s, when the small village of Bure in the North-East of France was chosen to site a laboratory for studying the local clay structure, and licensed in 1999.[313] The 1991 law on research on radioactive waste management suggested that another laboratory would be licensed to study a granitic geology, but due to local opposition in potential areas, this option was abandoned. In 2010, ANDRA defined a 'zone of interest' for further in-depth exploration (ZIRA) around Bure; the

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[311] Government of France 2006, Loi n° 2006-739 du 28 juin 2006 de programme relative à la gestion durable des matières et déchets radioactifs (Law for the sustainable management of radioactive waste and materials, number 2006-739, June 28 2006)

[312] See the latest French National plan for the management of radioactive materials and waste for 2016-2018: https://www.ecologique-solidaire.gouv.fr/sites/default/files/PNGMDR%202016-2018.pdf

[313] Government of France 1999, Décret du 3 août 1999 autorisant l'Agence nationale pour la gestion des déchets radioactifs à installer et exploiter sur le territoire de la commune de Bure (Meuse) un laboratoire souterrain destiné à étudier les formations géologiques profondes où pourraient être stockés des déchets radioactifs (Order authorizing ANDRA to install and operate on the territory of Bure an underground laboratory to study deep geological structures in which radioactive waste could be disposed of)

precise location of CIGEO was decided a few years later.[314] A first pilot industrial phase would precede full-scale operation, which should guarantee a defined level of retrievability and reversibility for at least a century.[315] Disposal would take place until around 2150, when it would be shut down and monitored for centuries.[316]

The hottest waste needs decades of cooling before it could be disposed of in CIGEO. Technical delays could also arise in dealing with issues such as the fire risk associated with tens of thousands of tons of bituminized waste from the first period of reprocessing. These delays might exceed the planned operational lifetime of existing HLW and ILW-LL storage facilities. There are no plans yet to reinforce or replace them accordingly.

Some of the “reusable materials” might need to be requalified as waste due to a lack of actual reuse; however, their management is neither considered in CIGEO’s current design, nor addressed through the study of other possible options. Including some of these materials in the inventory to be disposed of would require developments of the design of CIGEO and increase its footprint, potentially up to the limits of the geological zone under consideration today.

COSTS AND FINANCING

The only existing global estimates of detailed waste management costs for France are those the Court of Accounts (Cour des Comptes) published in 2012[317] and updated in 2014[318], summarized in *Table 12*. According to the Court, the total gross radioactive waste management costs related to nuclear activities amounted to €32 billion (US\$44 billion$_{2013}$) as of the end of 2013, of which 80 percent was incurred by EDF, 11 percent by Areva (now Orano) and 9 percent by the CEA.

TABLE 12: Gross nuclear waste management cost estimates in France as of 2013

GROSS COSTS, € MILLION$_{2013}$	EDF	CEA	AREVA	ANDRA	TOTAL
LONG-TERM WASTE MANAGEMENT	24,370	1,995	1,885	42	**28,292**
of which HLW and LL-ILW	21,981	1,626	1,154	1	24,762
LL-LLW	832	74	27	17	950
VLLW, SL-LLW and SL-ILW	1,557	295	704	24	2,580
POST-CLOSURE COSTS	1,208	411	42	42	**1,703**
RECOVERY AND CONDITIONING (OLD WASTE)	0	512	1,541	—	**2,053**
TOTAL	**25,578**	**2,918**	**3,468**	**84**	**32,048**

Source: Cour des Comptes 2014.

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[314] ANDRA 2009, Projet de stockage géologique profond réversible — Proposition d’une Zone d’intérêt pour la reconnaissance approfondie et de scénarios d’implantation en surface (Project of retrievable deep geological waste – proposal of a zone of interest for research and scenarios), report of the Strategic committee, https://www.andra.fr/stockage-profond-hama-vl-le-projet-se-precise

[315] Government of France 2016, Loi n° 2016-1015 du 25 juillet 2016 précisant les modalités de création d’une installation de stockage réversible en couche géologique profonde des déchets radioactifs de haute et moyenne activité à vie longue (Law number 2016-1015 defining the provisions for the licensing of a facility for the reversible disposal in a deep geological structure for long-lived high and intermediate level waste)

[316] ANDRA website, “Les differentes phases du project” (Project Phases), viewed 22 February 2019, https://www.andra.fr/cigeo/les-installations-et-le-fonctionnement-du-centre/les-differentes-phases-du-projet

[317] Government of France Cour des Comptes (Accounting Office) 2012, Les coûts de la filière électronucléaire (The Costs of Nuclear Power), public report

[318] Government of France Cour des Comptes (Accounting Office) 2012, Le coût de production de l’électricité nucléaire – Actualisation 2014 (The Costs of Nuclear Electricity – update 2014), Communication to an enquiry commission of the French National Assembly.

Although existing waste repositories to dispose of VLLW and LILW-SL roughly allow for disposing of 90 percent of the volumes of waste, the combined costs of the repositories CIRES, CSM and CSA only account for €2.6 billion (US$3.6 billion), or less than ten percent of the total costs. The lion's share of the projected costs is related to the disposal of long-lived waste (more than €25 billion or US$34.5 billion) and the recovery and conditioning of old waste (about €2 billion or US$2.8 billion). Both estimates are highly uncertain. Although the government projected the cost for the disposal of HLW and LL-ILW in CIGEO to be used for provisioning at €25 billion (US$32 billion), this arbitrarily settled a dispute about greatly varying estimates between the operators and ANDRA.[319]

Moreover, this cost estimate is based on a future inventory using the assumption that all spent fuel will be reprocessed. Past cost estimates provided by ANDRA have shown that including un-reprocessed spent uranium and MOX fuel in the considered inventory could lead to more than doubling the projected cost of CIGEO. The current estimate of gross spent fuel management costs is based on a projected reprocessing of all of it.

The 2006 law on radioactive waste management established that operators must provide the government administration with the information needed in a report that must be updated every three years. Regulation stipulates that dedicated assets have to cover the provisions, with a sufficient safety level, diversity, liquidity, and profitability.

In its 2014 report update, the Court of Accounts noted that the provisions to cover these future expenditures, related to future decommissioning and radioactive waste management, were calculated at €43.7 billion (US$60.3 billion) at the end of 2013, of which €11 billion (US$15.2 billion) was for nuclear waste management, and €10.1 billion (US$13.9 billion) was for spent fuel management. For EDF's spent MOX and URE fuel, the provision is based on the "cautious" assumption that it won't be reprocessed, but disposed of in a geological disposal – an assumption inconsistent with those for the cost of CIGEO. Thanks to discounting rates used, these provisions – 75 percent of which are borne by EDF, 14 percent by Areva (now Orano) and 11 percent by CEA – roughly amounted to half of the estimated value of the future costs.

TABLE 13: Provisions for decommissioning and nuclear waste management in France as of 2013

PROVISIONS, € MILLION$_{2013}$	EDF	CEA	AREVA	ANDRA	TOTAL
Decommissioning	13,024	2,931	3,661		19,616
Spent fuel management	9,779	342			10,121
Waste management, of which	7,542	1,311	2,113	47	11,103
retrieval and repackaging		432	1,240		1,672
long-term waste management	7,397	830	831	36	9,094
post-closure costs of waste disposal facilities	145	49	42	10	246
Last cores	2,313				2,313
Other		152	483		635
TOTAL	**32,658**	**4,736**	**6,258**	**47**	**43,699**
Share	75%	11%	14%		100%
Provisions/Gross costs	48%	66%	52%	56%	50%

Source: Cour des Comptes 2014.

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[319] Government of France 2016, Arrêté du 15 janvier 2016 relatif au coût afférent à la mise en œuvre des solutions de gestion à long terme des déchets radioactifs de haute activité et de moyenne activité à vie longue (The cost related to the implementation of solutions for the long term management of high level and intermediate level long-lived radioactive waste, Ministerial order, January 15)

Critics argue that the provisions to cover future costs are insufficient and create high uncertainties. The independent National Commission for the Evaluation of the Financing of Charges for the Decommissioning of Nuclear Facilities and the Management of Spent Fuel and Radioactive Waste (CNEF) was set up in 2011 to evaluate the control of operators by the government. It consists of parliamentarians and experts and should publish a report every three years. So far, however, it has reported only once, in 2012.[320] This report stated that the government lacks means to exert its control, the evaluations by the operators do not provide any margin for uncertainties, the information provided to the administrative authority is inadequate to check the regulation of dedicated assets, and CNEF found it hard to maintain its skills due to the low frequency of its work.

SUMMARY

The French nuclear program was first developed for military purposes but rapidly turned into a pillar of French energy policy. It led to the deployment of numerous reactors and nuclear facilities which have produced the largest stockpile of nuclear waste and materials in Europe. The strategic choice of a management scheme based on spent fuel reprocessing led to a complex set of various waste categories and nuclear materials, resulting in constantly increasing intermediate- to high-level long-lived waste quantities in storage facilities.

Most of the historical choices in France were made before a dedicated legal and regulatory framework was introduced. This process began with a law on research on radioactive waste management in 1991 and then a law on the management of nuclear materials and radioactive waste in 2006. Since then, the regular updating of a tri-annual plan aims at elaborating and implementing a strategy consistent with this complex inheritance.

Disposal solutions are operational for only some waste categories (such as very low-level, low-level short-lived and intermediate-level short-lived waste). All other categories lack solutions. Plans for a shallow disposal for low-level long-lived waste have been shelved. The project of deep geological disposal for intermediate-level long-lived waste and high-level waste still faces important technical and political hurdles. Moreover, France has not developed plans for disposing of growing stockpiles of nuclear materials (including plutonium, reprocessed and depleted uranium) that are at risk of not or only partially being reused.

This situation puts increasing pressure on the capacities and operational lifetimes of existing storage facilities, resulting in extensions, such as the new project of a centralized spent fuel storage pool. The currently projected costs and dedicated funds fail to account for these items and are thus likely to prove insufficient. EDF, which is supposed to cover the lion's share of the backend costs, at the same time bears the burden of increasing operational costs at its aging reactors and an "investment wall" due to the EPR construction fiasco of Flamanville-3 and a legal obligation to increase its share of renewables.

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[320] Government of France 2012, Commission nationale d'évaluation du financement des charges de démantèlement des installations nucléaires de base et de gestion des combustibles usés et des déchets radioactifs (National commission for the evaluation of the financing of charges for the decommissioning of nuclear facilities and the management of spent fuel and radioactive waste)

7.3. GERMANY

OVERVIEW

In 1955, both the Federal Republic of Germany (FRG) and the German Democratic Republic (GDR) established nuclear research programs. West Germany developed its nuclear program in two parallel streams: one on German reactor designs, and one based on the acquisition of US technology. The first light water reactor was ordered for the first nuclear power plant VAK Kahl in 1956. By the late 1980s, West Germany had 19 nuclear power plants in operation, contributing some 30 percent to the country's net electricity generation annually.

Meanwhile, East Germany was supplied by the Soviet Union. In 1966, it connected its first pilot reactor in Rheinsberg to the grid. Early plans of the GDR government called for the construction of 20 nuclear power plants by 1970, but only the five units of Greifswald were built.[321] In 1990, with unification, the German government decided to shut down all Soviet reactors. The decision was mainly economical: to continue operations under the newly applied West German Atomic Energy Act, a high number of safety requirements would have been necessary.[322]

In the early 2000s, the SPD-Green Party coalition reached a consensus with the utilities to abandon nuclear power. The agreement became law in 2002 (the Nuclear Phase-Out Law) and limited the lifetime of the reactors to around 32 years' worth of electricity generation (kilowatt-hour allotments). The law banned the construction of new nuclear power plants altogether.[323] In the fall of 2010, the Conservative-Liberal Democrat coalition reversed the phase-out and extended reactor operation times by 8 to 14 years, depending on the reactor type. These extensions, however, lasted less than a year. In 2011, three months after the Fukushima accident, the parliament adapted with broad support across the political spectrum the Atomic Energy Act (AtG) to instantly withdraw the operating licenses of eight reactors. The remaining nine plants are to be closed down by 2022.

By 2019, only three rather small prototype reactors have been decommissioned to greenfield status. Two larger plants have completed dismantling, but neither site can yet be released from regulatory control as nuclear waste is still stored in parts of the buildings.[324]

Contrary to East Germany, the West never mined any uranium. However, there is one uranium enrichment plant in Gronau and one fuel fabrication plant in Lingen. Gronau is operated by a subsidiary of URENCO Ltd. One-third of its shares are held by the German utilities Preussen Elektra and RWE, one-third by the UK government, and one-third by the Dutch government. In Lingen, Framatome (through its subsidiary Advanced Nuclear Fuels GmbH) manufactures fuel assemblies as well as powder and pellets for supplying all of Framatome's fuel fabrication plants. In the 1970s, there were plans for a complex nuclear disposal center in Gorleben including a spent fuel reprocessing plant, fuel fabrication plants, and facilities for all types of waste including a salt mine for deep geological disposal. Most of these plans were shelved and later on abandoned. The long-lasting surface and underground exploration (starting in 1979 and 1986 respectively) of the salt dome and its development to a pilot mine, along with the accumulation of a high radioactive inventory in its interim storage facility, turned Gorleben nonetheless into a central waste management site.

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[321] Jonas, A. 1959, "Atomic Energy in Soviet Bloc Nations", Bulletin of the Atomic Scientists, 1 November.

[322] Thierfeldt, S. and Schartmann, F. 2012, "Stilllegung und Rückbau kerntechnischer Anlagen", Brenk Systemplanung.

[323] Appunn, K. 2018, "The history behind Germany's nuclear phase-out", Clean Energy Wire, viewed 9 January 2019, https://www.cleanenergywire.org/factsheets/history-behind-germanys-nuclear-phase-out

[324] Schneider et al 2018.

WASTE CLASSIFICATION SYSTEM

The basic structure of the German classification system is relatively simple. Nuclear waste is classified according to its heat-generating properties in only two categories:

- heat-generating waste,
- and waste with negligible heat generation.

The first category corresponds broadly to the IAEA category of high-level waste (HLW), including both waste from reprocessing spent fuel, as well as spent fuel itself. The second category is essentially a combination of the IAEA categories for intermediate-level (ILW) and low-level waste (LLW). However, some of the heat-generating waste is considered ILW under the IAEA category. Some types of very low-level waste (VLLW) already exceed the current German clearance levels for conventional landfill. The latter therefore have to be disposed of in the deep geological disposal (DGD) facility for radioactive waste with negligible heat generation.[325]

German policy is to dispose of both categories of waste in deep geological repositories, but in different sites needing different design characteristics.

QUANTITIES OF WASTE

Germany has a legacy over large amounts of waste currently in interim storage, both in centralized interim storage facilities as well as on the reactor sites. After France and the UK, Germany has the largest volumes of waste in Western Europe. All the data below comes from the most recent inventory, which records waste volumes and activity as of April 1st 2016. *Table 14* shows the total volumes and mass of nuclear waste.

Heat-generating waste: So far, 15,155 t HM of spent nuclear fuel (SNF) have been produced. Half of it was sent for reprocessing, 327 tons was “exported without return”, and half is in interim storage (3,609 tons still in wet storage in pools at reactor sites). In addition, 577 m³ from reprocessing is currently stored mostly at reactor sites. There are still 26 casks containing waste from reprocessing stored in France and the UK. The German states (Länder) of Schleswig-Holstein, Baden-Württemberg, Hessen, and Bavaria have agreed to take over these casks. Germany expects that around 27,000 m³ of heat-generating waste will be disposed of in one DGD facility.

Waste with negligible heat generation: Around 120,000 m³ are stored in various forms across the country, not including around 21,000 tons of raw and pretreated waste, that has not undergone some form of conditioning (i.e. waste in its original form) and is stored on the producer’s sites. All waste with negligible heat generation are to be disposed of in the Konrad facility, which has a capacity of 303,000 m³. The stored waste is divided according to its processing state. Around 100,000 m³ of waste has been conditioned into Konrad containers, these are licensed for storage in the disposal facility Konrad. An additional 3,000 m³ has undergone product control. Around 24,000 m³ is stored in the centralized interim storage facilities (Gorleben, Mitterteich, Greifswald and Ahaus).

In addition to the large amounts of waste in interim storage, Germany has also already disposed of LILW in two DGD facilities. In the facility Morsleben (Saxony-Anhalt, 1971-1991 and 1994-1998), 37,131 m³ was disposed of. Around 47,000 m³ was disposed of in Asse II (Lower Saxony, 1967-1978). However, the pressurized salt is losing its stability and groundwater inflow makes continued dry operation

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[325] Government of Germany 2018, National Report Sixth Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

impossible. The site is in danger of collapsing, a worst-case scenario for deep geological disposal. In 2010, the complete retrieval of the estimated 220,000 m³ of mixture of radioactive waste and salt was announced although in practice it may not be technically feasible to retrieve all of it. Until today the disposal strategy is not decided and recovery has not started. One option is to dispose of the waste in the future DGD for HLW, if technically possible. The most costly scenario would be the search for and construction of a third DGD.

TABLE 14: Nuclear waste in Germany as of December 31, 2016

Type of waste	Type of storage	Storage site	Quantity
SNF (HLW)	Interim storage (dry)	Storage facilities at power plant sites	4,201 tons
	Interim storage (dry)	ZLN, Ahaus, Gorleben	675 tons
	Interim storage (wet)	Reactor storage pool at power plant sites	3,609 tons
	SNF sent to reprocessing	851 tons shipped to the UK; 5,393 tons shipped to France; 14 tons shipped to Belgium; 85 tons reprocessed at Karlsruhe, Germany.	6,343 tons
	SNF exported without return	283 tons of VVER fuel send to Russia; 17 tons shipped to Sweden; 27 tons of VVER fuel to be reused in Hungary	327 tons
HLW	Interim storage	Power plant sites, ZLN, Land collecting facilities, centralized storage facilities	577 m³
LILW*	Interim storage	Power plant sites	14,631 m³
	Interim storage	Unterweser	1,422 m³
	Interim storage	Gorleben	6,979 m³
	Interim storage	Mitterteich	8,200 m³
	Interim storage	ZLN Greifswald	6,830 m³
	Interim storage	Stade	4,403 m³
	Interim storage	Research facilities	61,965 m³
	Interim storage	Land collecting facilities	1,108 m³
	Interim storage	Ahaus	1,633 m³
	Interim storage	GNS and other storage facilities, Daher Nuclear Technologies, Nuclear Industry	13,160 m³
	Shut down geological repository	Asse II	47,000 m³
	Shut down geological repository	Morsleben	37,131 m³
VLLW	n.a.		
U-HOLDING WASTE	Tips + slurry settling facility	Wismut (in recultivation)	48 heaps with low active rocks of ca. 311 million m³, four tailings ponds holding ca. 160 million m³ of radioactive sludge

Source: Own compilation based on German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2018.

Note: *does not include around 21,000 tons of raw and pretreated waste.

With fixed grid disconnection dates for all its nuclear power plants, Germany has more certainty about the expected quantities of heat-generating waste. Overall, 27,000 m³ of heat-generating waste needs disposal.[326] In addition, Germany's National Sixth Report to the Joint Convention gives a rough estimate for the generation of operational waste of 45 m³ of waste with negligible heat generation per year and per reactor as well as a rate for the estimated decommissioning waste per reactor: around 5,000 m³ of waste with negligible heat generation.

WASTE MANAGEMENT POLICIES AND FACILITIES

The 2002 nuclear phase-out law terminated spent nuclear fuel reprocessing abroad as of June 2005. A scientific workgroup (Arbeitskreis Endlagerung) was commissioned by the government to submit recommendations for a criteria-based, transparent procedure for the search for and selection of repository sites.[327] From then on, the policy for spent nuclear fuel was direct geological disposal without reprocessing. As a consequence, spent fuel and high-level waste from reprocessing was stored in centralized interim storage facilities, mainly in Gorleben but also in Ahaus. Meanwhile most of the nuclear power plants run dry interim storage facilities for their spent fuel.

The Fukushima accident in March 2011 had a catalytic effect on German nuclear policy. With support from parties across the political spectrum, the government decided to shut down all nuclear power plants by 2022.[328] Long-lasting doubts about site selection and the quality of the geology at Gorleben were acknowledged by a group of State (Länder) governments. In a major political breakthrough, they announced support for a new start of a countrywide site selection process for a repository for heat-generating radioactive waste. A working group was set up to find a compromise between the political parties and the federal and state interests regarding the future policy for a DGD facility.[329] Two years later, the parliament passed the 2013 Repository Site Selection Act (StandAG). After forty years of exploration, the construction of an 800 m deep mine and infrastructure above ground, and after fierce political confrontation and debate, survey work in the Gorleben salt bed has been set on hold. No work takes place underground. But Gorleben is part of the new site selection process for final disposal, with 113 casks containing HLW (5 containing SNF and 108 containing HLW from reprocessing) and around 7,000 tons or around 6 percent of the German LILW inventory stored at its interim storage facility.

In 2014, the Commission on the Storage of High-Level Nuclear Waste (Repository Commission) was set up to audit the StandAG and develop recommendations for the site selection process. They define safety standards, assessment criteria and an adaptive procedure to enable revisions of decisions and to establish retrievability of the disposed waste. Furthermore, the site selection process is to be opened to all potential host rocks in Germany: claystone, rock salt and crystalline rock. Its final report recommends a three-phase process accompanied by public participation.[330] The government implemented these recommendations in its 2017 revision of the StandAG and set an aspirational date to find a site by 2031.

In parallel, the German government rearranged the responsibilities of its various agencies, aiming for more credibility and allowing for the rule of distance. In 2016, a new law transferred tasks previously

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[326] This includes 20,400 m³ of SNF, 3,400 m³ of structural parts and sleeves from SNF disposal, 1,440 m³ of vitrified wastes from reprocessing, 1,340 m³ from the THTR reactor, and 3,400 m³ of waste packages with structural parts of SNF.

[327] Arens, G. 2002, Arbeitskreis Auswahlverfahren Endlagerstandorte (AkEnd) (Recommendations of the AkEnd. Committee on a Selection Procedure for deep disposal of radioactive waste)

[328] von Hirschhausen, C. 2018, German Energy and Climate Policies: A Historical Overview. In Energiewende "Made in Germany" Springer, Cham. pp. 17-44.

[329] Hocke, P. and Kallenbach-Herbert, B. 2015, Always the Same Old Story? in A Brunnengräber et al. Challenges of Nuclear Waste Governance, Springer VS, Wiesbaden, pp. 177-201.

[330] German Commission on Storage of Highly Radioactive Materials 2016, Abschlussbericht der Kommission zur Lagerung hochradioaktiver Abfälle K-Drs. 268 (Final Report by commission on the storage of high-level nuclear waste)

undertaken by the public authority for radiation protection (BfS) to the public authority for the safety of nuclear disposal (BfE) and the new federal company for radioactive waste disposal (BGE).[331] All the federal regulation, licensing, and supervisory tasks are bundled in the BfE; the operational tasks of site selection, building and operation of the DGDs was transferred to the BGE, which is also responsible for the construction of the Konrad mine (now scheduled to open in 2027, more than half a century after site selection).

The ownership of the interim storage facilities for HLW was transferred to the federally owned company for interim storage (BGZ). In the coming years, the LILW storage facilities on the reactor sites will also be transferred to the public company.

To monitor the site selection procedure and to implement public participation, a pluralistically composed National Civil Society Board (NBG) was established. It started work in December 2016.[332] The institutionalized participation of civil society is a new approach for Germany. So far, public attention for the new site selection procedure and its participation process is weak.

COSTS AND FINANCING

Under the Atomic Energy Act (Atomgesetz, AtG), the operators of nuclear power plants must pay for decommissioning and for the management of the nuclear waste, including the cost of disposal. For historic reasons, two different funding systems are in place: one for the former East German reactors, which are now publicly owned and financed. For example, the funding for the decommissioning of the former GDR Greifswald and Rheinsberg power plants is completely provided by the Federal Ministry of Finance. Here, the last cost estimate (in 2016) for both sites was around €6.5 billion (US$7.3 billion) in total. The other funding system is for facilities in private ownership. There are also some prototype reactors in mixed-ownership. Here a proportional split of the costs between the public and the private utilities is clarified by special arrangements.[333]

In 2015, an auditing company on behalf of the German government estimated the cost of decommissioning and waste management for 23 commercial nuclear power plants at undiscounted €47.5 billion (US$53.4 billion), including:

- €19.7 billion (US$22.1 billion) for decommissioning and dismantling,
- €9.9 billion (US$11.2 billion) for casks, transport, and operational waste,
- €5.8 billion (US$6.5 billion) for interim storage,
- €3.7 billion (US$4.2 billion) for a disposal facility for waste with negligible heat generation, and €8.3 billion (US$9.3 billion) for a disposal facility for heat-generating waste.[334]

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[331] Government of Germany, Act on the reorganization of responsibility in nuclear waste management (Gesetz zur Neuordnung der Organisationsstruktur im Bereich der Endlagerung (BGBl., I, S. 1843 768/16).

[332] For more information, see: http://www.nationales-begleitgremium.de/DE/Home/home_node.html

[333] European Commission 2013, "EU Decommissioning Funding Data — Commission Staff Working Document," viewed 28 June 2019, http://aei.pitt.edu/42990/

[334] Warth & Klein Grant Thornton AG Wirtschaftsprüfungsgesellschaft 2015, Gutachtliche Stellungnahme zur Bewertung der Rückstellungen im Kernenergiebereich (Expert Opinion on the Evaluation of Provisions in the Nuclear Energy Sector), viewed 5 June 2019, http://bmwi.pro.contentstream.de/18004initag/ondemand/3706initag/bmwi/pdf/stresstestkernenergie.pdf

The nuclear utilities have built up €38.2 billion (US$42.9 billion) in provisions. These funds have been collected from consumers via electricity prices.[335] Clearly, the estimated costs for these processes exceed the provisions. If the polluter-pays-principle had been applied rigorously (which it should have, according to the Atomic Energy Act), the operators would have had to file for bankruptcy.[336] Concerns grew that the operators could leave the bill, in the case of bankruptcy, to the public and that safety and security during decommissioning, storage and waste management could be neglected for economic reasons.[337] In response, the government set up a commission (KFK) to review the financing system.

The commission recommended changing the funding system fundamentally, transferring financial and organizational obligations for the waste management from the operators to the federal government.[338] The recommendations were integrated into the new law.[339] The utilities are still responsible for decommissioning and conditioning, but are exempted from all downstream waste tasks. Accordingly, the utilities had to pay the amount of their former provisions for waste management of €24.1 billion, including a risk premium, into an external, segregated public fund. The Fund for the Financing of Nuclear Waste Management was set-up in mid-2017 to ensure that the money is invested 'securely and profitably'. Yet responsibility and future risks will have to be borne by the public, infringing the polluter-pays-principle.[340] In its first financial year, the fund only invested a fraction of its assets and the majority is still held at the Bundesbank at an interest rate of 0.4 percent. This led to around €39 million in interest expenses during the fund's first six months of existence.[341]

SUMMARY

In recent years, Germany has engaged in a lot of political activity in addressing nuclear waste, partially driven by the Fukushima accident in 2011, which had a catalytic effect on German nuclear policy. After agreeing to disconnect all nuclear power plants stepwise until 2022, political attention was shifted to decommissioning and storage/disposal. Forty years after the first site selection in which the salt dome in Gorleben had been surprisingly chosen, a new site selection procedure was institutionalized through a reshuffling of agency responsibilities, the creation of new federal companies and regulators, and the implementation of an external, segregated fund for waste management. The institutionalized participation of civil society is a new approach for Germany. If an actual level playing field among all institutions was established, still has to be seen. So far, public attention for the new site selection procedure and its participation process is weak.

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[335] Irrek and Vorfeld 2015.

[336] Kunz, F., Reitz, F., von Hirschhausen, C. and Wealer, B. 2018. Nuclear Power: Effects of Plant Closures on Electricity Markets and Remaining Challenges. In Energiewende "Made in Germany" Springer,Cham pp. 117-140.

[337] von Hirschhausen, C. and Reitz, F. 2014. Nuclear power: phase-out model yet to address final disposal issue. DIW Economic Bulletin, 4(8), pp. 27-35.

[338] Kommission zur Überprüfung der Finanzierung des Kernenergieausstiegs (Commission to Review the Financing of the Nuclear Phase-Out) 2016, "Verantwortung und Sicherheit — Ein neuer Entsorgungskonsens" (Responsibility and Safety — A New Disposal Consensus)

[339] Government of Germany 2016, Entwurf eines Gesetzes zur Neuordnung der Verantwortung in der kerntechnischen Entsorgung — Drucksache 18/10469 (Act on the Reorganization of the Organizational Structure in the Field of Disposal) German Parliament, 18th Legislative Period, 29 November 2016.

[340] Jänsch, E., Brunnengräber, A., von Hirschhausen, C. and Möckel, C. 2017. Wer soll die Zeche zahlen? Diskussion alternativer Organisationsmodelle zur Finanzierung von Rückbau und Endlagerung. (Who pays? Discussion of alternative organizational models for the finance of nuclear decomissioning and storage) GAIA-Ecological Perspectives for Science and Society, 26(2), pp. 118-120.

[341] Fonds zur Finanzierung der kerntechnischen Entsorgung (German Fund for the Financing of Nuclear Waste Management) 2018, Business Report 2017

Germany has a legacy of large amounts of waste currently in interim storage, both in centralized storage facilities and at reactor sites. Germany classifies its waste as two types: radioactive waste with negligible heat generation and radioactive waste with heat generation.

The future disposal path for high-level waste is still highly uncertain, with Germany only now entering the site selection process. The construction of the deep geological disposal facility at Konrad for low- and intermediate-level waste is still ongoing, and currently the facility is planned to open in 2027. Until then, all low- and intermediate-level waste will be in interim storage facilities. Interim storage of spent nuclear fuel and high-level waste will at least last until 2050, at best. The debate about the need to review the safety and the capacities for storage is heating as the selection of a final disposal site should not be driven by shortage of capacity or security concerns for interim storage.

Germany has gained some experience in the decommissioning of nuclear reactors, but all reactors currently in the post-operational stage still face several obstacles in order to conclude the process in a timely manner without escalating costs. All estimated future costs – especially future costs related to waste management – are uncertain due to cost increases and interest rates. It is questionable whether the financial resources set aside in the fund will cover these costs.

7.4 HUNGARY

OVERVIEW

The history of nuclear energy in Hungary dates back to the 1960s. The Hungarian government decided in 1966 to build a nuclear power plant with a total of four units. Construction in Paks started in 1974. Electricity generation there started in 1982. All four units are pressurized water reactors (VVER– 440/213). Paks is currently the only nuclear power plant in the world with such reactors operating in an extended fuel chain: instead of every 12 months, fuel is exchanged every 15 months.[342] In accordance with the service life extension program from 2012, the four unites are expected to operate another twenty years until the mid-2030s.

In 2018, the four reactors at Paks operated with high availability (89 percent), generating around 15 TWh of electricity, providing roughly half the country's power production.[343]

In January 2014, the Hungarian government signed an intergovernmental agreement with the Russian Federation to build two more units, with a capacity of 1,200 MW each. The units will be constructed at Paks, 100 km south of Budapest. However, construction of Paks II has not yet started which could delay the planned start of operation beyond the late 2020s.

The only uranium mine in Hungary was closed in 1997 as a result of inefficient operation.[344] Due to the planned expansion of Paks, Hungarian Uranium Resources Ltd. plans to re-open the mine, though authorities rejected the environmental permit of the investment in the first instance. Hungary has no spent fuel reprocessing capabilities.

WASTE CLASSIFICATION SYSTEM

Hungary's waste classification system is laid out in its national program for spent fuel and radioactive waste management. Its first principle is that waste generated in the controlled area shall be treated as radioactive until proven otherwise.[345] The program is based on the recommendations of the International Atomic Energy Agency (IAEA) and the EU Council Directive 2011/70/EURATOM. According to the 2nd Atomic Energy Act of 1996, the Hungarian government is required to organize the final disposal of radioactive waste.[346]

Hungary classifies radioactive wastes in four ways: by state, by heat generation, by radioactivity concentration, and by half-life.

- State-classified radioactive waste can be solid, of biological origin, liquid and non-inflammable, liquid and inflammable, and airborne waste.

- Based on heat generation there are distinctions between low-and intermediate-level waste (LILW) and high-level waste (HLW).

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[342] For more information about the reactor core (VVER-440/213), see the Paks power plant website: http://www.atomeromu.hu/en/Documents/2_Structure_of_Paks_npp.pdf

[343] Paks Nuclear Power Plant Website, viewed 26 February 2019, http://www.atomeromu.hu/hu/Rolunk/Hirek/Lapok/HirReszletek.aspx?hirId=650

[344] Paks Nuclear Power Plant Website, "Mining of uranium ore", viewed 26 February 2019, http://www.atomeromu.hu/en/Documents/7_1Life_of_uranium_1.pdf

[345] Government of Hungary 2017, "Hungary's national program for spent fuel and radioactive waste management", viewed 26 February 2019, http://www.mmediu.ro/app/webroot/uploads/files/2017-05-09-Program_national_HU.pdf

[346] Government of Hungary, Act CXVI of 1996 on Atomic Energy, viewed 26 February 2019, http://www.oah.hu/web/v3/HAEAportal.nsf/AF56E3A1E23F3932C1257CA700432BBC/$File/1996_116_tv_EN_2017_06_24_2017_12_31.pdf

- Low-, intermediate- and high-level radioactive waste categories are also used when differentiating by radioactivity.
- Waste classified by half-life of radionuclides can be short-, intermediate- and long-lived (longer than 30 years) waste.[347]

Executive Decree 23/1997 defines a level of radioactivity in low-level radioactive waste beneath which it has exemption (or clearance). But Hungarian regulations have another system that classifies radioactive waste on the basis of the gamma-radiation dose rate measured at 10 centimeters from the surface of the waste packages. In this case, low-level radioactive waste is less than 0.3 milli Sieverts per hour (mSv/h) and high-level waste is greater than 10 mSv/h.

QUANTITIES OF WASTE

The Hungarian government reports regularly on quantities of spent fuel and radioactive waste. Reports are prepared for the Joint Convention of the International Atomic Energy Agency (IAEA). The latest report was ready for the 2018 Convention. Until 1998 Hungary sent spent nuclear fuel to Russia for reprocessing (2,331 fuel assemblies or 273 tons heavy metal content). Since then, spent nuclear fuel has been stored temporarily at the Spent Fuel Interim Storage Facility near the Paks nuclear power plant.

TABLE 15: Nuclear waste in Hungary as of December 31, 2016

Type of waste	Type of storage	Storage site	Quantity
SNF (HLW)	Interim storage (wet)	Reactor storage pool at Paks	1,800 FA
	Interim storage (dry)	SFISF at Paks	8,707 FA
HLW	Interim storage	Paks	102 m^3
LILW LIQUID	Interim storage	Reactor storage tanks at Paks	8,131 m^3
LILW SOLID	Interim storage	Reactor storage facility at Paks	1,835 m^3
	Interim storage	Near–surface repository RWTDF	225 m^3
	Disposed waste	Near– surface repository RWTDF	4,900 m^3
	Interim storage	Near– surface repository NRWR	430 m^3
	Disposed waste	Near– surface repository NRWR	876 m^3
VLLW	n.a.		
U– HOLDING WASTE	Tips + slurry settling facility	in recultivation	10 million m^3 of waste rock piles and 3.4 million m^3 of heap leaching piles

Source: Government of Hungary 2017, National Report Sixth Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

Notes: FA = fuel assembly; SFISF = Spent Fuel Interim Storage Facility.

According to the National Report the radioactive waste from decommissioning will be placed at a different facility (in the Boda area in the south of the country). The estimated quantity of the decommissioning of Paks of low- and medium-level waste is 9,147 containers of 1.8 m^3 and 2,846 containers of 3.6 m^3 each. The estimated gross volume of decommissioning and operational high-level waste deposited in the planned deep geological repository is 300 m^3.

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[347] Government of Hungary 2017, National Report Sixth Report prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

WASTE MANAGEMENT POLICIES AND FACILITIES

Hungary's radioactive waste management approach is defined by the 1996 Act on Atomic Energy.[348] The Public Limited Company for Radioactive Waste Management is accountable for the overall four radioactive waste disposal sites in Hungary. For waste from the power sector there are two facilities:

- The National Radioactive Waste Repository (NRWR) at Bátaapáti is where the low- and intermediate-level radioactive waste from the Paks nuclear power plant is stored. Solid waste that arrives here is loaded into compacted forms, usually 200 liter drums. Liquid waste is collected into tanks. The capacity of this storage facility is 3,000 drums.[349]

- The second facility is a spent fuel interim storage facility (SFISF) near the Paks plant. This facility started operating in 1998. Before that, spent fuel was sent back to Russia. Since Hungary started dealing with spent fuel, the total storage capacity of the facility has been extended and now there is capacity for 9,308 spent fuel assemblies.[350]

In addition, some low-level waste from Paks was temporarily stored at the Radioactive Waste Treatment and Disposal Facility (RWDTF), which is used mainly for non-power waste.[351]

The Act on Atomic Energy regulates the management of radioactive waste and authorizes the government to issue executive orders specifying requirements in this field. The act serves as the framework to build and maintain facilities for waste disposal and interim storage for spent fuel. After Hungary's accession to the European Union (EU), the Act was adapted to comply with EU regulations and EURATOM. The Act specifies that radioactive waste management should not impose a burden on future generations. It created the Public Agency for Radioactive Waste Management which operated from 1998 to 2008. Then, this body was transformed into the Public Limited Company for Radioactive Waste Management (PURAM). Since 2008, PURAM has been responsible for operating radioactive waste storage and disposal and updating the plans of the activities financed by the Central Nuclear Financial Fund.

In 1971, the Hungarian government decided to build the Radioactive Waste Treatment and Disposal Facility for low- and intermediate-level waste from non-power sources. In 1995, a national program was announced to address the problem of high-level and long-lived radioactive waste. As a result, PURAM has established a spent fuel interim storage facility next to the Paks plant. The facility is capable (in its planned 36 modules) of storing spent fuel for a period of at least 50 years. By 2012, the facility was halfway completed.

Low- and intermediate-level waste from the Paks nuclear power plant goes to the repository at Bátaapáti.[352] The operating license allows the buffer storage of 3,000 drums (with a capacity of 200 liters each) containing low- and intermediate-level solid radioactive waste. According to PURAM, the capacity of the repository at Bátaapáti will meet the demand of the Paks plant, and the underground space will be extended to make it sufficient for the entire lifetime of the Paks I nuclear power plant.[353]

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[348] Government of Hungary, Act CXVI of 1996 on Atomic Energy

[349] Hungarian National Radioactive Waste Repository (NRWR) n.d., "16 drums loaded into 4 transport frames can be put on the vehicle," viewed 26 February 2019, http://www.rhk.hu/en/our-premises/nrwr/

[350] Hungarian National Radioactive Waste Repository (NRWR) n.d., "History of spent fuel storage," viewed 26 February 2019, http://www.rhk.hu/en/our-premises/isfs/history/

[351] Oroszi, B. 2019, "Tritium Leak and Waste Packaged in Plastic Bags: Questions about the Nuclear Cemetery," February 27, viewed 26 February 2019, https://english.atlatszo.hu/2019/02/27/tritium-leak-and-waste-packaged-in-plastic-bags-questions-about-the-nuclear-cemetery/

[352] The repository started operation in 2008. For more of its history, see http://www.rhk.hu/en/our-premises/nrwr/history/

[353] Government of Hungary 2005, Second Report prepared in the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, viewed 26 February 2019, http://www.oah.hu/web/v3/HAEAportal.nsf/5E4C87A0B24A7094C1257C5C00364137/$FILE/nationrep2.pdf

In 2015, the government began research for deep geological disposal in the Boda region. The current state of scientific knowledge suggests that clay is the most suitable geological medium in Hungary. The research process is now at the stage of selecting the best site. According to latest plans, the repository will be built between 2030 and 2064 in order to begin operating after the start of decommissioning of Paks.

In 1996 the Mayors of the potentially affected communities founded an association to organize their interests. The tasks of the association include providing information on the research process, controlling the monitoring network and multi-purpose development of the member communities. Together with PURAM the association organizes an annual event where professionals present information and provide an international perspective on the final disposal of high-level waste. Since 2003, PURAM has been conducting a poll every other year in the affected region about recognition of the waste disposal research and its level of acceptance in the local population.[354] Only the municipal association and PURAM (the official information sources) are available for residents to get information.

COSTS AND FINANCING

The Act on Atomic Energy regulates financing for the decommissioning of the Paks plant. It set up the Central Nuclear Financial Fund, which started operating in 1998. It is a treasury fund and part of the government's budget. In order to ensure its financial stability, the fund receives state central budget support. Until 2014, the National Atomic Energy Authority managed the fund; since then, it has been managed by the Ministry of National Development. According to the Budgetary Proposal of the Central Nuclear Financial Fund, the planned budget expenditure for ongoing waste management and other waste management projects (for example, for research into the final disposal of high-level waste and preparations for the decommissioning of nuclear facilities) will be HUF14.8 billion (US$53 million), while the revenue paid into the fund will be HUF27 billion (US$97 million) in 2019.[355] The overall size of the fund was HUF255 billion (US$910 million) by 2016.[356]

The act prescribes the polluter-pays-principle, in that the institution that generates the radioactive waste has to pay for its management. Thus the fund is financed by all the facilities that produce nuclear waste, while the biggest contributor is Paks (around 90 percent of the fund's annual income comes from the power plant). A significant part of the fund is spent on maintaining the waste disposal sites and the budget of PURAM. It is projected that in the long run, almost half of the fund's budget will be spent on dealing with spent fuel, and a quarter on decommissioning Paks. The total expenditure for the activities to be financed from the fund for the four operating reactors up to 2084 is projected to be €5.4 billion (US$6.24 billion). Under current plans, the payments of Paks nuclear power plant will cover only less than half of that.

It remains open how the rest will be financed. While accumulated reserved money also appears in the annual budget of the Central Nuclear Financial Fund, it might not really be available. According to the State Audit Office of Hungary, there are no actual savings behind the amount on the bank account, which will cause problems in the future when costs occur. Upcoming costs of the new planned units at Paks are not yet covered by the fund.[357]

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[354] Public Limited Company for Radioactive Waste Management (PURAM) n.d., "Lakossági kapcsolatok és kommunikáció" (Public relations and communications), viewed 8 March 2019, http://www.rhk.hu/projektjeink/nagy-aktivitasu-hulladekok/lakossagi-kapcsolatok/

[355] Parliament of Hungary 2019, A Központi Nukleáris Pénzügyi Alap 2019. évi költségvetési javaslata (Budgetary proposal of the Central Nuclear Financial Fund in 2019), viewed 8 March 2019, https://www.parlament.hu/irom41/00503/adatok/fejezetek/66.pdf

[356] Public Limited Company for Radioactive Waste Management (PURAM) n.d. "A feladatok finanszírozása" (Financing tasks), viewed 8 March 2019, http://www.rhk.hu/rolunk/mandatumunk/finanszirozas/

[357] Koritár, Z. 2018, "Postponed Policy," in A Brunnengräber et al. Challenges of Nuclear Waste Governance, Springer VS, Wiesbaden, pp. 123-137.

SUMMARY

While the nuclear history of Hungary dates back to the 1960s, radioactive waste management is still in its infancy. Regulation of waste management went through several alterations in the past decades in order to adopt EU laws. In addition, Hungary has implemented most of the legal and regulatory recommendations of the International Atomic Energy Agency. Hungary has long-term plans for nuclear waste management but might not be able to realize them by the time Paks II is built. The Central Nuclear Financial Fund was set up to cover costs for spent fuel and decommissioning of the four operating Paks reactors, but it falls short of covering the projected €5.4 billion (US$6.24 billion) in the long run. Moreover, though research on final radioactive waste disposal is proceeding, it is not at all certain if the best possible safety can be ensured. Currently two main nuclear waste facilities operate in Hungary. However, the need for a final repository is urgent. Waste quantities will rise substantially, not just from decommissioning of the four reactors of Paks nuclear power plant but also from the planned two new reactors at Paks II.

7.5 SWEDEN

OVERVIEW

Sweden's nuclear efforts began with a combined military and civil nuclear program based on heavy-water reactors in the late 1940s. Two research reactors were started in 1954 and 1960. A third underground reactor was started in 1964, which delivered district heating to the local community and some electricity to the grid. But its main purpose was to provide plutonium for the Swedish nuclear weapons program. All three early reactors have been or are being decommissioned.

After a long public debate in the mid-1960s, the government decided to abort the military program, together with the heavy-water power reactor program. Instead, nine boiling water reactors and three pressurized water reactors were commissioned between 1972 and 1985 at four sites.

Through the years and more rapidly in recent years, Sweden has reduced its nuclear capacity. Two reactors at the Barsebäck plant near the Danish border were shut down in 1999 and 2005. Two out of three reactors at the Oskarshamn plant were shut down in 2015 and 2017. At the Ringhals plant, two of its four reactors will be shut down in 2019 and 2020 and two will remain. There are three operating reactors at Forsmark. In 2018, Sweden's eight operating reactors supplied about a third of the country's electricity.[358]

Since 2016, there has been a political agreement that Swedish electricity generation should be 100 percent renewable by 2040. At the same time, there is no phase-out plan for the six reactors that will operate after 2020. The agreement just says that there shall be no subsidies for nuclear energy and the remaining reactors are to be shut down when they are no longer profitable. There are presently no plans to build new reactors in Sweden, although a legal ban against the construction of new nuclear power reactors was lifted in 2010.

In the 1960s, an underground waste reprocessing plant was planned, but construction was never started. Reprocessing research and development was, however, carried out in the 1960s, leading to waste streams that are a major part of the Swedish legacy waste problem. The high-level reprocessing waste from these activities is no longer in Sweden. In the late 1970s, Sweden signed reprocessing contracts with France and the UK but finally only 140 tons of spent fuel was reprocessed in the UK. For commercial and non-proliferation reasons, Sweden decided around 1980 to instead opt for only direct disposal of spent nuclear fuel.

Sweden has an operational repository for short-lived low-level and intermediate-level waste and a repository for spent fuel is in a licensing process. A repository for long-lived intermediate-level waste is also planned.

Sweden had a uranium mining facility at Ranstad operating for a short time in the 1960s. It was decommissioned in the 1990s, and environmental remediation is considered complete. Sweden also has a fuel fabrication plant in Västerås, presently owned by Westinghouse.

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[358] World Nuclear Association Website 2018, "Nuclear Energy in Sweden," viewed 22 April 2019, https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/sweden.aspx

WASTE CLASSIFICATION SYSTEM

Sweden differentiates nuclear waste based on its activity and lifetime. Its waste classification system was developed by the Swedish Nuclear Fuel and Waste Management Company (SKB) and lists the following five categories:[359]

TABLE 16: Categories of nuclear waste in Sweden as of 2018

Type of waste	Destination	Definition	Other considerations
CLEARED MATERIAL	No repository needed	Material with such small levels of radioactivity that it can be released from regulatory control	none
VERY LOW LEVEL WASTE, SHORT-LIVED (VLLW-SL)	Shallow landfill	Small amounts of short-lived nuclides with a half-life of less than 31 years (dose rate per package is less than 0.5 mSv/h). Long-lived nuclides with a half-life over 31 years can be present in restricted quantities	none
LOW-LEVEL WASTE, SHORT-LIVED (LLW-SL)	Final repository for short-lived waste (SFR)	Small amounts of short-lived nuclides with a half-life of less than 31 years. Dose rate per package (and unshielded waste) is less than 2 mSv/h. Long-lived nuclides with a half-life over 31 years can be present in restricted quantities	none
INTERMEDIATE LEVEL WASTE, SHORT-LIVED (ILW-SL)	Final repository for short-lived waste (SFR)	Significant amounts of short-lived nuclides with a half-life of less than 31 years. Dose rate per package is less than 500 mSv/h. Long-lived nuclides with a half-life over 31 years can be present in restricted quantities	Requires radiation shielding during transportation
LOW AND INTERMEDIATE WASTE, LONG-LIVED (LILW-LL)	Final repository for long-lived radioactive waste (SFL)	Significant amounts of long-lived nuclides with a half-life over 31 years are present, exceeding the restricted quantifies for short-lived waste	Requires special containment during transportation
SPENT FUEL/HIGH LEVEL WASTE (HLW)	Final repository for spent fuel	Typical heat decay >2kW/M^3 and contains a significant amount of long-lived nuclides with a half-life greater than 31 years, exceeding the restricted quantities for short-lived waste	Requires cooling and radiation shielding during intermediate storage and transportation

Source: SSM 2018

The classification differs slightly from the IAEA definition, in that instead of the agency's category of low-level waste (LLW) Sweden focuses on short-lived waste. The Swedish low-level and intermediate-level short-lived waste (LLW-SL and ILW-SL) are thus LLW according to the IAEA classification.

QUANTITIES OF WASTE

The Ministry of the Environment and Energy and the regulator, the Swedish Radiation Safety Authority (SSM), publish inventories every three years in the report to the IAEA Joint Convention[360] and also report in line with the EU Radioactive Waste Directive.[361] The latest inventories in the reports refer to December 31, 2016 and are shown in *Table 17*.

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[359] Swedish Radiation Safety Authority 2018, Sweden's second National Report on Implementation of Council Directive 2011/70/Euratom, viewed 22 April 2019, https://www.stralsakerhetsmyndigheten.se/en/press/news/2018/swedens-implementation-of-nuclear-waste-directive-reported-to-european-commission/

[360] Swedish Ministry of the Environment and Energy 2017, Sweden's sixth national report under the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management, Ds 2017:51, viewed 22 April 2019, https://www.regeringen.se/rattsliga-dokument/departementsserien-och-promemorior/2017/10/ds-201751/

[361] Swedish Radiation Safety Authority 2018, Sweden's second National Report on Implementation of Council Directive 2011/70/Euratom, viewed 22 April 2019, https://www.stralsakerhetsmyndigheten.se/en/press/news/2018/swedens-implementation-of-nuclear-waste-directive-reported-to-european-commission/

TABLE 17: Nuclear waste in Sweden as of December 31, 2016

Type of waste	Type of storage	Storage site	Quantity
SNF (HLW)	Interim storage (wet)	Reactor storage pool at Paks	1,800 FA
	Interim storage (wet)	Central near-surface interim storage facility (CLAB) in pools 75 meters underground at Oskarshamn NPP	31,817 FA or 6,267 tHM**
	SNF sent to reprocessing	140 tHM to the UK from the Oskarshamn NPP; 56 tHM to France from the Barsebäck NPP	206 tHM***
LLW-SL AND ILW-SL	Interim storage	At the Studsvik site and the nuclear power plants	8,500 m^3
ILW-LL	Interim storage	At the Studsvik site, reactor sites, and the intermediate storage facility (CLAB)	5,300 m^3
VLLW	Interim storage	At reactor sites	2,900 m^3
LLW-SL AND ILW-SL	Disposed waste	Near-surface repository (SFR) 50 meters below the sea bottom outside Forsmark NPP	38,922 m^3
VLLW	Shallow landfill	Shallow landfill burial at reactor sites (except Barsebäck) and at Studsvik	27,841 m^3

Source: SKB 2017

Notes: FA = fuel assembly. NPP = nuclear power plant. * includes 0.04 tHM of spent research R1 reactor fuel at the Studsvik site. ** includes 2.7 tHM of spent fuel pieces from the hot lab at the Studsvik nuclear research facility and 22.5 tHM spent MOX fuel from Germany. *** In addition, 4.7 tHM of spent research R1 reactor fuel has been sent for reprocessing to the UK and at least 13 tHM of spent research R2/R2-0 reactor fuel has been sent to the US and Belgium for reprocessing.

There are currently almost 7,000 tons of spent nuclear fuel in Sweden, mostly in a centralized wet storage facility (CLAB). The spent fuel remains in pools at the reactor sites for only a few years. Around 8,500 m^3 of short-lived low- and intermediate-level waste and 5,300 m^3 of long-lived intermediate-level waste is currently in intermediate storage. Legacy waste is mainly at the Studsvik site, but increasing amounts are at the reactor sites where decommissioning is underway. Short-lived low- and intermediate-level waste from reactor operations is placed in an existing repository (SFR) where now close to 40,000 m^3 of waste has been disposed of. Very low-level waste is disposed of in shallow landfill burial sites and there are now almost 30,000 m^3 in four facilities. In addition, there are 2,900 m^3 of very low-level waste still in storage.

Based on industry scenarios of operation time, the final amount of spent fuel in Sweden is expected to add up to 11,400 tons. Estimated waste amounts after decommissioning all nuclear facilities sum up to 153,000 m^3 of short-lived low- and intermediate-level waste and 16,400 m^3 of long-lived intermediate-level waste.[362]

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[362] Swedish Nuclear Fuel and Waste Management Company (SKB) 2017, Plan 2016. Costs from and including 2018 for the radioactive residual products from nuclear power. Basis for fees and guarantees for the period 2018–2020, SKB TR-17-02, pp. 35-36, viewed 22 April 2019, http://www.skb.com/publication/2487964/

WASTE MANAGEMENT POLICIES AND FACILITIES

Under the 1984 Nuclear Activities Act, it is the responsibility of the nuclear industry and its utilities to both finance and carry out management and final disposal of radioactive waste.[363] The Act is presently under review. The industry has to deliver a research and development report every three years to the regulator, the Swedish Radiation Safety Authority (SSM). The government has to review and approve the report and can do so with conditions from the industry. This is the only way for the government to request changes to the industry's radioactive waste plans, and it has seldom done so.

The regulator, SSM, reviews the licensing of nuclear facilities such as repositories based on the Nuclear Activities Act. Since the late 1990s, all nuclear facilities also need to have a permit according to the Swedish Environmental Code. The dual-path licensing process leads to recommendations from SSM and the Land and Environmental Court to the Swedish government, which makes the final licensing decision.

The nuclear industry has created a private company to carry out its responsibilities. The Swedish Nuclear Fuel and Waste Management Company (SKB) operates existing facilities and develops new ones. Another company, Svafo AB, was created to take responsibility for the legacy waste consisting mostly of nuclear waste from the historic military and civil research programs. Since 2009, Svafo AB has been owned by the nuclear industry.

Spent nuclear fuel from the nuclear power plants is first cooled over several years. It is then moved to a centralized intermediate storage facility, CLAB, located at the Oskarshamn nuclear power plant. The wet storage facility has two water pools in caverns 50 meters underground in granite bedrock. The spent fuel is transported from the other reactor sites in a special ship, Sigrid, which is also used for transportation of other radioactive waste between nuclear sites.

Like many other countries, Sweden has been working for a long time on deep geological disposal for high-level waste. Since the mid-1970s, the nuclear industry has been developing a repository system called KBS-3 for final disposal of spent nuclear fuel. A repository is planned at about 500 meters deep in granite bedrock. The spent fuel is to be encapsulated in a 5-centimeter-thick copper canister and deposited in holes in the floor of underground tunnels. A buffer of bentonite clay is to be put around the canisters, and the tunnels will also be filled with clay. The granite rock has water flowing through it, but the copper and clay are intended to provide a man-made barrier to isolate the waste from the environment for hundreds of thousand years.

The process of choosing the disposal site was long and complicated. Finally, in 2009 the nuclear waste company SKB chose the bedrock at the Forsmark nuclear power plant. A license application was submitted in 2011, and the regulator SSM and the Environmental Court submitted their opinions to the government in January 2018 after a long process. The court recommended declining a permit under the Environmental Act, unless it was shown that the integrity of the copper canister could be demonstrated to assure sufficient long-term safety. The regulator SSM recommended that the government approve the permit, as any problems with the copper canister could be dealt with later in the step-wise decision-making process according to the Nuclear Activities Act. The license application is now under governmental review, and it is unclear whether the copper corrosion issues will be a major problem going ahead. A government decision may come in 2020.

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[363] Swedish National Council for Nuclear Waste 2011, Licensing under the Environmental Code and the Nuclear Activities Act of a final repository for spent nuclear fuel Report 2011:2e, viewed 22 April 2019, https://www.karnavfallsradet.se/sites/default/files/documents/report_2011_2.pdf

If the government decides to say yes, it will first give "permissibility" according to the Environmental Code and can add conditions. The Environmental Court will have to give a permit with conditions. The government will then issue a license according to the Nuclear Activities Act and the regulator SSM will start its step-wise decision-making process, where a decision will be taken for the beginning of construction, for operations, and for full operations. This process will take several more years and it is unlikely that construction will start before 2025. If a license is granted, it is estimated that the repository will take 10 years to build and be operational for about 60 years.

In addition to the planned deep geological disposal for HLW, several repositories for other waste types are in operation or planned:

- There are plans for a specific repository called SFL for long-lived low- and intermediate-level waste (LILW-LL). However, so far SKB has not presented a method or begun the process of searching for potential sites.

- There is an interim storage facility for mostly long-lived LILW-LL inside a rock cavern at the Studsvik site. The waste comes from various sources, the majority being legacy waste.

- A repository called SFR was commissioned in 1983 for short-lived low- and intermediate-level waste (LLW-SL and ILL-SL) from nuclear power plants. The repository is situated 75 meters under the seabed outside the Forsmark nuclear power plant. There is an on-going licensing process for an expansion planned 120 meters below the seabed for waste from decommissioning. There have been problems with the integrity of the concrete barriers and with corrosion of canisters in the SFR repository. There are also a number of containers with legacy waste, many of which have to be retrieved due to uncertainty about what is in the containers, or because it is now known that they contain long-lived waste.

- At the Studsvik nuclear research site, a hot lab carries out commercial testing of spent fuel specimens. At the facility, there is also an incinerator to compact radioactive waste and a smelter to decontaminate and melt radioactive metal for free release. The facilities at Studsvik were gradually privatized beginning in the 1980s. In 2017, the French utility EDF's subsidiary Cyclife bought most of Studsvik AB's facilities, but not the hot lab.

- There are shallow landfill burial sites for very low-level radioactive waste at the Ringhals, Forsmark and Oskarshamn nuclear power plants and at the Studsvik site. The Studsvik landfill is permanently closed.

COSTS AND FINANCING

In international comparison, Sweden was early in financing radioactive waste management, as defined in the original 1981 Financial Act. The 2006 Financial Act defines the responsibility of the nuclear operator, or anyone producing radioactive waste, for decommissioning and guaranteeing that the full costs will be borne by the producer.[364] A fee on electricity from nuclear power and guaranteed securities by the power plant owners are the two main pillars of financing waste management and decommissioning of reactors. The nuclear industry produces the PLAN report every three years with projections of future costs based on different scenarios. The report provides data for the calculation of radioactive waste fees and securities. It is scrutinized by the Swedish National Debt Office, which also puts it out for public review. Until 2018 this responsibility lay with the regulator SSM, but the responsibility was moved due the perceived increasing risk of the system being underfinanced. The debt office gives recommendations to the government, which makes the final decision.

For the period 2018-2020, the average fee is SEK50/MWh (US$5.40/MWh) of produced nuclear electricity. The fee is set per nuclear power plant and is the highest for Oskarshamn (SEK64/MWh, around US$6.90/MWh) and lowest for Forsmark (SEK33/MWh or around US$3.50/MWh). The government also sets the levels of security amounts to be covered by the operators, both in the case that the fees do not cover the planned costs and to allow for unexpected costs. For the period from 2018-2020, the "financial amount" of securities for possible cost increases is SEK29 billion (US$3.1 billion) and the "complementary amount" of securities for unforeseen new costs is SEK15 billion (US$1.6 billion).

The fees from the operators are put in a special Nuclear Waste Fund that is separate from the government budget. At the end of 2017, the fund amounted to SEK67 billion (US$7.2 billion). The total future costs for management and final disposal of all radioactive waste as well as for decommissioning of the nuclear reactors is estimated to be SEK100-110 billion (US$10.7-11.8 billion).[365] Since the financial crisis of 2008 has resulted in a much lower rate of return on long-term bonds than expected, risks increased that the system is underfinanced.

The Financial Act was extensively revised in 2017 to try to manage the risks to the financial system. The funds in the nuclear waste fund can now be put into less secure investments than government bonds to allow for a higher rate of return on the fund capital; the industry is allowed to calculate with the remaining operators for 50 years.

By using a separate Studsvik Act from 1988, Sweden has until recently sought to cover the costs for managing and disposal of the legacy radioactive waste.[366] These costs were also to the responsibility of the operators of the nuclear power plants, as they could be regarded as beneficiaries from the early nuclear research activities. The fee to the nuclear waste fund was on the order of SEK1-3/MWh (US$0.10-0.30/MWh) of nuclear electricity. However, the system was abolished at the end of 2017 and remaining responsibilities were incorporated into the revised Financial Act.

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[364] Government of Sweden 2006, Lag om finansiering av kärntekniska restprodukter (Act on the Financing of Management of Residual Products from Nuclear Activities 2006:647), viewed 28 June 2019, https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2006647-om-finansiering-av-karntekniska_sfs-2006-647

[365] Swedish Nuclear Fuel and Waste Management Company (SKB) 2017

[366] The act is named after the Studsvik nuclear research facility where most of the legacy wastes are stored.
Studsvik Act. Lag (1988:1597) om finansiering av hanteringen av visst radioaktivt avfall m.m. (on financing of the management of certain radioactive waste etc.), available at https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-19881597-om-finansiering-av-hanteringen-av_sfs-1988-1597

SUMMARY

The current Swedish governance system for nuclear waste management and disposal was created in the early 1980s and puts the responsibility for both financing and implementation clearly on the nuclear industry.

Sweden is only using wet interim storage for spent nuclear fuel and all fuel is centralized in one facility. Sweden has an operational repository for short-lived nuclear waste that is under a re-licensing process to allow expansion for decommissioning waste.

Sweden has advanced plans for a deep geological disposal for spent nuclear fuel. The licensing process has advanced to government decision-making. There has been scientific criticism of using copper as a canister material, making it uncertain whether a license will finally be given.

The Swedish financing system for nuclear waste management and decommissioning of reactors is well-developed and transparent. There are considerable sums available in a nuclear waste fund but also discussions about increasing risks that the system will still be underfunded.

7.6 SWITZERLAND

OVERVIEW

In contrast to the large countries that developed and built atomic bombs, Switzerland can be described as a nuclear follower. From the outset, the country's limited size meant that it had neither the financial nor the human resources to launch such an ambitious program as the construction of a highly sensitive nuclear development project. Nevertheless, nuclear armament was considered for Switzerland after World War II. This episode is significant in that it had a decisive influence on the later structures in the country's nuclear field.

Furthermore, Geneva became the location of several international conferences on nuclear energy from 1955 onwards. Following the First International Conference on Atomic Energy in 1955, Switzerland acquired the swimming pool reactor exhibited at the time from the US on extremely favorable conditions. This project laid the foundation for Switzerland's entry into nuclear power.

In the 1960s, Switzerland developed its own heavy water reactor line and implemented it in a cavern in the western Swiss municipality of Lucens.[367] In 1969, a few months after the start of operations, a partial meltdown occurred. This event was the de facto end of Switzerland's nuclear armament ambitions. Switzerland also withdrew from the military weapons program in 1988.[368]

Between 1969 and 1984, five reactors with outputs between 350 and 1000 megawatts were connected to the grid at the sites of Beznau and Leibstadt, Mühleberg and Gösgen.[369] The expansion of nuclear power plants at five further sites was abandoned mainly due to the opposition that emerged in the 1970s and the oversized program. In 2018, nuclear power contributed around 40 percent of Switzerland's electricity.[370] An expansion of nuclear energy in the future is unlikely. The 2003 Nuclear Energy Act stipulates that the construction and operation of a nuclear installation requires a general license from the Federal Council.[371] The nuclear industry in Switzerland aims to advance and complete the search for sites for repositories for low- and intermediate-level, and high-level waste until new reactor types become commercially available.

Switzerland has no uranium mines and does not enrich uranium or manufacture or reprocess fuel elements. A ten-year moratorium on the export of irradiated fuel elements for reprocessing came into force in 2006 and was recently extended to 2020.[372] In 2016, the return of reprocessed and vitrified waste from

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[367] Aemmer, F. 1992, Geschichte der Kerntechnik in der Schweiz. Die ersten 30 Jahre 1939–1969 (History of nuclear technology in Switzerland. The first 30 years 1939-1969), Schweizerische Gesellschaft für Kernfachleute (SGK),Olynthus Verlag für verständliche Wissenschaft und Technik

[368] Wildi, T. 2003, Der Traum vom eigenen Reaktor (The dream of one's own reactor), Chronos Verlag.

[369] Naegelin, R. 2007, Geschichte der Sicherheitsaufsicht über die Schweizerischen Kernanlagen 1960–2003 (History of safety oversight of Swiss nuclear facilities), Hauptabteilung für die Sicherheit von Kernanlagen.

[370] Statista 2019, "Anteil des atomar erzeugten Stroms an der gesamten Stromproduktion in der Schweiz von 2003 bis 2017" (Share of nuclear electricity as percent of the energy mix in Switzerland from 2003 to 2017), viewed 10 May 2019, https://de.statista.com/statistik/daten/studie/29583/umfrage/anteil-der-atomenergie-an-der-stromerzeugung-in-schweiz-seit-1998/

[371] This regulation was already introduced by the Federal Decree of 10 October 1978 and adopted by the Nuclear Energy Act (KEG) of March 21 2003, Articles 10 and 13, which can be read in German at https://www.admin.ch/opc/de/classified-compilation/20010233/201801010000/732.1.pdf

[372] Parliament of Switzerland, Amtliches Bulletin, 15.079 Moratorium für die Ausfuhr abgebrannter Brennelemente zur Wiederaufarbeitung, Verlängerung (Swiss Parliamentary debates 15.079 Moratorium for the Return of Waste for Reprocessing), viewed 28 June 2019, https://www.parlament.ch/de/ratsbetrieb/amtliches-bulletin/amtliches-bulletin-die-verhandlungen?SubjectId=37419

the La Hague and Sellafield reprocessing plants was completed, concluding the chapter on reprocessing (plutonium fuel cycle) for Switzerland.[373]

WASTE CLASSIFICATION SYSTEM

Switzerland started developing its waste classification scheme in the late 1970s following mainly a two-repository strategy.[374] Over the decades, this classification scheme has been refined to provide data on the volumes of radioactive waste known today as Model Inventory for RadioActive Materials (or MIRAM inventory).[375] Switzerland classifies waste based on its radioactivity and differentiates between spent nuclear fuel (SNF), vitrified fission product solutions, alphatoxic waste (ATA) with values greater than 20,000 Bq/g, and low- and intermediate-level waste.[376] In fact, this subdivision follows the concept of geological disposal, which only provides for these two types of repository.

Short- and medium-lived waste includes low- and intermediate-level waste from the operation of nuclear power plants and the entire range of waste from medicine, industry, and research.[377] The former includes high-level spent fuel elements, vitrified waste from earlier reprocessing, and long-lived intermediate level transuranic waste. In recent years, Switzerland has endeavored to separate the very short-lived low-level waste via decay storage facilities, which means that such waste can be disposed of without taking account of radioactivity, and thus reduce the amount of waste destined for final disposal.

QUANTITIES OF WASTE

The Swiss Federal Nuclear Safety Inspectorate (ENSI) annually reports the number of packages of waste stored in interim storage facilities. A compilation of the interim inventory can be found in Switzerland's reports for the Joint Convention.[378] Accounting for radioactive waste in Switzerland is simpler than in many other countries because it essentially comes from only two main sources: nuclear power plants; and medicine, industry, and research.[379] This makes the management of radioactive waste relatively simple compared to other countries.

However, Switzerland's nuclear waste is heterogeneous with regard to the heavy metals and organic compounds stored in it. In addition, there are the different reactor types, different fuel elements used and different fuel burn-ups, including those from the Lucens core meltdown accident reactor and the DIORIT research reactor.

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[373] Nuklearforum Schweiz 2016, "Letzter Transport von Wiederaufarbeitungsabfällen in die Schweiz, 21.12.2016" (Last transport for reprocessing waste in Switzerland), viewed 22 April 2019, https://www.nuklearforum.ch/de/aktuell/e-bulletin/letzter-transport-von-wiederaufarbeitungsabfaellen-die-schweiz

[374] Verband Schweizerischer Elektrizitätswerke (VSE), Gruppe der Kernkraftwerkbetreiber und –Projektanten (GKBP), Konferenz der Überlandwerke (UeW), Nationale Genossenschaft für die Lagerung radioaktiver Abfälle 1978, Die nukleare Entsorgung in der Schweiz (Nuclear disposal in Switzerland), February 9.

[375] Nagra 2014, Modellhaftes Inventar für Radioaktive Materialien MIRAM 08, NTB 08-06.

[376] Swiss Federal Nuclear Safety Inspectorate (ENSI) 2015, Abfallbewirtschaftung im Vergleich, Forschungsprogramm, Radioaktive Abfälle' der Arbeitsgruppe des Bundes für die nukleare Entsorgung (Waste management in comparison, ‚Radioactive Waste Research Program' of the Federal Working Group on Nuclear Waste Disposal), Project report, February, pp. 53

[377] IAEA 2019, Predisposal Management of Radioactive Waste from the Use of Radioactive Material in Medicine, Industry, Agriculture Research and Education, Specific Safety Guide, No. SG-45

[378] Swiss Federal Nuclear Safety Inspectorate (ENSI) 2017, Implementation of the Obligations of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, viewed 22 April 2019, https://www.ensi.ch/wp-content/uploads/sites/5/2017/10/Joint_Convention-Sixth_national_report-Switzerland_2017.pdf

[379] Naegelin 2007

The following table lists the waste quantities that are currently stored in interim storage facilities.

TABLE 18: Nuclear Waste in Switzerland as of 2016

Type of waste	Type of storage	Storage site	Quantity
SNF + HLW	Interim storage (wet and partly dry	Reactor storage ponds and interim storage ZWIBEZ at power plant site	688.8 tHM
	Interim storage (wet)	Power plant Gösgen, storage ponds and additional wet storage	238 tHM
	Interim storage (dry)	Centralized storage facility ZZL	450.4 tHM
ATA*	Interim storage	Centralized storage facility ZZL	99 m^3
	Interim storage	Centralized storage facility BZP (PSI)	83 m^3
LILW*	Interim storage	Reactor storage and ZWIBEZ	3,865 m^3
	Interim storage	Centralized storage facility ZZL	2,339 m^3
	Interim storage	Centralized storage facility BZL (PSI)	2,109 m^3

Source: Own depiction based on ENSI (2017).
Notes: *ATA (alpha toxic waste) and LILW are both conditioned and unconditioned. BZL = Bundeszwischenlager (Federal Interim Storage Facility); PSI = Paul-Scherer-Institut; ZWIBEZ = Zwischenlager Beznau (Interim Storage Facility at NPP Beznau); ZZL = Zentrales Zwischenlager (Central Interim Storage Facility).

Plutonium from reprocessing was used for MOX fuel elements. In 2013, the plutonium stock amounted to one kilogram. In addition, there are former plutonium reserves of 20 kilograms from the early days, which were stored for decades under strict safety conditions at the Paul Scherrer Institute until they were finally exported to the US in 2016 after having been mixed with uranium to make it non-weapons-grade. In addition to this inventory, more than 5,000 tons of radioactive waste dumped in the Atlantic between 1969 and 1982.

The quantities of waste expected by 2075 are listed by waste category and installation in reports released by Nagra, the Swiss National Cooperative for the Disposal of Radioactive Waste. The estimated total amount of nuclear waste produced in Switzerland in an expected operational period of 60 years is around 4,000 tons of spent fuel and HLW and 63,000 m^3 of LILW. In addition, 20,000 m^3 of LILW are expected from medicine, industry, and research.[380]

WASTE MANAGEMENT POLICIES AND FACILITIES

The 2003 Nuclear Energy Act is the central policy instrument to regulate radioactive waste in Switzerland. The concept of deep geological disposal was developed by the Expert Group on Disposal Concepts for Radioactive Waste (EKRA).[381]

Since 1972, operators of nuclear power plants and the federal government have been operating a National Cooperative for the Disposal of Radioactive Waste (Nagra). It is responsible for planning and implementing the disposal of radioactive waste and is supervised by the Swiss Federal Nuclear Safety Inspectorate (ENSI). During the planning phase (such as the site selection process in the sectoral plan for deep geological repositories), the safety authority ENSI cannot make any decisions but only

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[380] Nagra, 2017, Radioaktive Abfälle, woher, wieviel, wohin? (Radioactive waste, from where, how much and where will it go?) viewed 16 May 2019, https://www.nagra.ch/data/documents/database/dokumente/$default/Default%20Folder/Publikationen/Broschueren%20Themenhefte/d_th2_RadAbfall_2017.pdf

[381] Commission for Radioactive Waste Disposal Concepts (EKRA) 2000, Final Report: Disposal Concepts for Radioactive Waste, Federal Office of Energy, Bern

issue statements.[382] The Federal Office of Energy and the Department of the Environment, Transport, Energy and Transport (DETEC) are responsible for licensing. The Nuclear Safety Commission accompanies the program as a second opinion body, and the Federal Council or DETEC makes formal decisions.

Initially, waste is stored in ponds at nuclear power plants for several years and then transferred to interim storage facilities. For high-level waste, there are three interim storage facilities:

- the Gösgen facility for wet storage of spent fuel from the Gösgen nuclear power plant;
- the ZWIBEZ facility at Beznau for interim dry storage of spent fuel from the Beznau plants in storage containers;
- and the ZWILAG facility at Würenlingen, a central interim storage facility for high-level waste as well as for vitrified waste from earlier reprocessing.

The low- and intermediate-level waste is stored at various locations near the power plants and in ZWILAG. In addition, there is the Federal Interim Storage Facility next to ZWILAG in Würenlingen, which receives waste from medicine, industry, and research.

Overall, storage capacities are sufficient. However, Switzerland's interim storage includes other challenges such as waste distribution across various plants and facilities, and the temporary character of the interim storage facilities. Especially for longer periods of time, these conditions result in increased risks.

Switzerland launched its sectoral plan procedure for deep geological repositories in 2008. It aims to define one or more deep geological repositories for radioactive waste in three stages.[383] The host rock selected for the high-level waste is the Opalinus Clay, an approximately 100-meter thick clay layer which lies in a sediment cover above the crystalline basement. Three sites along the border with Germany have been selected, with priority to the Zürcher Weinland area in the vicinity of the city of Schaffhausen. The building, closing, and monitoring of the repositories is estimated to take more than a century. The deep geological repositories concept is intended to permit the retrieval of waste until the end of operation.

The plan for deep geological repositories is intended to guarantee an extensive participation of the regional and local population. However, in practice this is reduced to offering hearings and providing information. Decisions, particularly on safety and site issues, are made exclusively by Nagra or the authorities. Nagra expects a repository to be available by 2060 at the earliest.[384]

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[382] Munz, M. 2016 Interpellation in the Swiss Parliament on 14.12.2016, number 16.4056, Hat das ENSI im Sachplanverfahren geologische Tiefenlager Beratungs- und Aufsichtsfunktion (Does ENSI have a supervisory function for the sectoral plan procedure of the deep geological repository). The Federal Council answered on February 15, 2017.

[383] ENSI website n.d., Sectoral Plan for Deep Geological Repositories, viewed 28 June 2019, https://www.ensi.ch/en/waste-disposal/deep-geological-repository/sectoral-plan-for-deep-geological-repositories-sgt

[384] Nagra 2016, Waste Management Report 2016 from the Waste Producers, Technical Report 16-01E

COSTS AND FINANCING

In Switzerland, the polluter-pays-principle applies: waste producers are responsible for the implementation of the waste management programs. The main producers are nuclear power plants, the majority of which are directly or indirectly owned by the public sector.

In 1984 and 2000 respectively, the Swiss government set up two funds: one to finance decommissioning, the other to finance the disposal of waste. The Federal Council is responsible for supervising the funds. It oversees the administrative commission of the Decommission Fund for Nuclear Facilities and Waste Disposal Fund for Nuclear Power Plants (STENFO).[385] STENFO provides an update on cost estimates for decommissioning and disposal every five years.

Operators of nuclear power plants have to pay fees for the two funds. The fees are calculated to cover the estimated costs with an assumed operation time of 50 years.[386] By 2018, operators had paid CHF7.5 billion (US$7.39 billion) into the funds and were expected to pay a total of CHF24 billion (US$23.76 billion).[387] The cost calculations are subject to ongoing changes.

However, cost estimates for decommissioning and waste disposal have increased more than tenfold over the last 30 years. In the early 1980s, operators expected decommissioning and disposal to cost around CHF2 billion (US$1.97 billion). By 1994, Nagra had already estimated only the disposal costs at CHF4 billion (US$3.94 billion). Today, the total cost for a 50-year operating period is estimated at around CHF25 billion (US$24.63 billion) with an additional CHF2.5 billion (US$2.46 billion) for MIR waste.[388] Calculations by Oxford University suggest even higher costs.[389]

One reason for the uncertainty of the cost estimates is the lack of experience and reference projects.[390] This applies above all to disposal costs, for which only tunnel reference projects are available – certainly a weakness of these estimates. In addition, costs have been calculated exclusively for deep geological repository projects at a depth of around 500 meters. Other variants of deep geological disposal (such as a deep borehole option) have not been included.

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[385] STENFO, Decommission Fund for Nuclear Facilities and Waste Disposal Fund for Nuclear Power Plants, see http://www.stenfo.ch/en/Home

[386] Government of Switzerland 2007, Verordnung über den Stilllegungsfonds und den Entsorgungsfonds für Kernanlagen (Decree on the decommissioning fund and the nuclear waste disposal fund), viewed 22 April 2019, https://www.admin.ch/opc/de/classified-compilation/20070457/index.html

[387] Swiss Nuclear 2019, Stand der Stilllegungs- und Entsorgungsfonds (Status of decommissioning and disposal funds), viewed 22 April 2019, http://www.swissnuclear.ch/de/Stand-Stilllegungs-und-Entsorgungsfonds.html

[388] Swiss Federal Office of Public Health 2018, Der Bund aktualisiert seine Kostenschätzungen für die Entsorgung radioaktiver Abfälle (The Federal state updates its cost estimates for disposal of radioactives wastes), November 30, viewed 22 April 2019, https://www.bag.admin.ch/bag/de/home/gesund-leben/umwelt-und-gesundheit/strahlung-radioaktivitaet-schall/radioaktive-materialien-abfaelle/entsorgung-von-radioaktiven-abfaellen/der_bund_aktualisiert_seine_kostenschaetzungen_fuer_die_entsorgung_radioaktiver_abfaelle.html

[389] Budzier, A. et al. 2018, Oxford Global Projects, Quantitative Cost and Schedule Risk Analysis of Nuclear Waste Storage, Schweizerische Energie-Stiftung, viewed 22 April 2019, https://www.energiestiftung.ch/files/energiestiftung/fliesstextbilder/Studien/QRA%20Report%20V1.0.pdf

[390] Schweizerische Energie-Stiftung, Atommüll müsste massiv teurer sein (Nuclear should be much more expensive), viewed 22 April 2019, https://www.energiestiftung.ch/atomenergie-kosten.html

SUMMARY

The management of radioactive waste in Switzerland follows international practices, which are mainly coordinated by large international bodies (IAEA, NEA/OECD). As a small country, Switzerland has never played a leading role in the nuclear field, but essentially has followed international practices.

The basic concept of a final disposal in Switzerland is the multiple barrier concept. The gradual abandonment of reprocessing in the late 1970s led to a major change for the storage strategies for high-level waste. Instead of vitrified high-level waste from reprocessing, the spent fuel elements had to be packed in special storage containers made of steel or a combination with copper.

Like many other countries, Switzerland is still at a very early stage in its disposal program after more than 50 years of its nuclear program. Meanwhile, high-level waste and spent fuel continue to be stored in interim storage facilities, while low- and intermediate-level waste is mostly conditioned and stored in decentralized interim storage facilities. The Swiss repository concept follows the original Swedish concept at a depth of 500 meters. The site selection program is underway and is intended to be complete by 2030. A repository for high-level waste will not be available before 2060.

In Switzerland, as elsewhere, the polluter-pays-principle applies. The operating companies, which are mainly financed by public funds, are responsible for the planning and implementation of interim storage and final disposal. The provisions for disposal are managed in two funds. The total costs for a 50-year operating period are estimated to be at least CHF25 billion (US$24.63 billion). It remains to be seen to what extent the Swiss disposal concept, the organization of such a program, and the financing model will be effective.

7.7 THE UNITED KINGDOM

OVERVIEW

The UK was one of the earliest developers of nuclear technology. This was initially for the purpose of producing nuclear weapons starting in the 1940s, and the site at Sellafield (formerly Windscale) in North West England was used to develop the 'Windscale piles' for the production of plutonium for weapons. This was followed by the development of dual-use reactors, which were used both for plutonium production for weapons as well as electricity generation.[391]

The UK has been through three distinct phases in development of power reactors. The first was the development of the Magnox design, based on the dual-use reactors. They used natural uranium and were graphite-moderated and cooled by carbon dioxide. All are now closed. A second phase was also based on gas-graphite reactors, the Advanced Gas Cooled Reactors (AGRs) now using enriched uranium.[392] A third, truncated phase involved importing pressurized water reactors (PWR) and one was completed in 1997. Nuclear power plants contributed at peak levels 28 percent of electricity generation in the UK in 1998, but this has gradually declined to 21 percent in 2017 as old plants have been shut down and age-related problems affect plant availability.[393, 394]

After a long gap, Hinkley Point C, a European Pressurized Water Reactor (EPR) of similar design to the earlier PWR, is now under construction. While five further large new nuclear stations might be built, this is now open to question as developers have stopped work, citing financial problems.[395]

The dismantling of old nuclear structures is a slow process. "Care and maintenance"[396] (a UK term) is the status where all buildings have been removed from the reactor site except for the reactor building, pond structures and intermediate- and low-level waste (ILW) stores. These remaining facilities are then weather-proofed. It is expected that they will be dismantled after around 80 years. Only one Magnox station has yet reached care and maintenance status, and the UK's Nuclear Decommissioning Authority (NDA) predicts that the others will do so by 2029.[397]

The UK has a wide range of other nuclear structures. Besides facilities for producing nuclear weapons, these include two fast breeder reactors, several prototype reactors, and many other research facilities. The UK has never mined or milled any uranium, but it has plants for all other stages of the nuclear fuel chain. This includes conversion, enrichment and fabricating nuclear fuel, as well as reprocessing spent fuel to separate out plutonium and uranium. The UK has operated two large reprocessing plants at Sellafield. One, B205, is designed to reprocess metallic fuel from Magnox reactors; it opened in 1962 and is due to close in 2020. The other is a Thermal Oxide Reprocessing Plant (THORP), opened in 1994 and closed in 2018.[398] THORP has reprocessed significant quantities of foreign fuel, notably from Japan and

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[391] Pocock, R.F. 1977. Nuclear power. Its development in the United Kingdom. Gresham Books

[392] MacKerron, G. and Sadnicki, M. 1995, UK nuclear privatisation and public sector liabilities (No. 4). University of Sussex, Science Policy Research Unit.

[393] Department of Energy and Climate Change 2009, 60th Anniversary Digest of UK Energy Statistics, pp. 40.

[394] Department of Energy, Industry and Industrial Strategy 2018, Digest of Energy Statistics 2018, pp. 117.

[395] Vaughan, A. 2019 'UK's nuclear plans in doubt after report Welsh plant may be axed,' The Guardian, viewed 22 April 2019, https://www.theguardian.com/environment/2018/dec/10/uk-nuclear-plant-hitachi-wylfa-anglesey

[396] Nuclear Decommissioning Authority (NDA) 2018, Business Plan 1 April 2018 to 31 March 2021, viewed 28 June 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695245/NDA_Business_Plan_2018_to_2021.pdf, pp. 9

[397] Nuclear Decommissioning Authority (NDA) 2018

[398] Government of the UK 2018, End of reprocessing at THORP signals new era for Sellafield, viewed 5 April 2019, https://www.gov.uk/government/news/end-of-reprocessing-at-thorp-signals-new-era-for-sellafield

Germany, but its main activity was always reprocessing of UK-owned fuel from the AGRs. It operated well below capacity and was closed as a result of commercial and technical problems. The UK also has an operating dry fuel store at Sizewell and disposal sites for low-level waste (LLW) at Drigg, near Sellafield and at Dounreay in Scotland.

The Sellafield site is especially complex and hosts hundreds of disused buildings and stores. Much work remains to be done before all the waste there can even be characterized, let alone managed safely.[399] Like most other countries, the UK plans to use Deep Geological Disposal (DGD) to dispose of intermediate-level waste (ILW) and high-level waste (HLW) but has made little progress to date. Scotland's policy is different from that of the rest of the UK, and envisages near-surface disposal of all nuclear waste within its borders.[400]

WASTE CLASSIFICATION SYSTEM

The UK waste classification system is close to the IAEA system. The categories are primarily based on activity levels with no explicit consideration of whether wastes are short-lived. They are as follows:[401]

- Very low-level waste (VLLW): waste with low enough levels of radioactivity to be predominantly disposed of at licensed landfill sites
- Low-level waste (LLW): waste with low levels of radioactivity which still needs to be managed in engineered shallow repositories
- Intermediate-level waste (ILW): contains activity above the upper limit for LLW but is not heat-generating
- High-level waste (HLW): produced from reprocessing spent fuel, heat-generating as well as highly radioactive.

Definitions of what is and is not waste vary by country and over time. Like France, UK policy does not define separated plutonium, spent fuel, and depleted or reprocessed uranium as waste, and so these are not included in the official waste inventory. This decision is officially rationalized on the grounds that all these materials might be used in fabricating nuclear fuel in the future. However, such uses are far from certain, and even if all are used in fuel fabrication, they would lead to further waste streams and these do not appear in the official UK waste inventory.

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[399] National Audit Office (NAO) 2018, The Nuclear Decommissioning Authority: progress with reducing risk. HC 1126, viewed 22 April 2019, https://www.nao.org.uk/wp-content/uploads/2018/06/The-Nuclear-Decommissioning-Authority-progress-with-reducing-risk-at-Sellafield.pdf

[400] Government of Scotland 2011, Scotland's higher activity radioactive waste policy, viewed 22 April 2019, https://www.gov.scot/publications/scotlands-higher-activity-radioactive-waste-policy-2011/

[401] Department of Business Energy and Industrial Strategy (BEIS) and NDA 2017, Radioactive wastes in the UK: UK radioactive waste inventory report, viewed 22 April 2019, https://ukinventory.nda.gov.uk

QUANTITIES OF WASTE

The UK government publishes a waste inventory every three years. The data below comes from the most recent inventory, which records waste volumes and activity as of April 1st, 2016 as well as expected future volumes. Among the features of the inventory are:

- There are many different waste streams identified (1,337 in total). These streams are divided into 24 waste groups.
- A high proportion of all nuclear waste is in 'raw' (in UK terms 'reported') form. This is waste that is not yet conditioned or packaged. Of the 24 waste 'groups' only one is described as 'conditioned waste'. While the proportion of waste in this raw form has not been disclosed it seems probable that it is well over half of total volumes.
- Liquid and gaseous discharges are not included in the inventory, which therefore consists of different forms of solids.
- Most of the waste by activity levels (58 percent) is concentrated at Sellafield (only 0.03 percent was at military sites).
- Foreign-owned wastes are not included in the UK inventory. Some substitution agreements between the UK government and the governments of owners of foreign-owned wastes held in the UK have specified that the countries with ownership will receive back the same amount of radioactivity as that contained in the original spent fuel. However, these returned wastes will be in the form of HLW, much smaller in volume than the various waste streams produced by the reprocessing of that fuel.

Because the UK will not have an operational DGD facility for decades to come, successive UK inventories show that the volumes and activity of higher activity wastes continue to accumulate and require ever-growing interim storage facilities.

The *Table 19* shows the volumes and mass of nuclear waste in storage as at 1 April 2016. The HLW arises entirely as a by-product of reprocessing and is currently stored at Sellafield. This waste is initially in the form of highly active nitric acid (Highly Active Liquor or HAL), which undergoes an evaporation process before it is vitrified into glass blocks inside stainless steel canisters.

ILW is much more diverse and also lacks a current disposal route, and so must be stored. About 74 percent by volume of ILW is at Sellafield. Nearly all the rest is at power stations. When packaging occurs, it can be in cement (inside steel or concrete containers) or immobilized in polymer inside mild steel containers. LLW and VLLW are routinely disposed of and so the volumes currently awaiting disposal are small.

TABLE 19: Nuclear waste in the United Kingdom as of December 31, 2016

Type of waste	Type of storage	Storage site	Quantity
SNF (HLW)	Interim storage (wet)	Storage pools at nuclear power plants	3,549 tHM
	Interim storage (wet)	Sellafield	4,151 tHM
HLW	Interim storage	Sellafield	1,960 m^3
ILW	Interim storage	Sellafield, Aldermaston, Dounreay, Harwell, NPPs	99,000 m^3
LLW	Interim storage	Sellafield, Capenhurst, Dounreay	30,100 m^3
	Disposed waste	Closed (in 2005) near-surface repository at Dounreay	33,600 m^3
	Disposed waste	New near-surface repository at Dounreay	3,130 m^3
	Disposed waste	Near-surface repository LLW repository at Drigg	905,000 m^3
VLLW	Interim storage		935 m^3
	Dump sites		n.a.

Source: own compilation based on BEIS/NDA 2017, Naumann 2010.
Notes: The UK does not classify spent nuclear fuel, uranium or plutonium as wastes.
Excluding plutonium and uranium.

The significance of ILW and especially HLW derive from their high levels of radioactivity relative to LLW and VLLW. HLW contains by far the bulk of activity levels in the UK inventory, much of which will reduce over the next century as a result of radioactive decay though there will remain very long-lived radionuclides which must be isolated for thousands of years.

QUANTITIES OF OTHER RADIOACTIVE MATERIALS NOT CLASSIFIED AS WASTE

At this point, the UK does not classify uranium, separated plutonium and spent fuel as waste because plutonium and uranium might be used as ingredients of future nuclear fuel. However, it is in practice very unlikely that there will be such use and these materials will probably be managed as wastes at some future point. SNF is included in *Table 19*. The UK holding of stocks of separated plutonium will amount to 140 tons at the end of reprocessing in 2020, of which 23 tons will be foreign-owned. This is the world's largest stockpile of civil separated plutonium.[402] The UK also held, as at April 2016 113,000tHM of natural, depleted and reprocessed uranium, nearly all of it at Sellafield. Most of this very large stock consisted of depleted uranium following uranium enrichment.[403]

Overall, plutonium, spent fuel and uranium will, once finally classified as waste, add very significantly both to the activity (spent fuel and plutonium) and volume (uranium) of UK nuclear wastes, a high probability that current policy ignores. The UK inventory also anticipates that there will be very large future waste arisings between 2016 and 2125. Given a set of future scenarios that assumes no further new build

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[402] NDA 2019, Progress on plutonium conditioning, storage and disposal, viewed 22 April 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791046/Progress_on_Plutonium.pdf

[403] Department for Business, Energy and Industrial Strategy, and NDA, 2017, Radioactive Wastes in the UK: Radioactive Wastes and Materials not Reported in the 2016 Waste Inventory, March, pp. 16.

of nuclear power the expectation of future waste volumes is as follows:[404]

- HLW 366 m^3
- ILW 299,000 m^3
- LLW 1,570,000 m^3
- VLLW 2,720,00 m^3

The future volume of HLW is relatively small because reprocessing has limited future lifetime. However, ILW volumes are expected to rise roughly threefold and LLW by about 1.5 times. Most of this future waste will derive from decommissioning of power plants, and facilities at Sellafield (where the latter are expected to account for 62 percent of all future ILW, 84 percent of future LLW and 95 percent of future VLLW).

WASTE MANAGEMENT POLICIES AND FACILITIES

The UK produced military wastes from the 1940s and civilian wastes from the 1950s. LLW was always disposed via shallow burial. Serious policy for other potential wastes was for many years solely a commitment to reprocessing all spent fuel. Reprocessing was based on the conviction that the plutonium would initially be needed for weapons and then later that it would be needed to fuel fast breeder reactors. This latter rationale evaporated and in 1994 fast reactor development was abandoned, though reprocessing continued.[405] All ILW was subject to interim storage.

Policy for higher activity wastes (ILW and HLW) was neglected until the 1970s when the Royal Commission on Environmental Pollution recommended that new nuclear power should not be developed until credible waste management routes were demonstrated.[406] This led to explicit plans for deep geological disposal of ILW and, implicitly if later in time, HLW. Attempts to achieve this all failed due to local resistance at proposed sites.

An independent Committee on Radioactive Waste Management (CoRWM) reported in 2006 in favor of Deep Geological Disposal (DGD) for all higher activity waste.[407] It also suggested robust interim storage and a new voluntary process in which local communities would be invited to negotiate terms under which they would accept development of DGD. The government chose to endorse this general approach in 2008 and pursued one serious (but failed) attempt to get buy-in from communities around Sellafield to agree to host a DGD.[408] The government is engaged, as of early 2019, in a renewed process designed to find a willing host community for DGD.[409]

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[404] Department for Business Energy and Industrial Strategy 2017, Radioactive Wastes in the UK: UK Radioactive Waste Inventory Report, pp. 23.

[405] International Panel on Fissile Materials 2015, Plutonium separation in nuclear power programs: Status, problems, and prospects of civilian reprocessing around the world.

[406] Royal Commission on Environmental Pollution 1976, Nuclear power and the environment: 6th report of the Royal Commission on Environmental Pollution, Cm 6618

[407] Committee on Radioactive Waste Management 2006, Managing our radioactive waste safely: CoRWM's recommendations to Government Doc 700

[408] Defra, BERR and the devolved administrations of Wales and Northern Ireland 2008, Managing our radioactive waste safely: a framework for implementing geological disposal, viewed 24 April 2019, https://www.gov.uk/government/publications/managing-radioactive-waste-safely-a-framework-for-implementing-geological-disposal

[409] World Nuclear News 2018, "UK relaunches repository site selection process," 20 December, viewed 22 April 2019, http://www.world-nuclear-news.org/Articles/UK-relaunches-repository-site-selection-process

The UK's Department of Business Energy and Industrial Strategy (BEIS) is in charge of nuclear waste policy. Closure of the Magnox stations and the poor and deteriorating state of Sellafield made it clear by the early 2000s that a more coherent policy and higher expenditures were needed to manage waste in the short- and medium-term. The 2004 Energy Act provided the foundation for setting up the Nuclear Decommissioning Authority (NDA) in 2005.[410] Its purpose is to deliver the decommissioning and clean-up of all publicly-owned nuclear sites and also to undertake the long-term management of nuclear waste. It is the first time that an institution has been developed in the UK with the primary purpose of nuclear waste management.

The NDA recognized that Sellafield was the most problematic site, containing a huge range of ex-military and ex-civilian buildings and wastes. Sellafield contains four so-called Legacy Ponds and Silos, all representing major hazards, as well as being home to virtually all UK spent fuel, much of which has been reprocessed there. This means that cleaning up Sellafield is the highest priority for the NDA.[411]

The NDA attempted to innovate in managing the nuclear sites, which it now owns. In particular, it has held competitions to appoint 'Parent Body Organisations' (PBOs) to oversee the work of the site license companies at each site for specified periods. These competitive processes were designed to encourage cost reductions and bring in wider international expertise. However, the model has not worked well and the NDA is taking direct management responsibility for the two largest segments of the UK decommissioning and waste management task: Sellafield and the Magnox sites.[412]

Apart from final disposal sites for LLW near Sellafield and Dounreay the UK has no other long-term sites. Interim storage, as indicated in *Table 19*, is practiced for all other wastes at many sites, though Sellafield holds the majority of all wastes by volume and activity.

COSTS AND FINANCING

The total costs of managing all of the UK's nuclear waste is very high. The NDA provides estimates for the future costs of public sector 'legacy' waste. This legacy covers waste which has either arisen in the past or is unavoidable in the future (mainly because of the need to decommission many nuclear structures). As of 2006, the NDA estimated the undiscounted future costs of its task to amount to £53 billion (around US$98 billion in 2006). By 2018 this had escalated to an estimate of £121 billion (US$162 billion) of which costs at Sellafield, where escalation has been concentrated, were an expected £91 billion (US$121 billion). The NDA now puts an uncertainty range on its central estimate of £99–225 billion (US$129-292 billion).[413] Expenditures are expected until around 2125.

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[410] Government of the UK 2004, Energy Act, viewed 28 June 2019, http://www.legislation.gov.uk/ukpga/2004/20/contents

[411] National Audit Office (NAO) 2018, part 2.

[412] James, S. 2018, 'Magnox becomes NDA subsidiary,' Nuclear Matters, 4 July, viewed 22 April 2019, www.nuclearmatters.co.uk/2018/07/magnox-becomes-nda-subsidiary

[413] NDA 2018, Annual Report and Accounts 2017, viewed 22 April 2019, https://www.gov.uk/government/publications/nuclear-decommissioning-authority-annual-report-and-accounts-2017-to-2018

The UK has a poor historic record in financing waste. Only for very brief periods has it set up small segregated funds for public sector wastes and these were all abandoned. Currently, there are three different systems of finance:

- For public sector wastes, the main system is an annual government grant-in-aid, in the absence of any fund to pay for public sector-owned wastes. This grant finances the NDA and is supplemented by income that the NDA receives from services it provides, such as managing spent fuel via reprocessing, and long-term spent fuel storage. In 2017-18 this commercial income totaled £1.2 billion (US$1.5 billion) most of which was for spent fuel services. The UK government grant amounted to £2.1 billion (US$2.7 billion) making the total spent in 2017/18 around £3.3 billion (US$4.3 billion). Sixty percent of this was spent at Sellafield. Total annual NDA expenditure has been around £3 billion (US$3.9 billion) for several years. In future, commercial income from spent fuel services will fall steeply, because of the closure of all reprocessing by 2020.

- The second finance system is the Nuclear Liabilities Fund (NLF), an independent trust, which has a genuine fund currently amounting to £9.26 billion (around US$12 billion).[414] It is used for the decommissioning and waste liabilities in private ownership i.e. the AGR reactors (excluding ongoing payments to the NDA for spent AGR fuel). These reactors are all owned by EDF Energy. The fund is expected to cover the discounted value of EDF Energy liabilities. Qualifying expenditure has to be approved by the fund. Because the reactors are still operating, expenditure from the fund has so far been limited, primarily for a dry spent fuel store at Sizewell.

- The third system is a planned Funded Decommissioning Plan, which will apply to new reactors. Reactor owners are to develop a plan which is subject to government approval. It covers all future liabilities and is designed to ensure that owners of reactors bear the full costs of decommissioning and waste management.[415] These arrangements will include a system in which a waste transfer price will be set in future, at which point, after reactor shutdowns, owners will pay the British government to take ownership of the wastes. The intention is to ensure that this price will be high enough to more than cover all subsequent waste management costs.

SUMMARY

The UK has a legacy of over 1,300 waste streams, and a policy history of largely neglecting the active management of decommissioning and waste until the setting up of the Nuclear Decommissioning Authority in 2005. Future wastes to 2125 are expected to be significantly larger in volume than the inventory as at 2016 and more future wastes will derive from decommissioning.

The required expenditure to manage this waste is extremely high and the task very challenging. The great bulk of future expenditure on waste management will come from annual public expenditure and is expected to exceed £120 billion (US$156 billion). Spent fuel, separated plutonium and uranium are not considered as waste in the UK and this means that actual waste volumes are higher than official estimates. In keeping with other countries, policy for higher activity waste is to use deep geological disposal. However progress has been slow, and no repository is likely to be available before 2040 at the earliest.

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[414] Nuclear Liabilities Fund 2018, Protecting the future: Annual Report and Accounts 2018, viewed 22 April 2019, http://www.nlf.uk.net/media/1076/nlf_annual_report_2018.pdf

[415] Government of the UK 2011, Energy Act 2008 "Funded decommissioning programme guidance for new nuclear power stations", December, Part 2b

7.8 THE UNITED STATES OF AMERICA

OVERVIEW

The United States was one of the earliest developers of nuclear technology, first for the development of the atomic bomb. Then, after World War II, the Atoms for Peace program reoriented a significant research effort towards civilian nuclear power programs. The country's nuclear powered electricity program began in 1959 with the start of the Dresden plant near Morris, Illinois.[416] Currently, 97 reactors operate at 59 sites around the country, providing about 20 percent of US electricity generation.[417] Only two reactors are under construction, both at the Vogtle plant in Georgia. They are Westinghouse AP-1000 designs. Construction of two additional AP-1000 reactors in South Carolina was abandoned in July 2017 due to construction problems and cost overruns.[418]

The recent trend in US nuclear power has been towards shuttering reactors. Since 2013, eight reactors have permanently shut down, and 11 more reactors threaten to close by 2025. Seven nuclear power plants have fully decommissioned, leaving only independent spent fuel storage facilities on site. The commercial sector has one stand-alone spent fuel pool facility in Morris, Illinois. Six reactors have shut down at plants that host operating reactors. Four shut down plants are actively decommissioning their reactors, while five others are in what the Nuclear Regulatory Commission terms SAFSTOR (for SAFe STORage), a situation of stasis, where a plant is maintained until it can be fully decommissioned. The US Nuclear Regulatory Commission rules require plants to fully decommission within 60 years of shutdown.[419]

Due to its long history with nuclear power, there are numerous fuel chain facilities in the US.[420] At the very front end, there is a uranium mill in Utah and 11 licensed in situ leaching facilities in the US, but only 5 are currently extracting uranium (four in Wyoming and one in Nebraska).[421] Twenty uranium recovery facilities are undergoing decommissioning.[422] The US has one uranium hexafluoride conversion facility, the Honeywell plant in southern Illinois, which has been idle since early 2018 due to the decreased need for uranium as a reactor fuel.[423]

Currently there is one uranium enrichment plant in operation in the US, the Louisiana Energy Services centrifuge plant, in Eunice, New Mexico. This plant is owned by the European company Urenco, meaning there are no solely US-owned uranium enrichment plants. The Nuclear Regulatory Commission has granted licenses to AREVA's Eagle Rock centrifuge enrichment plant in Idaho and GE's Global Laser Enrichment plant in North Carolina, but neither plant has been constructed. The American Centrifuge Plant in Piketon, Ohio, and the older gaseous diffusion plants in Paducah, Kentucky and Portsmouth, Ohio are all shut down.[424] Commercial spent fuel was reprocessed briefly at the West Valley Demonstration Project in West Valley, New York, from 1966-1972, though the site is now the location of considerable volumes of high- and low-level nuclear waste.

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[416] Walker, S.1992, Containing the Atom: Nuclear Regulation in a Changing Environment 1963-1971, University of California Press.

[417] US Nuclear Regulatory Commission (NRC) 2019, "List of Operating Power Reactors," viewed 9 May 2019, https://www.nrc.gov/reactors/operating/list-power-reactor-units.html

[418] Plummer, B. 2017, 'U.S. Nuclear Comeback Stalls As Two Reactors Are Abandoned,' The New York Times, July 31, viewed 9 May 2019, https://www.nytimes.com/2017/07/31/climate/nuclear-power-project-canceled-in-south-carolina.html

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[422] NRC 2019, Locations of Uranium Recovery Sites Undergoing Decommissioning, viewed 9 May 2019, https://www.nrc.gov/info-finder/decommissioning/uranium/

[423] NRC 2018. January 11th Letter from Jeff Fulks, Plant Manager, Honeywell Conversion Plant to Craig Erlanger, viewed 28 June 2019, https://www.nrc.gov/docs/ML1802/ML18023A384.pdf

[424] NRC 2019, Fuel Cycle Facilities, viewed 9 May 2019, https://www.nrc.gov/materials/fuel-cycle-fac.html

The US produces both low-enriched uranium and high-enriched uranium fuels, though domestic commercial reactors are all of the light-water type and use only low-enriched fuel. The following facilities currently produce low-enriched uranium fuel: the Global Nuclear Fuel Americas plant in Wilmington, North Carolina; the Westinghouse Columbia Fuel Fabrication Facility in Columbia, South Carolina; and the Framatome, Inc plant in Richland, Washington. The AREVA plant in Lynchburg, Virginia, has been shut down. Both low- and high-enriched uranium fuels are made at the Nuclear Fuel Services facility in Erwin, Tennessee and the BWXT Nuclear Operations Group in Lynchburg, Virginia.

WASTE CLASSIFICATION SYSTEM

The US waste classification system differs from that of the International Atomic Energy Agency (IAEA) and many other countries. Because of the long history of nuclear weapons development in the US, the nation has a larger variety of waste streams than other countries that only have a commercial nuclear power sector. To deal with this material, the US developed a complex classification scheme based both in law and regulation. The US has spent nuclear fuel, high-level nuclear waste from the reprocessing of spent nuclear fuel (the vast majority of which is in the nuclear weapons complex), and transuranic waste, a definition reserved only for waste in the nuclear weapons complex.[425] This waste requires disposal in a deep repository. Waste associated with the nuclear weapons complex also includes a relatively new category designated as Waste Incidental to Reprocessing. This material is largely composed of the "heel" of high-level tank waste sludge from the reprocessing of spent fuel to extract plutonium for nuclear weapons. This heel is difficult and costly to remove from the tanks. The US Energy Department therefore plans to leave it in some of the underground tanks, which they plan to fill with grout and then average the concentration of radionuclides across the entire tank volume, achieving average concentrations that classify as low-level waste (LLW).[426]

Low-level nuclear waste in the US is defined by what it is not. In the law, it is defined as material that is not spent fuel, high-level waste (HLW), or byproduct material, for instance. US low-level waste is divided into four subcategories implicitly based on the source of the material. Whether waste is Class A, B, C or Greater Than Class C depends on the presence of certain key radionuclides and the half-lives of these radionuclides.[427] Class A, B, and C waste can be disposed of at shallow land burial sites. The Department of Energy and the Nuclear Regulatory Commission are currently determining whether Greater Than Class C waste requires deeper disposal.

Critiques of the US waste classification system focus on the fact that the system is based on the source of the waste, not the risk posed by it. For instance, HLW and Class A waste can both contain the same radionuclides, but because HLW originated from the reprocessing of spent fuel, it must be disposed of differently than Class A waste.[428] Other waste categories in the US include mill tailings and depleted uranium. The latter is not likely to be appropriate for shallow land burial.

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[425] US Transuranic waste contains "transuranic" elements, those with atomic numbers larger than uranium, at concentrations of greater than 10 nanocuries per gram. See NRC 2018, Greater Than Class C and Transuranic Waste, Federal Register, 83FR6475, February 14, pp. 6475-6477, viewed 9 May 2019, https://www.federalregister.gov/documents/2018/02/14/2018-03085/greater-than-class-c-and-transuranic-waste

[426] Macfarlane, A. 2019 '"Incidental" nuclear waste: reconceiving a problem won't make it go away,' the Bulletin of the Atomic Scientists, January 31, viewed 9 May 2019, https://thebulletin.org/2019/01/incidental-nuclear-waste-reconceiving-a-problem-wont-make-it-go-away/

[427] The US NRC includes a table and detailed algorithm for determining the correct class of waste in its 10 Code of Federal Regulations Section 61.55.

[428] Blue Ribbon Commission on America's Nuclear Future, 2012, Report to the Secretary of Energy, viewed 9 May 2019, https://www.energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf

QUANTITIES OF WASTE

Though there are no complete accounting records, the US has likely the largest and most complex volumes of nuclear waste in the world. There are no official reports of volumes of spent fuel in the commercial sector because the regulator does not require reporting of spent fuel volume. Inventories of other waste are published sporadically in varying government documents. Given that proviso, *Table 20* shows an estimate of the various waste volumes in the US. The federal government owns large volumes of high-, transuranic, and low-level waste at a variety of facilities. All high-level waste and spent fuel remain in temporary storage. Some transuranic waste from military sites has already been permanently disposed of at the Waste Isolation Pilot Project (WIPP), a deep geological disposal facility, in southeastern New Mexico, and the Nevada National Security Site. Low-level waste is disposed of at 18 different government facilities in the US. Mill tailings include both governmental and commercial waste.

In the commercial sector, spent fuel remains at nuclear power plants in cooling pools or dry storage. Research, isotope production, and test reactors also house spent fuel. Class A, B, and C, low-level waste has been disposed of at multiple facilities, but Greater Than Class C waste remains in storage awaiting a decision on how to dispose of it.

TABLE 20: Nuclear waste in the United States as of December 31, 2016

Type of waste	Type of storage	Storage site
OWNER: US GOVERNMENT		
HLW & SNF	14,000 tons	-
TRU (WIPP)	64,630 m^3**	93,500 m^3***
TRU (Nevada, closed facility)	-	200 m^3
Depleted uranium	75,296 tons	-
Mill tailings	228 million tons	-
LLW (class A, B, C)*	17 million m^3	-
OWNER: COMMERCIAL OPERATORS		
SNF (HLW)	81,518 tons****	-
SNF (university) research reactors	1,042 kgU	-
SNF (research and fuel chain facilities)	79 kgU	-
LLW (operating sites)	-	4.8 million m^3
LLW (closed sites)	-	438,000 m^3
GTCC	-	130 m^3

Sources: compiled from the US General Accounting Office (2019), Department of Energy (2009, 2017, 2018, and 2019), and Nuclear Energy Institute (2018).

Notes: *does not include an additional 129 reactor compartments in near-surface disposal at government facilities. **as of December 31, 2017. ***as of June 2018. ****as of December 31, 2018. TRU = Transuranic waste; WIPP = Waste Isolation Pilot Project; GTCC = Greater-Than-Class-C Radioactive Waste.

Estimates on future waste quantities are not available. However, a large light water reactor produces about 20 metric tons of spent fuel annually. Given that, the volume of spent fuel in the US grows by about 2,000 metric tons a year.

WASTE MANAGEMENT POLICIES AND FACILITIES

A number of laws and regulations guide the management of nuclear waste in the US. On the commercial side, the Department of Energy is statutorily responsible for managing and disposing of high-level nuclear waste, including spent nuclear fuel from commercial reactors, whereas low-level waste is managed by private entities. Both high- and low-level waste management and disposal are regulated by the Nuclear Regulatory Commission.

After the 1974 'peaceful' nuclear device test by India, the US began a policy of 'indefinitely deferring' reprocessing of commercial spent nuclear fuel. Though the policy was reversed by various (largely Republican) presidents, reprocessing of spent fuel has never been an economically viable management option in the US. The West Valley Demonstration Project did reprocess some spent fuel from 1966-1972, but was never economically successful. Ownership of the site has since passed to the Department of Energy.

Disposal of high-level nuclear waste in the US is governed by the Nuclear Waste Policy Act of 1982 as amended in 1987. This law established the need for the deep geological disposal (DGD) of commercial spent nuclear fuel and high-level waste from the nuclear weapons complex. It required the US Nuclear Regulatory Commission to license a repository site selected and operated by the Department of Energy based on radiation standards developed by the US Environmental Protection Agency. The Nuclear Waste Policy Act established a 'standard contract' under which licensees maintained ownership of the spent fuel until the Energy Department took title to it when it was to be moved off site to a final repository. Currently, spent fuel remains at reactor sites, with the exception of minor amounts of spent fuel moved to reactors owned by utilities or a central storage facility owned by the utility (the Morris facility in Illinois).

In the amendments to the Nuclear Waste Policy Act, the US Congress selected Yucca Mountain, Nevada, as the only site to be evaluated for its suitability for DGD. The Department of Energy submitted a license application to construct a repository to the Nuclear Regulatory Commission in 2008, but President Obama's administration withdrew the license application in 2009, dismantled the Office of Civilian Radioactive Waste Management at the US Department of Energy, and in its stead established the Blue Ribbon Commission on America's Nuclear Future to devise a new strategy for the back end of the nuclear fuel chain. The Blue Ribbon Commission issued its report in 2012, stressing the urgent need for DGD and emphasizing that choosing a site must be conducted using a consent-based approach.[429] Though the Nuclear Waste Policy Act is still the law of the land, Congress is currently divided over the fate of Yucca Mountain.

The Yucca Mountain repository host rocks are volcanic tuff (solidified ash) located in a seismically and volcanically active area. The repository horizon would be located above the groundwater table in a geochemically oxidizing environment, in contrast to the repository programs of other countries. The site itself was selected by the Department of Energy along with three other sites, including the Columbia River basalts near the Hanford site in Richland, Washington and bedded salt in northern Texas. The original Nuclear Waste Policy Act required the simultaneous characterization of three sites, but in amending the law, Congress focused solely on Yucca Mountain. The state of Nevada has consistently opposed the site since the passage of the amendments to the act in 1987, referring to them as the 'Screw Nevada' bill.

At nuclear power plants, spent fuel is stored either in reactor cooling pools, almost all of which have been re-racked to increase storage volume to almost four times the original size, or in dry storage.[430]

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[429] Blue Ribbon Commission on America's Nuclear Future 2012

[430] Alvarez, R et al. 2003, Reducing the hazards from stored spent power reactor fuel in the United States, Science and Global Security, 11(1), pp. 1-51.

In many power plants, the spent fuel pools are almost full. As a result, 56 out of 59 nuclear power plants in the US have some type of dry storage on site.[431] Some power plants do not maintain the ability to offload a full reactor core, and there is no regulation that requires them to do so. Nor do regulations require the reporting of spent fuel quantities or the way in which spent fuel is managed in the pools. As a result, it is unknown whether plants disperse recently discharged spent fuel in the pool or place it in a single location in the pool, and there are no official government accounts of volumes of spent fuel at reactor sites.

Recently, the Nuclear Regulatory Commission received two license applications to build centralized spent fuel storage facilities, one from Holtec International in southeastern New Mexico near the WIPP site and the other from Waste Control Specialists near the low-level waste disposal facility in Andrews, Texas. The Nuclear Regulatory Commission licensed a centralized storage facility near Salt Lake City, Utah in 2006, but the state and the US Department of Interior blocked the site from ever operating.[432]

The US hosts the only deep geological disposal in operation worldwide: the Waste Isolation Pilot Project (WIPP). Located at a depth of 600 m in bedded salt, the facility disposes of transuranic waste from nuclear weapons complex facilities near Carlsbad, New Mexico. The WIPP site was volunteered by the local community in the 1970s, and the site began receiving waste in 1999. It enjoys strong support from the local community, which saw improvements in their schools, and the addition of many amenities as white-collar workers moved in to the Carlsbad field office of the Energy Department. Even after an accident in 2014 that released radioactivity and shuttered the facility for over two years, the community remains supportive.

Low-level waste in the US is governed by the Low-Level Waste Policy Act of 1980 as amended in 1985. This law established that states must manage and control the disposal of their low-level waste and but are allowed to form 'compacts' with other states. These compacts would select one site in one of the states in the compact to site a disposal facility. Ten compacts were formed though ten states did not join any compacts. Only three compacts succeeded in establishing new low-level waste disposal facilities.

Four low-level waste disposal facilities have closed in the US:

- the Maxey Flats facility in Kentucky, which operated from 1963-1977 and was owned by NECO (which became US Ecology) and suffered extensive contamination of soil, surface water and groundwater;
- the Sheffield facility in Illinois operated from 1967-1978, also owned by NECO;
- the West Valley, New York facility closed in 1975;
- and the Beatty, Nevada facility operated from 1962-1993, and owned by US Ecology.

Four low-level waste disposal facilities operate now. Two of them, the Barnwell, South Carolina, facility, run by Energy Solutions and the Richland, Washington, facility run by US Ecology only accept waste from their compact. The Clive, Utah, facility owned by Energy Solutions accepts waste from any state, and the Waste Control Solutions facility in Andrews, Texas, will accept waste from outside their compact with a prior arrangement.

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[431] NRC 2019, US Independent Spent Fuel Storage Installations, viewed 9 May 2019, https://www.nrc.gov/docs/ML1907/ML19071A163.pdf

[432] World Nuclear News 2013, 'Cancellation leaves no options for US nuclear waste,' January 4, viewed 9 May 2019, http://www.world-nuclear-news.org/Articles/Cancellation-leaves-no-options-for-US-waste

COSTS AND FINANCING

High-level nuclear waste disposal is supported by the Nuclear Waste Fund, which was established by the 1982 Nuclear Waste Policy Act. This money is dedicated solely to the development of a DGD for high-level waste. The fund charges electricity ratepayers US$1 per MWh and is managed by Congress. Over time the fund has amassed over US$34.3 billion.

Though the fund was supposed to act as an escrow, or trust, account, Congress has instead used it to offset the US debt. Money collected into the fund is treated like tax revenue whereas money appropriated out of the fund is subject to spending restrictions. As a result, Congress has difficulty supplying funds when needed. Money is no longer being collected in the fund as a result of a federal lawsuit against the Department of Energy in 2013, because the agency had not made enough progress removing fuel from power plants.[433] The Department of Energy's cost estimates of disposing of US high-level waste at repository at Yucca Mountain was US$96 billion in 2008 dollars.[434] The Energy Department has already spent approximately US$15 billion developing Yucca Mountain.

The financial picture at US nuclear power plants is more complicated because of the 'standard contract' contained in the Nuclear Waste Policy Act. The law required the Department of Energy to begin to take title to spent fuel at reactor sites by January 31, 1998 and move it to a geologic repository. Of course, this did not occur and the contract was violated. US courts have ruled in favor of power plant licensees, who are now paid compensation. The US Department of Justice administers a Judgment Fund of taxpayer money, about US$2 million per day, to all power plants that sued the government to recover funds, operating or shut down, to help manage their spent nuclear fuel.[435]

All nuclear power plant licensees are required to show that they have sufficient funds to decommission their reactors when they eventually shut down. Most plants accumulate the necessary funds over the operating life of their plants. Every two years they report the amount of their decommissioning funds to the Nuclear Regulatory Commission, which uses an algorithm to determine whether they are accumulating sufficient funds. Decommissioning funds may not be allocated to the management of spent nuclear fuel.

SUMMARY

The US has one of the most challenging tasks of any country in managing its nuclear waste. Not only are there large volumes of waste on the commercial side, the nuclear weapons complex created impressive quantities of extremely difficult-to-manage waste materials. Managing and disposing of all this waste will take many decades and cost many hundreds of billions of dollars. The US has largely solved the problem of dealing with low-level waste; it is still struggling to deal with intermediate- and high-level waste. No clear solution is evident in the near future.

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[433] Ewing, R. et al. 2018, 'Reset of America's Nuclear Waste Management, Strategy and Policy,' Stanford University, George Washington University, October 15, viewed 9 May 2019, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/reset_report_2018_final.pdf

[434] US Department of Energy 2008, Revised Total System Life Cycle Cost Estimate and Fee Adequacy Report for Yucca Mountain Project, viewed 9 May 2019, https://www.energy.gov/articles/us-department-energy-releases-revised-total-system-life-cycle-cost-estimate-and-fee

[435] Dillon, J. 2019, 'Perry: "We have to find a solution,"' Energywire, March 27, viewed 9 May 2019, https://www.eenews.net/energywire/stories/1060130031

8 TABLE OF ABBREVIATIONS

ABBR.	WASTE TYPE
VLLW	Very low-level waste
VSLW	Very short-lived waste
LLW	Low-level waste
LLW-LL	Low-level waste, long-lived
LLW-SL	Low-level waste, short-lived
LILW	Low- and intermediate-level waste
LILW-LL	Low- and intermediate-level waste, long-lived
LILW-SL	Low- and intermediate-level waste, short-lived
ILW	Intermediate-level waste
ILW-LL	Intermediate-level waste, long-lived
ILW-SL	Intermediate-level waste, short-lived
HLW	High-level waste

ABBR.	NAME IN ENGLISH (AND IN ORIGINAL LANGUAGE IF APPLICABLE)
ABWR	Advanced boiling water reactor
AGR	Advanced gas cooled reactor
AKEND	Selection Procedure for Repository Sites Working Group (Arbeitskreis Auswahlverfahren Endlagerstandorte)
ANDRA	French national agency for radioactive waste management (Agence nationale pour la gestion des déchets radioactifs)
ASN	French Authority for Nuclear Safety (Autorité de Sûreté Nucléaire)
ATA	Alphatoxic waste
BEIS	UK Department of Business Energy and Industrial Strategy
BFE	German Federal Office for the Safety of Nuclear Waste Management (Bundesgellschaft für kernteschnische Entsorgungssicherheit)
BFS	German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz)
BGE	German Federal Company for Waste Disposal (Bundesgellschaft für Endlagerung)
BGZ	German Federal Company for interim storage (Gesellschaft für Zwischenlagerung)
BRC	Below Regulatory Control (the US term for what the IAEA calls Exempt)
BWR	Boiling water reactor
BZL	Federal Interim Storage Facility of Switzerland (Bundeszwischenlager)
CCSE	The Compensation Fund for the electricity sector (La Cassa conguaglio per il settore elettrico)
CDD	French National Commission for sustainable develoment and (Commission du Développement durable et de l'Aménagement du territoire de l'Assemblée nationale française)

CEA	Commission for atomic energy and alternative energies, France (Commissariat à l’énergie atomique et aux énergies alternatives)
CORWM	Committee on Radioactive Waste Management of the UK
CSM	Center of storage at La Manche, France (Centre stockage de la Manche)
CTS	Centralized Temporary Storage
DEFRA	Department for Environment, Food and Rural Affairs of the UK
DETEC	Swiss Department of the Environment, Transport, Energy and Communication
DGD	Deep geological disposal
DOE	Department of Energy, US
EDF	French national electricity company (Électricité de France)
EDF Energy	British subsidiary of the French company Électricité de France
EKRA	Swiss Commission for Radioactive Waste Disposal Concepts (Entsorgungskonzepte für radioaktive Abfälle)
ENSI	Swiss Federal Nuclear Safety Inspectorate (Eidgenössische Nuklearsicherheitsinspektorat)
EPR	European pressurized water reactor
EURATOM	European Atomic Energy Community
FBR	Fast breeder reactor
GCR	Gas cooled reactor
GW	Gigawatts (installed capacity)
GWh	Gigawatt hours (generated electricity)
HAL	Highly active liquor, refers to nitric acid
IAEA	International Atomic Energy Agency
ICPE	French Classified Installation for Environmental Protection (Installation Classée pour la Protection de l’Environnement)
ISDC	International Structure for Decommissioning Costing
KEG	Switzerland’s Nuclear Energy Act (Kernenergiegesetz)
LLWR	Low-level waste repository
LWR	Light water reactor
MIR	Medicine, industry, and research
MIRAM	Swiss Model Inventory for Radioactive Materials (Modellhaftes Inventar für Radioaktive Materialien)
MOX	Mixed oxide fuel
MW	Megawatts (installed capacity)
MWh	Megawatt hours
NAGRA	Swiss National Cooperative for the Disposal of Radioactive Waste (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle)
NAO	National Audit Office of the UK
NBG	German National Civil Society Board (National Begleitsgremium)

NDA	Nuclear Decommissioning Authority of the UK
NEA	Nuclear Energy Agency of the OECD
NLF	Nuclear Liabilities Fund of the UK
OECD	Organization for Economic Cooperation and Development
P+T	Partitioning and transmutation
PBOs	Parent body organisations (in the UK)
PHWR	Pressurized heavy water reactor
PIMCU	Public Joint Stock Company Priargunsky Industrial Mining and Chemical Union
PNGMDR	French National Plan for the Management of Nuclear Materials and Radioactive Wastes (Plan national de gestion des matières et déchets radioactifs)
PSI	Paul Scherer Institute
PWR	Pressurized water reactor
RAWRA	Czech Radioactive Waste Repository Authority
RBMK	Light water-cooled and graphite-moderated Reactor
SFISF	Spent fuel interim storage facility
SFL	Swedish final repository for long-lived radioactive waste (Slutförvar för långlivat [radioaktivt avfall])
SFR	Swedish final repository for short-lived radioactive waste (Slutförvar för [kortlivat] radioaktivt [avfal]l)
SKB	Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering)
SNF	Spent nuclear fuel
SSM	Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten)
STENFO	Swiss Decommission Fund for Nuclear Facilities and Waste Disposal Fund for Nuclear Power Plants
SVAFO	Swedish nuclear waste disposal company
t HM	Tons of heavy metal
THORP	Thermal oxide reprocessing plant
UNGG	Uranium Naturel Graphite Gaz reactor
VVER	Water-water energetic reactor from Russia (Vodo-Vodyanoi Energetichesky Reaktor)
WIPP	Waste Isolation Pilot Project
WNWR	World Nuclear Waste Report
ZWIBEZ	Interim Storage Facility at NPP Beznau (Zwischenlager Beznau)
ZZL	Central Interim Storage Facility (Zentrales Zwischenlager)

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IMPRINT

THE WORLD NUCLEAR WASTE REPORT – FOCUS EUROPE
November 2019

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COVER PHOTO:
Sean Gallup/Getty Images News
The photo shows castor containers filled with highly radioactive waste from decommissioned nuclear power plants at the Zwischenlager Nord storage facility on June 8, 2011 in Lubmin, Germany.

PRINT:
Arnold Group, Großbeeren

www.WorldNuclearWasteReport.org