THE GLOBAL CRISIS OF NUCLEAR WASTE

A REPORT COMMISSIONED BY GP FRANCE

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Authors: Pete Roche, Bertrand Thuillier, Bernard Laponche,
Miles Goldstick, Hideyuki Ban and Robert Alvarez
Coordination: Shaun Burnie, Greenpeace Germany
Graphic design: Alexandra Bauch, büreau-abcd.com
Translations: Jean-Luc Thierry, Emma Morton Saliou

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AUTHOR'S BIOGRAPHIES

BIOGRAPHIES

ROBERT ALVAREZ an Associate Fellow at the Institute for Policy Studies, in Washington DC. Alvarez served as senior policy adviser to the U.S. Energy Department's secretary and deputy assistant secretary for national security and the environment from 1993 to 1999. During this tenure, he led teams in North Korea to establish control of nuclear weapons materials. He also coordinated the Energy Department's nuclear material strategic planning and established the department's first asset management program. Before joining the Energy Department, Alvarez served for six years as a senior investigator for the US Senate Committee on Governmental Affairs, and as one of the Senate's primary staff experts on the US nuclear weapons program. In 1975, Alvarez helped found and direct the Environmental Policy Institute, a respected national public interest organization.

HIDEYUKI BAN is Co-Director of Citizen's Nuclear Information Center (CNIC) in Tokyo. Since 2013, he has been a member of the Japanese Ministry for Economy, Trade and Industry's Joint Radioactive Waste Working Group of the Nuclear Energy Subcommittee, Advisory Committee for Natural Resources and Energy. He is the author of multiple analysis and the books "Our Path to a Nuclear-Free Japan: Policy Outline for a Nuclear Phaseout" (co-autor) and "Critique Japan's Nuclear Policy Framework".

MILES GOLDSTICK since 2008 has worked at the Swedish Environmental Movement's Nuclear Waste Secretariat (Milkas) a coalition between Friends of the Earth Sweden and the Swedish Anti-nuclear Movement. Goldstick has been researching and writing on the nuclear fuel cycle since the mid-1970s. He holds a Ph.D. in Ecology and Environmental Protection at the Swedish University of Agricultural Studies in Uppsala, Sweden. He is the author of multiple analysis, and the book "Wollaston" on the impact of uranium mining on the native peoples of Saskatchewan, Canada.

BERNARD LAPONCHE
Paris Polytechnic School engineer, State Doctor in Nuclear Reactor Physics, PhD in Energy Economics, Bernard Laponche worked at the Atomic Energy Commission (CEA) in the 1960s and 1970s. Union representative at the CFDT in the 1970s, Director and then Director General of the French Agency for Energy Management (AFME, nowadays ADEME) from 1982 to 1987, he pursued from 1988 to 2012 an activity of international consultant (Eastern European countries and Mediterranean, China ...) in the field of energy efficiency (co-founder of "International Council on Energy", ICE) and was Dominique Voynet's technical advisor for energy and nuclear safety in 1998-99. He is a co-founder and member of the "Global Chance" and "Shared Energy" associations and co-author of "Energy Efficiency for a Sustainable World" and "Ending Nuclear Energy; why and how".

PETE ROCHE
Pete Roche is an energy consultant based in Edinburgh and policy adviser to the Scottish & UK Nuclear Free Local Authorities. Until April 2004 he was a nuclear campaigner for Greenpeace UK for thirteen years. He has an honours degree in Ecological Sciences from Edinburgh University. He was co-founder of the Scottish Campaign to Resist the Atomic Menace (SCRAM) in 1976, which organised some of the largest anti-nuclear power demonstrations in the UK at the Torness nuclear station outside Edinburgh in the 1970s and 80s. For 30 years, he has worked on environmental matters as campaigner, and on energy efficiency matters, both as an installer and as a consultant. He has represented Greenpeace at international and national fora, including OSPAR, IMO, and UN meetings, and the BNFL National Stakeholder Dialogue in the UK. He was also a member of the UK Government's Committee Examining Radiation Risks of Internal Emitters, and acted as a consultant for the Committee on Radioactive Waste Management (CoRWM). More recently he has been advising members of the Scottish Parliament on Energy Efficiency and Microgeneration. In his spare time Pete take part in a local 'logs for labour' scheme which involves helping with the management of local woodlands to feed his biomass heating system.

BERTRAND THUILLIER is an agronomist and Associate Professor at Polytech Lille in Lille I University. He graduated from the Institut National Agronomique Paris-Grignon (INA-PG), former student of the Asian Institute of Management in Manila, Philippines, and holds a PhD of Sciences (Biology) from the University of Reims. After having worked in the military sector, then in the food industry within a research center for three years, he has becomed in the same group the head of the industrial coordination to manage the Quality Control, Production, and Logistic operations; he had also have to set up quality assurance plans in Europe, mainly in Italy, Netherlands, Germany, Switzerland and Spain. Now, he manages his own consulting and IT company for the food industry and cosmetics in the field of New Product Development and Product Evaluation; he teaches Sensory Evaluation in different universities, and particularly the methodological aspects and the corresponding statistics. He was one of the first independent experts to highlight in a very detailed and deep analysis in 2012 the flaws of the Cigéo project in France, pointing in particular the risk of fires, and the weaknesses in the design of the French geological storage project in Bure - All of these mentioned elements were also recalled in 2017 by the IRSN in its ‘Dossier d’Options de Sureté’ (Safety Options File)

EXECUTIVE SUMMARY

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> ***"Their toxicity in general terms, both radioactive and chemical, is greater by far than any industrial material with which we have hitherto dealt in this or in any other country."***
>
> Johns Hopkins University professor Abel Wolman in January 1959 at the first U.S. congressional inquiry into nuclear waste..

The international nuclear fuel chain consists of multiple steps, all of which produce varying volumes of nuclear waste. The chain starts with uranium exploration, mining, milling, conversion into feedstock for uranium enrichment plants, then fuel fabrication, followed by commercial nuclear reactor operation, leading to nuclear spent fuel, which is either stored or reprocessed. More than 60 years of commercial nuclear programs has produced radioactive materials that will remain hazardous to humans and the environment on a time scale that far exceeds the existence of human civilization.

Greenpeace commissioned experts on nuclear waste to produce an overview of the current status of nuclear waste across the world. As the nuclear industry continues to struggle to compete in the rapidly evolving global energy market, the toxic legacy of decades of nuclear reactor operation and all the waste that continues to be produced to support it, remains central to any debate on the future of nuclear power, including decisions on nuclear reactor phase out. For every year of nuclear reactor operation, volumes of nuclear waste will continue to be generated across the world. Without exception, no solution has been found for longterm management the vast volumes of nuclear waste. This includes the highly radioactive spent fuel produced in all nuclear reactors, for which to date all efforts to find secure and safe permanent disposal options have failed.

FROM MINE TO REACTOR

Uranium mining produces a large amount of waste. This often contains elevated concentrations of radioisotopes compared to normal rock. Other waste piles consist of ore with too low a grade for processing. These waste piles threaten local populations due to the release of radon gas and seepage water containing radioactive and toxic materials. Uranium mill tailings have through the decades been dumped as sludge first directly into the environment and later in special ponds or piles, where they are abandoned.

The mining and milling process removes hazardous chemicals from their relatively safe underground location and converts them to a fine sand, then sludge, making them more susceptible to dispersion throughout the environment. After about 1 million years, the radioactivity of the tailings and thus its radon releases will have decreased so that it is only limited by the residual uranium contents, which continues to produce new thorium 230. The world's inventory of uranium mill tailings amounts to about 2.3 billion tons as of 2011[1]. The predominant reactor type worldwide, the light water reactor, depends on uranium fuel that is enriched. The concentration of the fissile isotope uranium-235 in natural uranium is only around 0.71%. To make nuclear fuel for most reactors this has to be increased to around 3 – 5% through the operation of uranium enrichment plants. A significant waste product of enrichment operations is depleted uranium, with current estimates of 1.7 million tons worldwide.

SPENT FUEL

The next stage in the nuclear fuel chain after enrichment nnd fuel fabrication, the last step before insertion of the enriched nuclear fuel in a nuclear reactor, which then generates electricity. Every 12-18 months this fuel is discharged from the reactor as spent nuclear fuel. The International Atomic Energy Agency (IAEA) estimates that around 370,000 metric tons of heavy metal (MTHM) of spent fuel has been produced since the advent of civil nuclear power production, of which 120,000 MTHM has been reprocessed.[2] There is now a global stockpile of around a quarter of a million tons of highly radioactive spent fuel in around 14 countries. The majority of this spent fuel remains in cooling pools at reactor sites that lack defense-in-depth such as secondary containment and are vulnerable to loss of cooling, and in many cases lack independent back-up power. The Fukushima accident in March 2011 made it clear that the high heat hazard of spent fuel pools was not an abstract issue.[3] The Atomic Energy Council at the time warned Prime Minister Kan that loss of control of the spent fuel pools at Fukushima Daiichi could lead to radioactive contamination so severe "*[W]e would have to evacuate 50 million people. It would have been like losing a major war… I feared decades of upheaval would follow and would mean the end of the State of Japan." as Prime Minister Kan was to say.4* Each year of commercial reactor operation worldwide produces around 12,000 tons of additional spent fuel. One reason why reactor lifetimes and decisions on nuclear phase out are central is because of the amount of high level nuclear waste the world will have to eventually manage.

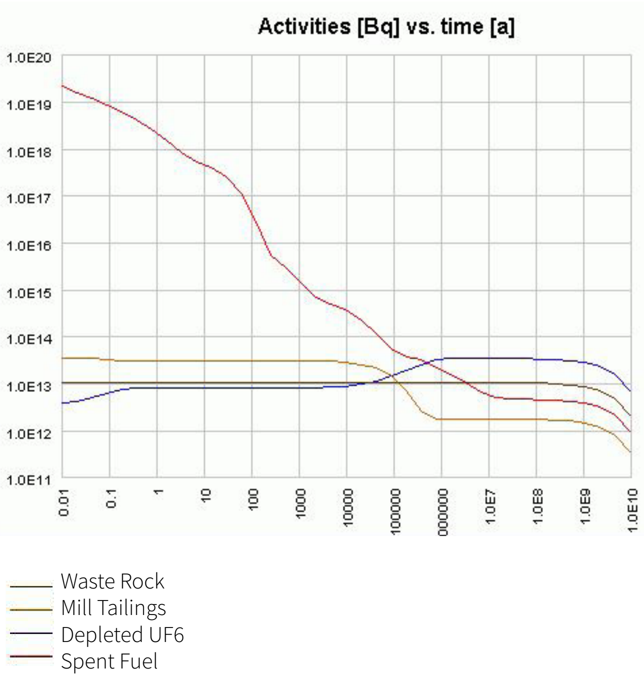
PLUTONIUM REPROCESSING

Technology developed in the early years of the U.S. and Russian nuclear weapons programs, commercial reprocessing has been deployed in several countries with the aim of chemical separation of plutonium from reactor spent fuel. The plutonium was produced as a result of the fissioning of uranium in nuclear reactors. The original justification for reprocessing was for plutonium production for nuclear weapons use, which evolved to include plutonium production to be used to fuel Fast Breeder Reactors, which in turn would produce more plutonium. Despite the failure of commercial fast breeder reactor programs, reprocessing or the separation of plutonium continues in France, Russia, with the UK ending reprocessing in 2020, and Japan's program stalled by years of delay.

In addition to direct discharges of nuclear waste via pipelines, and atmospheric releases of radioactivity, reprocessing produces multiple other waste streams, the most hazardous of which are liquid high level wastes.[5]

TIMESCALES FOR RADIOLOGICAL HAZARDS WITH NO SOLUTIONS

The use of nuclear power to generate electricity over the past six decades has created a nuclear waste crisis for which there is no solution on the horizon, but which will require the safe storage and management, and ultimately final disposal for hundreds of thousands of years forever. To illustrate the kinds of timescales we need to take into account, the chart below[6] compares the radioactivity of the various wastes generated by a 1,000 MW nuclear power reactor each year. Initially the activity of the spent fuel is by far the greatest, but this decreases continuously. The radioactivity of depleted uranium, on the other hand, actually increases in the long -term, so that after half a million years it overtakes spent fuel. (NB. both scales are logarithmic).



ESCALATING COSTS AND ENORMOUS UNCERTAINTIES

As with the financing of new nuclear reactors, the cost implications of managing and eventually disposing of nuclear waste, including spent fuel, are forever escalating. What is clear is that no country has a credible estimate of the total costs that will be incurred to manage nuclear waste over many decades let alone centuries. Even recent cost estimates are lacking in many countries. Almost without exception the costs listed below do not include the vast quantities of other nuclear wastes arising from the nuclear fuel chain. The enormous future financial burden will inevitably end up being paid by taxpayers.

In **France**, it's highly complicated to assess the total cost of waste management, particularly since it increases over the time. According to the Court of Auditors, in 2013, the total gross costs for long-term waste management was €32 billion (of which €26 billion to be financed by EDF (81%). This number does not include costs of spent fuel management which was estimated at €16 billion by EDF on 31 December 2013. Lastly, regarding the cost of the Cigeo project for the deep geological disposal of high-level and medium-level waste: in 2015, ANDRA estimated that the project would cost €35 billion. But in 2016, a governmental decree decided it would cost €25 billion.

In **Belgium** total costs, including a margin for unplanned events, were estimated at €3 billion in 2011[7], and now stand at €8 or even €10 billion[8].

In **Sweden** in 2017 the Swedish Nuclear Fuel and Waste Management Co (SKB) estimated total future costs to the point of closure of all the facilities for handling all the nuclear waste originating from nuclear reactors to be €9.5 billion, of which €3 billion is for managing spent fuel[9].

In **Japan** the cost of waste disposal was estimated by the Ministry of Economy Trade and Industry (METI) in 2011 as €29 billion[10]. But this is based on a wholly unrealistic schedule, whereas there will be inevitable delays of decades and long leading to much higher costs.

In the **United States** in 2008, the Department of Energy (DOE) issued a revised life-cycle cost estimate totalling €100 billion for the disposal of 70,000 metric tons of commercial power reactor spent fuel at the Yucca Mountain site – but with more than 112,000 tons of spent fuel projected as reactors continue to operate these costs will also significantly increase.

For the **UK** current cost models of the planned Geological Disposal Facility (GFD) €12.6 billion as of 2008 but exclude spent fuel from new nuclear reactors.[11] But as with nations worldwide, there are enormous uncertainties.

NUCLEAR WASTE DISPOSAL PLANS: SELECT COUNTRY REVIEW

Greenpeace commissioned a series of contributions from experts that reviewed recent history, current and future nuclear waste policies, with particular focus on spent fuel management. While there are many more countries worldwide with nuclear waste legacies, including those that have never operated nuclear reactors, but have been major suppliers of uranium, the selection of these countries reflects a common theme: no nation has yet resolved how to safely manage nuclear waste. Below is a selecttion of summary points from each country report, including examples that are common to all nations struggling to manage nuclear waste. The nuclear industry world-wide, with varying degrees of national government support,maintains a commitment to geological disposal of spent fuel, the most hazardous nuclear waste. Yet nowhere in the world has a viable, safe and long term sustainable underground repository been established. Even in Sweden and Finland where nuclear industry initiatives are most advanced, there remain major uncertainties over the scientific justification for disposal, as well as obstacles to the realization these projects centered around political, legal and public acceptance issues. Key issues that remain unresolved internationally, includ:

• The timeframes required to safely stop nuclear waste from spreading into the environment, including potential radiological impacts on future human society, extend centuries and hundreds of thousands of years into the future;

• When the stability of nations, is measured in years and perhaps decades into the future, what will be the viability of states over the thousands of year timeframes required to manage nuclear waste;

• Is it possible to ensure geological integrity, including disposal shaft and site water-tightness;

• How can future maintenance be guaranteed and carried out in underground nuclear waste facilities which may have collapsed;

• Securing sufficient financing, as costs remain estimates, and when the timeframes involved go well beyond the commercial viability of the current producers of nuclear waste, including highly vulnerable electric utilities;

• How will the waste and its container system itself evolve over centuries and beyond.

The common conclusion from the country reviews is that none of these issues and more have been resolved. Given the uniquely hazardous nature of nuclear waste, in particular high level waste, it is therefore incumbent upon governments, regulators and industry and a priority that the management of nuclear waste be a secured at the highest level of safety and security, to reduce hazards, both ongoing and future arising.

For high level waste, including spent fuel, the only credible conclusion is that a first step is to minimize the problem, which means in practice, halting its production at the earliest opportunity through nuclear reactor phase out. For existing spent fuel, secure dry cask storage remains the least threatening option over the coming decades. Industry claims that they are making significant progress in the management of high level nuclear waste lack credible evidence.

BELGIUM

Despite decades of investment in research and development, the planned high-level waste disposal site in the Mol region of Belgium, there remain inherent, significant and multiple risks. These include:

• The choice of a clay matrix for deep disposal, a rock that is saturated in water and not self-supporting;

• the depth of the site, too close to the surface and a few dozen metres from important drinking water sources;

• The insufficient thickness of the layer, which furthermore dips (by a small percentage, equivalent to a 40 metre drift for a 2% dip over 2 km). Infrastructure of this kind could require a strictly horizontal design for reasons of traffic and branching.

Also noteworthy are the many operational risks associated with co-activity and significant disturbances from powerful ventilation nearby residential areas. Project costs have fluctuated, with current total costs, including a margin for unplanned events, which were estimated at €3 billion in 2011[12], now stand at €8 or even €10 billion euros[13].

FRANCE

As a result of having the second largest nuclear reactor fleet in the world, (58 operating power reactors), France has an enormous nuclear waste crisis extending across all categories of waste. More than 60 years after the start of the French nuclear program, the country is no closer to 'solving' its nuclear waste crisis or acknowledging the scale of the challenge. Reprocessing has complicated the nuclear waste crisis in France, with reprocessing wastes, plutonium, vitrified high level waste and spent Mixed Oxide plutonium fuel (MOX). In terms of high level waste legislation has been passed to explore the feasibility of deep storage in a clay site. The envisaged facilityof France's high level waste (and medium level waste) disposal plans is the CIGEO Project (for 'industrial centre for geological storage') located in Bure. Vulnerabilities, shortcomings and obstacles have already been identified by three official opinions – that of the ASN, the IRSN and independent peer review –which raises serious questions about the CIGEO Project presented by the ANDRA.

Key summary issues in the French chapter of this report:

• Disposal plans for the Bure site are "High-level, long-lived" (HLLL) waste of around 10,000 cubic meters (non-conditioned volume) and approximately 30,000 cubic meters of conditioned waste for deep deposit (60,000 packages); "Medium-level, long-lived" (MLLL) waste: around 70,000 cubic meters (non-conditioned volume) and approximately 350,000 cubic meters of conditioned packages for 180,000 packages, including 75,000 asphalt packages;

• These figures do not include waste products classified as "nuclear materials", which should eventually be classified as waste and which, in the case of high- or intermediate-level, long-lived waste, involves processing similar to that currently planned within the CIGEO Project. One example is spent fuel, not destined for processing (including spent MOX fuels). Similarly, neither have provisions been made for the plutonium currently stored at La Hague;

• In terms of risks – ANDRA has admitted that "an explosion could lead to a loss of confinement" of the CIGEO site[3] with the potential release of radionuclides into the repository;

• Most serious risk is that of fire, given the co-existence in ILLL cells of hydrogen, flammable packages. The IRSN has demonstrated that this storage weakness is real and that a risk exists for a full-blown fire in a storage cell which could also lead to venting of radioactive gases. The IRSN modeling shows that a heat wave from a fire started in one package could spread to a target package in a matter of hours. It would be impossible for 'normal' operations to resume after such an accident.

• Over the long term the risk from water migration also exists at the CIGEO site. ASN called on ANDRA to demonstrate water flow mechanisms in the CIGEO rock in its simulations to enhance the demonstration of storage system robustness. The risk of water infiltration in the geological layers is probably the biggest 'technical' – and unpreventable – long-term risk;

• As with other nations, national legislators have imposed the concept of reversibility in the Law of 28 June 2006: Article 5;

• However, in reality, reversibility as planned is not credible, is restricted to the period of operation (equivalent to few future generations), and it is now known that the recoverability of one or more nuclear waste packages – the actual application of reversibility– is only obligatory in the pilot industrial stage, early in the site's period of operation not after its final closure;

• Burying such waste in a completely irreversible manner in the deep underground, without any hope of changing strategy, inflicts upon future generations a problem of underground pollution that they will discover and suffer from, with practically no ways of solving it;

• There is currently no credible solution for long term safe disposal of nuclear waste in France, the urgent matter is reducing risks from existing waste, including spent fuel. The French state must focus on safety and security improvements to current storage and disposal sites,

• The French government and parliament must urgently re-examine the CIGEO project, which will inevitably lead to a dead-end, and incur necessarily considerable costs that would ultimately fall to French citizens. And develop interim dry storage facilities coupled with high level research programmes for reducing the radioactivity and lifetime of the most dangerous waste.

• There needs to be an overhaul of the current management strategy for radioactive waste, developed after a long period of disinterest and based on a choice of either fuel reprocessing, plutonium production or the (questionable) differentiation between high-potential materials and waste.

JAPAN

As with most nations with a half century or more nuclear program, Japan was forced to abandon its plans for disposal of high level nuclear waste in the ocean by the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, the so called London Dumping Convention (LDC) 1972.

• Due to high seismic risks, the focus has been on technical barriers (more than natural barriers) to ensure the safety of geological disposal in Japan. Despite decades of investment, Japan has failed to demonstrate the viability of geological disposal.

• Nuclear fuel cycle policy remains centered on the reprocessing of all spent fuel which is currently not classified as high level nuclear waste. Change in this policy remains the only viable future option — the plutonium reprocessing program is decades behind schedule, billions of euros over budget, and is not attainable;

• The one underground research project is in Horonobe on the northern island of Hokkaido whose geology is relatively young having been formed only about 100,000 years ago - mudstones, which contain large numbers of fissures and great amounts of underground water. The water includes both water from the ground surface and fossiliferous seawater;

• No suitable site has been identified that meets this criteria – with high level of public opposition to even a suggestion of a site in their community — 21 out of 46 prefecture governors have already stated they do not accept further research into geological disposal in their locality;

• Current cost estimates remain entirely lacking in credibility at 3.8 trillion yen (2.9 billion euro);

• The reality is that spent fuel is high level nuclear waste, with no rationale for reprocessing and plutonium separation. Spent fuel will remain at reactor storages sites, and the Rokkasho-mura plant for the foreseeable future. As the Science Council of Japan correctly warned in its 2012 report to the Cabinet Office, the only option is to commit to interim storage of high level waste for a period of up to 300 years.

SWEDEN AND FINLAND

Since the mid-1970s, the nuclear industry and government have been putting great financial resources towards dealing with long-term management of the full range of nuclear waste, particularly spent fuel. There is currently interim storage of spent fuel for about 30 years at the underground Clab facility, located at Oskarshamn. There is an ongoing, formal review of a Swedish Nuclear Fuel and Waste Management Co (SKB) application to build an underground spent fuel management system using the KBS-3 method. The technical issues and challenges for the KBS-3 facility in Sweden apply as well to the partially built "Onkalo" facility in Finland, where the geological conditions are in general sim ilar to Sweden. The nuclear industry worldwide hails progress in Sweden and Finland as a vision of the future but the reality is very different:

• The safety of the KBS-3 method is based on a number of unproven principle assumptions, of which one is that the canister material, copper with an iron insert, will corrode so slowly that the radionuclides will not be released over the period the waste is dangerous to life forms.

• Due to the complex factors that cause corrosion, it is uncertain if copper and iron are suitable materials. Research independent of the nuclear industry has found that leakage due to copper corrosion may begin after 100 years, and leakage from most canisters would occur after about 1,000 years.21F[14] Further, tests simulating the intended system with spent fuel in a canister have not been carried out;

• In 2018 the Swedish Radiation Safety Authority (SSM) gave conditional approval for the KBS-3 project, which included resolution of the copper corrosion issues;

• a landmark ruling in 2018, by the Land and Environment Court puts the entire KBS-3 project in doubt. The court found that the safety case has not been demonstrated and that the effects of the proposed project cannot be predicted with enough certainty to permit the formulation of any final conditions.

The court also took the position that financial responsibility in the longterm needs to be clarified.

UNITED KINGDOM

With one of the largest and most complex nuclear waste problems in the world, the launch of two new consultation documents[15] in January 2018 marked the start of the UK Government's sixth attempt in the past 42 years to find a community willing to host a radioactive waste dump. The UK's nuclear waste legacy has been made dramatically more dangerous and expensive by its decades long plutonium reprocessing program based at Sellafield in the north of England. Having failed to find a site for a nuclear waste dump during the past four decades, the Government decided to try a new approach based on what it called "voluntarism and partnership". However, there are no indications that this latest effort – the so called Geological Disposal Facility (GDF) to overcome decades of failure will be secured:

• multiple official bodies have warned that the Sellafield site for poses a "significant risk to people and the environment" and having accumulated "…an extraordinary accumulation of hazardous waste, much of it stored in outdated nuclear facilities";

• the local council, that hosts the Sellafield nuclear complex, and which has most experience of attempts to find a site for a geological disposal facility over the decades, has already described the 2018 program by Government as fundamentally flawed. In particular it regrets the failure to address the need for secure interim storage, despite the most dangerous elements within spent fuel waste being too hot to place underground for well over a century;

• it s doubtful whether it will ever be possible to demonstrate with any scientific credibility that the resultant radiation dose to people from a UK nuclear waste repository would be at an acceptably low level into the far distant future;

• with no solution on the horizon, the UK has embarked on a new nuclear reactor construction program which will compound the nuclear waste problem and result in vastly increased radioactivity from spent fuel and other highly radioactive wastes which will have to be stored indefinitely at vulnerable sites scattered around our the British coast.

UNITED STATES

After 60 years (1957-2017), nuclear power reactors in the United States have generated roughly 30% of the total global inventory of spent nuclear fuel (SNF) – by far the largest.. Yet at the same time, decades long efforts and billions of dollars of investment have failed to secure one geological disposal site for commercial spent fuel. The Yucca Mountain underground facility, selected on political grounds and decades in the construction was cancelled on scientific and public acceptance grounds by the Obama administration in 2010.

• for nearly 30 years, the Nuclear Regulatory Commission (NRC) waste-storage requirements have been contingent on the timely opening of a permanent waste repository which has allowed reactor operators to legally store spent fuel in onsite cooling ponds much longer, and at higher densities (on average four times higher), than was originally intended – approximately 70 percent of spent fuel in the U.S. remains in vulnerable cooling pools;

• the large accumulation of spent nuclear fuel in U.S. reactor pools poses a far more potentially consequential hazard. This is because the pools are holding several irradiated cores or 3-4 times more spent nuclear fuel than the original designs intended. The pools lack defense-in-depth such as secondary containment and their own back-up power;

• a 2008 estimate by the Department of Energy (DOE) issued a revised life-cycle cost estimate totalling US$113 billion (2016 dollars) (97 billion euros (2018) for the disposal of 70,000 metric tons of commercial power reactor spent fuel at the Yucca Mountain site in Nevada and amount that exceeds the current stockpile as of 2018. Under current law, spent nuclear fuel more than that amount would have to be disposed in a second disposal site;

• the Yucca Mountain site does not meet the basic geological requirements for long term storage established by the International Atomic Energy Agency including a “stable geochemical or hydro chemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals; and long term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity and heat flow”;

• the U.S. lacks a coherent policy for long-term surface storage of spent fuel and other high level wastes, which is the only viable option at present. In recognition of the major uncertainties, the DOE has stated that “extended storage, for periods of up to 300 years, is being considered within the U.S.”

1 See slide No.61http://www.wise-uranium.org/stk.html?src=stkd01e

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http://www.wise-uranium.org/stk.html?src=stkd02e

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8 Les échos.be – Des milliards supplémentaires pour stocker les déchets nucléaires – 22 August 2018 (in French).

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14 Szakálos Peter, Leygraf Christofer, Rosengren Anders, Seetharaman Seshadri, Grinder Olle, Linder Jan. 2018-04-26. "Analys av kärnbränsleförvarsfrågan efter mark-och miljödomstolens yttrande till regeringen." ("Analysis of the nuclear fuel management issue after the Land and Environment Court's statement to the government.") In Swedish only. 4 pp. Available at (5 October 2018): http://www.nonuclear.se/szakalos-et-al20180426analys-av-karnbransleforvarsfragan.
This document was submitted to the government for its ongoing review, and the government has requested comments from SKB by 30 April 2019. The authors include a group of specialists at The Royal Institute of Technology (KTH) in Stockholm, who are at the forefront of copper corrosion research worldwide, and a former employee of SSM. Research in Sweden on copper corrosion by independent specialists was spearheaded by KTH Associate Professor Gunnar Hultquist, who died in February 2016. He initiated an experiment in 1986 showing that copper corrodes in oxygen-free water. His results were eventually confirmed internationally by independent methods.

15 Department for Business, Energy and Industrial strategy (BEIS) Press Release 25th January 2018
https://www.gov.uk/government/news/local-communities-to-give-views-on-permanent-disposal-of-radioactive-waste

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NUCLEAR WASTE: THE SITUATION TODAY

NUCLEAR WASTE: THE SITUATION TODAY

Pete Roche

The entire nuclear fuel cycle, from uranium mining, enrichment, reactor operation and reprocessing to nuclear reactor decommissioning produces hazardous nuclear waste.

Uranium mining generates radioactive tailings, which are collected in engineered tailings dams and covered with a layer of clay and rock to try to inhibit the leakage of radon gas.

Low-level Wastes (LLW) is generated by the industry in large volumes. It comprises paper, rags, tools, clothing, filters etc. It is often simply buried in shallow landfill sites.

Intermediate-level Wastes (ILW) includes things like resins, chemical sludges and the metal cladding stripped off waste fuel, as well as contaminated parts of reactors which have been decommissioned. Even this ILW, which contains higher amounts of radioactivity than LLW, is buried in shallow landfill sites in some countries. Although not the most radioactive category of waste, ILW usually requires some form of shielding and needs careful management to protect the health of workers and the environment.

The most hazardous waste is High Level Waste (HLW) or spent fuel, removed from nuclear reactors, which stays radioactive for hundreds of thousands of years. Standing one metre away from a spent fuel assembly which was removed from a reactor a year ago could kill you in about one minute.[1] In some countries the situation is exacerbated by 'reprocessing' this spent fuel – which involves dissolving it in nitric acid to separate out weapons-useable plutonium. This process leaves behind a highly radioactive liquid waste.

The International Atomic Energy Agency estimates that around 370,000 metric tonnes of heavy metal (MTHM) of spent fuel has been produced since the advent of civil nuclear power production, of which 120,000 MTHM has been reprocessed.[2]

No country in the world has yet secured a solution for high-level waste.[3]

Nuclear waste inventory (IAEA estimates, 2018)[1]

	Solid radioactive waste in storage (m^3)	Solid radioactive waste in disposal (m^3)	Proportion of waste type in disposal
VLLW	2,356,000	7,906,000	77%
LLW	3,479,000	20,451,000	85%
ILW	460,000	107,000	19%
HLW	22,000	0	0%

Note: all volumetric figures are provided as estimates based on operating and proposed final disposal solutions for different types of waste.

URANIUM MINING

Most uranium ore is mined in open pit or underground mines. The uranium content of the ore is often between only 0.1% and 0.2%. Therefore, large amounts of ore have to be mined to get at the uranium. In the early years up until the 1960's uranium was predominantly mined in open pit mines from ore deposits located near the surface. Later, mining was continued in underground mines, but many of these closed in the 1980s after uranium prices dropped. The United States had hundreds of underground mines during the Cold War era. After deposits were exhausted many of these were simply abandoned, often without even securing the mine opening presenting a hazard even today.[4]

Waste rock is produced during both types of mining. This often contains elevated concentrations of radioisotopes compared to normal rock. Other waste piles consist of ore with too low a grade for processing. These waste piles threaten local populations due to the release of radon gas and seepage water containing radioactive and toxic materials.

According to the seminal work on nuclear chemistry published in 1995 by Hoppin, Rydberg, and Liljenzin:

> ***"...Ra [Radium] and Rn [Radon] are among the most radio-toxic substances existing, causing bone and lung cancer at relatively low concentrations, [consequently] special attention must be devoted to their appearance in nature*** [5] ***"***

URANIUM MILLING

Ore mined in open pit or underground mines is crushed and leached in a uranium mill – basically a chemical plant designed to extract uranium from ore. It is usually located near the mines to limit transportation. In most cases, sulphuric acid is used as the leaching agent, but alkaline leaching is also used. As the leaching agent not only extracts uranium from the ore, but also several other constituents like molybdenum, vanadium, selenium, iron, lead and arsenic, the uranium must be separated out of the leaching solution. The final product produced from the mill, commonly referred to as "yellow cake" (U3O8 with impurities), is packed and shipped in casks.

A waste product of ore processing is the uranium mill tailings which are normally dumped as sludge in special ponds or piles, where they are abandoned. The largest such piles in the U.S. and Canada contain up to 30 million tonnes of solid material. In Saxony, Germany the Helmsdorf pile near Zwickau contains 50 million tonnes, and in Thuringia the Culmitzsch pile near Seelingstädt 86 million tonnes of solids.[6]

Milling does not remove long lived decay products such as thorium-230 and radium-226, nor does it remove all of the uranium - about 5% to 10% remains - so the sludge still contains about 85% of the initial radioactivity along with heavy metals and other toxic contaminants such as arsenic, and chemical reagents used during the milling process. The mining and milling process removes hazardous chemicals from their relatively safe underground location and converts them to a fine sand, then sludge, making them more susceptible to dispersion throughout the environment.

Radon-222 gas emanates from tailings piles and has a half-life of 3.8 days. This may seem short, but due to the continuous production of radon from the decay of radium-226, which has a half-life of 1600 years, radon presents a long-term hazard. Further, because the parent product of radium-226, thorium-230 (with a half-life of 80,000 years) is also present, there is continuous production of radium-226.

After about 1 million years, the radioactivity of the tailings and thus its radon releases will have decreased so that it is only limited by the residual uranium contents, which continuously produces new thorium-230.

Radon release is a major hazard which continues after uranium mines are shut down. The U.S. Environmental Protection Agency (EPA) estimates the lifetime excess lung cancer risk of residents living near a bare tailings pile of 80 hectares at two cases per hundred. Since radon spreads quickly with the wind, many people receive small additional radiation doses. Although the excess risk for the individual is small, it cannot be neglected due to the large number of people concerned. EPA estimated that the uranium tailings deposits existing in the United States in 1983 would cause 500 lung cancer deaths per century, if no countermeasures were taken.[7]

Due to the long half-lives of the radioactive constituents involved the safety of tailings deposits have to be guaranteed for very long periods of time. After rainfall, erosion gullies can form; floods can destroy the whole deposit; plants and burrowing animals can penetrate into the deposit and thus disperse the material, enhance the radon releases and make the deposit more susceptible to climatic erosion. When the surface of the pile dries out, the fine sands are blown by the wind over adjacent areas. Seepage from tailings piles is another major hazard posing a risk of contamination to ground and surface water. Residents are also threatened by radium-226 and other hazardous substances like arsenic in their drinking water supplies and in fish from the area. The seepage problem is very important with acidic tailings, as the radionuclides involved are more mobile under acidic conditions.

Tailings dam failures have caused pollution problems at uranium mines across the globe. Twenty-one dam failures have been documented by WISE International.[8]

Closure of a uranium mill produces large amounts of radioactively contaminated scrap which will have to be disposed in a safe manner. In the case of Wismut's Crossen uranium mill, in Germany, to reduce cost some of the scrap is intended to be disposed in the Helmsdorf tailings, but there it can produce gases and thus threaten the safe final disposal of the sludge.[9]

The WISE International Uranium Project detailed the world inventory of known uranium mill tailings in 2011. The South African tailings are from uranium by-product recovery from gold mining; and part of the Australian tailings are from uranium co-product recovery with copper mining (Olympic Dam). Nevertheless the world's inventory of uranium mill tailings amounts to 2,352.55 million tonnes.[10]

Country	Million tonnes of uranium mill tailings
Australia	79
Bulgaria	16
Canada	202.13
Czech Republic	89
France	29.318
Germany	174.45
Hungary	29.4
Kazakhstan	165
Kyrgyzstan	32.3
Namibia	350
Russia	56.85
South Africa	700
Ukraine	89.5
USA	235
Uzbekistan	60

Source: www.wise-uranium.org/mdaf.html

In 2010 Greenpeace International documented the legacy of waste and environmental destruction left by the French nuclear industry mining of uranium in Niger.[11] Clouds of dust caused by controlled explosions at the open pit mine carry radioactive gas towards the towns of Arlit and Akokan. Mountains of industrial radioactive waste sit in the open air for decades. And the shifting of millions of tonnes of rock and earth has corrupted the once clean source of groundwater that is also rapidly disappearing due to industrial overuse. In November 2009 Greenpeace and its partners were able to complete a brief scientific investigation of the area measuring radiation levels in and around the mining towns. In some cases readings went above 100 times internationally recommended levels. In about ten years' time the local economy around Arlit and Akokan will dry up as the mines run out of uranium, but the people and a legacy environmental pollution will be left behind for centuries to come.[12]

The waste in Niger includes an estimated 40 million tons of radioactive residues from two mines and 1600 tonnes of contaminated solid waste, as well as additional liquid waste.[13]

It's a similar story in other parts of the world. In the East Singhbhum district of Jharkhand State in Eastern India there are hundreds of cases of congenital illness and other birth defects in addition to a high incidence of infertility, miscarriages and pre-mature deliveries near the Jadugora uranium mines which have some of the best quality uranium ore, and magnesium diuranate deposits in the world. "*Miners working in the mine areas inhale the dust and radon gas. Besides, the uranium ore are transported in uncovered trucks through roads that are full of bumps. This cause the debris to fall off on the sides of the road. Radiation are also caused by dumping of mine's tailings in uncovered ponds*," said Ankush Vengurlekar, a photojournalist who has documented people's suffering because of the "unsafe" mining.

Locals say villages lying close to the tailing ponds are the worst affected. During the dry season, dust from the tailings blows through these villages. During the monsoon rains, radioactive waste spills into the surrounding creeks and rivers, causing further internal radiation as villagers use the contaminated water for washing and drinking and also use the nearby ponds for fishing.[14]

Earlier this decade when it looked like there might be a renaissance in nuclear power construction Chinese, Canadian and French firms rushed to exploit uranium deposits in new countries in Africa. In 2010 one commentator said "*Getting a mine going in Texas takes two bookshelves full of authorisations. In Niger you give a shovel to a guy on $2 a day and you're mining uranium.*"[15] Even so, in 2016 almost 75% of world uranium production was still taking place in the top three producing countries, Kazakhstan, Canada and Australia.[16]

Uranium mining is just the start of the nuclear fuel chain, but these stories serve to illustrate how the nuclear industry, after making a profit, often loads its liabilities onto local residents, taxpayers and electricity consumers. All the way through the nuclear chain, local populations are subjected to increased health risks, and yet more often than not they have not been asked if they are willing to put up with those increased risks.

URANIUM ENRICHMENT

The raw material obtained from uranium mining is known as yellowcake. It contains U_3O_8 and impurities. To use this in electricity generating nuclear power stations it has to be made into nuclear fuel. Firstly the uranium has to be converted to uranium hexafluoride (UF_6), a compound that can easily become a gas. This property is required for the subsequent enrichment process.

Yellowcake still contains some impurities so prior to enrichment has to be further refined before or after being converted to uranium hexafluoride (UF_6), (known as 'hex'). Conversion plants are operating commercially in the USA, Canada, France, Russia and China. This conversion generates yet more waste. Conversion wastes are usually dumped in large compounds next to the conversion plant.

In France, for instance, the Comurhex Malvési conversion plant, converts U_3O_8 to UF_4. Further processing to UF_6 is done at the Comurhex plant in Pierrelatte. On March 20, 2004, a dam failure at a decantation and evaporation pond at the Malvési conversion plant released approx. 30,000 cubic metres of liquid and slurries. The dam failure is believed to have been caused by an "*abnormal presence of water*" due to heavy rain in summer 2003. Production had to be halted again for two months after heavy rainfall at the end of January 2006, to maintain the required safety margin for the ponding water in the compound. However, rain water came into contact with the spilled slurries from the 2004 event still lying outside of the dams, and contaminants thus dissolved were released into the environment. On March 5, 2006, strong winds resulted in an overflow of several decantation ponds due to insufficient safety margins of the ponding water levels, leading to another spill of nitrate-contaminated waters.

On June 20, 2006, a further spill of an unreported amount of contaminated slurries occurred which covered a surface area of 350 square meters and went undetected for a month.[17]

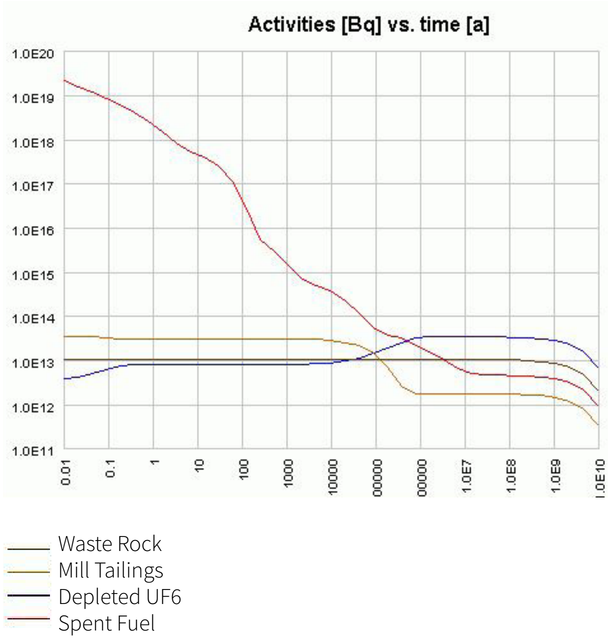
The concentration of the fissile isotope uranium-235 in natural uranium is only around 0.71%. To make nuclear fuel for most reactors this has to be increased to around 3-5%. This is known as the enrichment process. In commercially available enrichment plants this is done by a physical process, either by gas diffusion, or by using a centrifuge. For each tonne of enriched uranium, 7 tonnes of depleted uranium (DU) are generated. The ultimate fate of the depleted uranium is mostly unclear, but most of it is stored as UF_6 in steel containers in open yards near the enrichment plants. The U.S. has launched a program to convert the depleted uranium hexafluoride to a chemical form that is more suitable for long term storage.

The most recent inventory of worldwide depleted uranium that appears to be available come from the OECD's Nuclear Energy Agency[18] in 1999:
The OECD report said stocks of depleted uranium arising from the enrichment process are expected to increase by up to 57 000 tU annually for the foreseeable future – so an almost 5% increase every year.

The next step in nuclear fuel production is to convert the enriched UF_6 to uranium dioxide for use in nuclear fuel rods. Minor amounts of waste are produced at this stage of the process.

Country	Stored as	Stocks in tU
USA	UF_6	480,000
Russia	UF_6	450,000
	Metal & oxide	10,000
France	U_3O_8	140,000
	UF_6	50,000
UK (BNFL)	UF_6	30,000
Netherlands, Germany, UK (Urenco)	UF_6	16,000
Japan	UF_6	10,000
China	UF_6	2,000
South Korea	UF_6	200
Total		1,188,200

To illustrate the kinds of timescales we need to take into account, the chart below[19] compares the radioactivity of the various wastes generated by a 1,000 MW nuclear power reactor each year. Initially the activity of the spent fuel is by far the greatest, but this decreases continuously. The radioactivity of depleted uranium, on the other hand, actually increases in the long term, so that after half a million years it overtakes spent fuel. (NB. both scales are logarithmic).



NUCLEAR POWER GENERATION

The next stage in the nuclear fuel chain is the insertion of nuclear fuel in nuclear reactors which then generates electricity. Eventually this fuel is discharged from the reactor as spent nuclear fuel.

In 2011 the International Panel on Fissile Materials (IPFM) published a report which analysed the policy and technical challenges faced over the past five decades by international efforts at long-term storage and disposal of spent fuel from nuclear power reactors. These challenges have so far prevented the licensing of a geological repository for spent fuel or high-level reprocessing waste anywhere in the world.[20] It looks in particular at ten countries Canada, France, Germany, Japan, South Korea, Russia, Sweden and Finland, the United Kingdom and the United States. This list includes the largest and oldest nuclear energy programmes and covers more than 80% of the world's nuclear power capacity.

The inventory of spent fuel in those ten countries at the end of 2007 was as shown in the table below. This table draws on the most systematic reporting on spent fuel inventories by country which is done by the national reports required under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management. The IPFM report draws on national reports submitted to the third review meeting held in 2009. The Sixth review meeting was held from 21 May to 1 June 2018. We will, therefore examine national reports submitted to this meeting, where available:

http://www-ns.iaea.org/conventions/results-meetings.asp?s=6&l=40

The UK report is not available on the IAEA website but is available here:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data file/672640/20171020_-_UK_Sixth_National_Report_to_the_Joint_Convention.pdf

The Swiss report is available here:
https://www.ensi.ch/de/wp-content/uploads sites/2/2017/10/Joint_Convention-Sixth_national_report-Switzerland_2017.pdf

Country	Spent Fuel inventory (tons of heavy metal) end of 2007	Spent fuel policy
Canada	38 400	Direct disposal
Finland	1 600	Direct disposal
France	13 500	Reprocessing, disposal, storage
Germany	5 850	Direct disposal (now)
Japan	19 000	Plan of reprocessing, disposal for now
Russia	13 000	Some reprocessing
South Korea	10 900	Storage, disposal undecided
Sweden	5 400	Direct disposal
United Kingdom	5 850	Reprocessing but future unclear
United States	61 000	Direct disposal

Table 1.2 : Spent fuel inventories in cooling ponds and dry-cast storage as of the end of 2007 for the 10 countries in the present study - except for France and Japan. For the data for France and Japan, see respective chapters

From the national reports submitted to the Sixth Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management held in 2018 (where these are available) otherwise from the Fifth Review Meeting held in 2015, we can build up a picture of the inventory of High and Intermediate Level Waste and spent fuel in the main global nuclear countries as shown in the table below. Unfortunately not every country uses the same units of measurement, or the same definition of different categories of waste. Nevertheless we can see that there is now a global stockpile of around a quarter of a million tonnes of uranium of highly radioactive spent fuel spread around 14 countries, and around 370,000 cubic metre of liquid or vitrified high level waste.

	High Level Waste	Spent Fuel	ILW	Policies
Argentina (up to late 2013)		4,243 tHM		Spent fuel is currently in wet storage.
Belgium (as at 31st Dec 2016)	600 m^3 – 4 500 m^3 (depending on the future management of commercial spent fuel).	4080 tHM (incl 66 tHM of MOX fuel)*	11 100 m^3 – 10 430 m^3 (depending on the future management of commercial spent fuel),	Reactors to be phased out by 2025. At 31 December 2016, the national policy for the management of spent fuel from commercial nucle-ar power plants is the safe storage of spent fuel.
Brazil (as at March 2014)		1,398 fuel assemblies		Spent fuel in storage.
Canada (as at 31st Dec 2016)		52,655tHM	32,891m^3 (plus 263m^3 from decommission-ing activities)	Direct disposal
China (as at 31st Dec 2013)		3973.5tHM		Plan is to reprocess spent fuel, but spent fuel is currently stored.
Finland (5th Review) (as at end 2013)		16,382tHM	(including LLW pre-disposal 2056m^3 and disposed 7567m^3)	Direct disposal (spent fuel shipments from Loviisa to Mayak in Russia were terminated in 1996)
France (as at 31st Dec 2015)	14,555 containers of vitrified waste. 3,200m3 equivalent conditioned end of 2013*	La Hague 9681tHM (plus 32tHM foreign) EDF NPPs 4221tHM CEA 88tHM	14,284 containers of compacted metal waste plus 46 300 m^3 not from reprocessing. 135,000m^3 Long-lived ILW and Long-lived LLW.**	Reprocessing disposal and direct storage.
Germany	Approx. 700 m^3 of vitri-fied waste in canisters	20,400 m^3 of packaged fuel from light water re-actors for direct disposal; Approx. 1,340 m^3 packaged fuel from the Hamm-Uentrop thorium high-temperature reactor	Approx. 740 m^3 of structural parts and sleeves (CSD-C) in canisters from repro-cessing of spent fuel in reprocessing plants abroad (France) Approx. 3,400 m^3 of waste packages with structural parts of the spent fuel for direct disposal	Spent fuel formerly sent to UK and France for reprocessing. Direct storage now.

	High Level Waste	Spent Fuel	ILW	Policies
Japan (5th Review) (as end of end March 2014)	415m³ of High Level Liquid; 247 x 120-litre container; 346 x 160-litre container; 1442 x 170-litre container	16,889tHM	696,896 x 200 litre drums at power stations and 110,296 elsewhere.	Formerly reprocessing abroad; plans to move to domestic reprocessing but failed until now.
Russia as at 1st Jan 2017	18,640m³ liquid High Level Waste plus 480 tonnes solid HLW.	22,449tHM	94,800m³ liquid ILW plus 1680 tonnes solid	Incomplete Reprocessing, disposal and storage.
South Korea (4th Review) (as at end of 2010)		11,370tHM	87,176 x 200 litre drums at NPPs (plus 18,228 elsewhere)	Direct disposal
Spain (October 2014)		4592tHM	7494m³ Low & Intermediate Level Waste. Plus 30188m³ at El Cabril.	Spanish policy is that spent fuel should be considered waste.
Sweden (as at 31st Dec 2016)		6758tHM	L&ILW 40,232m³	Direct disposal
Switzerland (as at 31st Dec 2016)	about 1,139 t of spent fuel had been shipped from the Swiss NPPs to the reprocessing facilities in France and the UK	1377tHM	Conditioned L/ILW 7271m³. Unconditioned 1224m³	Moratorium on reprocessing introduced 2003. Direct storage.
United Kingdom (as at 1st April 2016)	**1,960m³** (1,100 liquid, 867 vitrified) 3,700 tonnes (not packaged 1,400; packaged 2,300)	In reactor ~2,800tHM In store~4,800tHM Expected future arisings from existing reactors ~2,900tHM **TOTAL 10,500tHM**	99,000m³ (120,000 tonnes)	Magnox fuel reprocessing complete Dec 2020. Oxide fuel reprocessing will end 2018.
United States (June 2017)	348,298m³	80,296tHM	91,003 m³ of defense-generated TRU waste emplaced at WIPP.	Direct disposal

*In 2025, when the last Belgian commercial nuclear reactor will be permanently shut down,
the total quantity of spent fuel stored at the Doel and Tihange sites will reach a maximum of 4 880 tHM.

**From https://inventaire.andra.fr/sites/default/files/documents/pdf/fr/2015_-_rapport_de_synthese.pdf

REPROCESSING

In the early days of nuclear technology, making use of the plutonium generated as by-product in first-generation, uranium-fuelled nuclear reactors became a subject of fascination in the nuclear world. During the nuclear fission process some of the non-fissionable portion of uranium – uranium-238 – absorbs a neutron turning it into plutonium-239. This can be used a new kind of reactor – the fast breeder reactor. If the reactor core is surrounded by a 'blanket' of uranium-238 the fast breeder reactor can theoretically generate more of its own fuel. These breeder reactors could produce more plutonium than they consumed thus greatly extending the lifetime of uranium reserves. Decision-makers were impressed by this concept, and research & development funds were distributed generously.

To achieve this, plutonium had to be separated from spent nuclear fuel by dissolving it in boiling concentrated nitric acid to separate out uranium and plutonium in a process known as reprocessing. Multiple waste streams are created by these physical and chemical processes, including high level liquid waste. High levels of radioactivity are also discharged into the atmosphere and the marine environment. Most fission product releases and plutonium releases from the UK and French nuclear programmes result from their respective reprocessing activities. It has been estimated that reprocessing alone accounts for about 80% of the radiation dose to the public (collective dose) of the French nuclear industry. In the UK it has been estimated that about 90% of nuclide emissions and discharges from the UK nuclear programme result from reprocessing activities.[21]

The reprocessing idea has been an environmental and financial disaster. In the UK, for instance, Dounreay, in the far North of Scotland, which was the site of the UK's fast reactor research centre, is now being decommissioned. Between 2030 and 2033 the site is expected to reach a so-called 'Interim End State'. This will cost £192m in the financial year 2018/19 alone. The total discounted cost for decommissioning Dounreay is expected to be £2.7bn.[22]

Reprocessing at Sellafield in North West England is ending. The Thermal Oxide Reprocessing Plant (THORP) which has been reprocessing oxide fuels from the UK's Advanced Gas-cooled Reactors and Light Water Reactors in Europe and Japan is due to close this year.

The reprocessing at THORP has been a commercial and industrial failure. At its opening in 1994, British Nuclear Fuels Ltd (BNFL) claimed that the £2.8 billion (US$4.7 billion) THORP had secured overseas contracts amounting to 5,334 tonnes of Light Water Reactor (LWR) spent fuel from utilities in Japan, Germany, Switzerland, Italy, Spain, Sweden, the Netherlands and Canada. The economic justification was bitterly contested by opponents in the run-up to its opening in 1994 when it was projected to generate some £9 billion (US$15 billion) for BNFL and "make a profit of at least £500M [US$840 million] during its first ten years of operation". The reality was a failure to complete overseas reprocessing contracts by 2003, eventually completed nearly ten years later in 2009; the cancellation of 20% of its orders, and a multiple plant failures and accidents.

The associated Sellafield MOX Plant failed to operate as planned due to design failures and was permanently shutdown in 2011.

The older Magnox Reprocessing Plant which reprocesses spent fuel from the UK's now closed older generation of reactors will close in 2020. Sellafield will cost £2bn in 2018/19 to run. Altogether the total cost for decommissioning Sellafield is expected to be £120bn.[23]

The UK Government National Audit Office's most recent report on Sellafield said the site's

"…*most hazardous facilities include four legacy ponds and silos that hold large quantities of nuclear materials, and the stores that house most of the UK's plutonium inventory. Sellafield Limited … that manages the day-to-day work on the site has put in place five long-term programmes to deal with these hazards. These programmes will take decades to complete, as they require the construction of new plants and the development of bespoke technologies to retrieve and handle waste. For example, the Magnox swarf storage silo, operational since 1964, contains waste sludge from legacy nuclear operations that is both radioactive and corrosive. The facility is expected to pose a significant hazard until 2050.*"[24]

One of the legacy ponds – the Magnox spent fuel storage pond – was described in 2015 as “*the most dangerous industrial building in Europe*”. The 150-metre-long open-air pond is visited by birds and cracks have caused radioactive material to leak into the soil. No one knows exactly what’s in there, but it may contain a tonne of plutonium.[25]

PLUTONIUM

The global stockpile of separated plutonium is about 520 tonnes, of which about 290 tonnes is material in civilian custody.[26] It takes perhaps 8kgs of reactor-grade plutonium to make a nuclear bomb.[27]

Country	Civilian Plutonium (tons)
Russia	57.2
US	7
UK	110.3
France	65.4
China	0.04
India	0.4
Japan & Others	49.3
Total	**290**

Source: http://fissilematerials.org

The UK has accumulated the largest stockpile of civil plutonium in the world. Once considered to be a valued asset this is now viewed as a costly liability and a target for terrorists. Estimates suggest that the taxpayer currently spends £80m a year to store it safely and stop it from falling into the wrong hands.[28] The Nuclear Decommissioning Authority (NDA) said in 2014 that its preferred option for dealing with this legacy is to reuse it in reactors, but

“…*we believe there is insufficient understanding of the options to confidently move into implementation*.”

Since then no further announcements have been made by the NDA or the UK Government. According to the NDA, it would take 40 years to use all of the reusable plutonium if there were five Light Water Reactors using 30% MOX (mixed plutonium oxide and uranium oxide) fuel the timeframe would change with a different number of reactors or different types of reactor or a different MOX proportion.[29]

The storage of spent MOX is much more complicated than normal spent fuel, and it has to be cooled for much longer – perhaps as long as 100 years.[30]

Japan has a stockpile of 47 tonnes of plutonium, and is facing international pressure to reduce it ahead of the expiry of a civil nuclear treaty with the US. The uncertainty is forcing the Government to rethink its decades-old strategy of achieving energy independence through the use of nuclear reactors and reprocessed fuel.[31] It says it will boost measures to curb surplus plutonium. Japan possesses about 10 tons of plutonium inside the country and 37 tons in Britain and France, the two countries contracted to reprocess spent nuclear fuel. The total amount is equivalent to about 6,000 bombs of the type that devastated Nagasaki in 1945. But the prospect for substantially curtailing the country’s plutonium stockpile is becoming increasingly murky. Japan has abandoned its prototype fast-breeder project at Monju. And of the nine reactors that have resumed operations following the introduction of more stringent safety standards after the Fukushima disaster in 2011, only four can use MOX fuel.[32]

Added to this the Japanese government persists in trying to start the Rokkasho reprocessing plant – now planned for the first half of 2021. Construction started in 1993. If the Rokkasho reprocessing plant begins operation, it will create a surplus of eight tons of plutonium every year.[33]

SPENT FUEL STORAGE

According to the IAEA less than a third of the world's spent fuel arisings have been reprocessed. The rest is stored pending a decision about a final resting place – some in wet storage ponds and some in dry stores.

After fuel is removed from a reactor core, the radioactive fission products continue to decay, generating heat. All nuclear power plants in the US store the fuel onsite at the bottom of deep pools for at least 4 years while it slowly cools. Most spent nuclear fuel in the US is stored in specially designed pools at individual reactor sites around the country.[34]

However, a fire from spent fuel stored at a U.S. nuclear power plant could have catastrophic consequences, which "*could dwarf the horrific consequences of the Fukushima accident*," according to Edwin Lyman, a physicist at the Union of Concerned Scientists. "*We're talking about trillion-dollar consequences*," says Frank von Hippel, a nuclear security expert at Princeton University, who teamed with Princeton's Michael Schoeppner on the modelling exercise.

At most U.S. nuclear plants, spent fuel is densely packed in pools, heightening the fire risk. Nuclear Regulatory Commission (NRC) has estimated that a major fire at the spent fuel pool at the Peach Bottom nuclear power plant in Pennsylvania would displace an estimated 3.46 million people from 31,000 square kilometers of contaminated land, an area larger than New Jersey. But Von Hippel and Schoeppner think that NRC has grossly underestimated the scale and societal costs of such a fire. Their model suggests that as many as 18.1 million people could require relocation.[35]

The NRC has considered whether to compel the nuclear industry to move most of the cooled spent fuel now held in densely packed pools to concrete containers called dry casks. Such a move would reduce the consequences and likelihood of a spent fuel pool fire. As recently as 2013, NRC concluded that the projected benefits do not justify the roughly $4 billion cost of a wholesale transfer. But the NRC has underplayed the risk of a spent fuel fire.

Even in France, where spent fuel is eventually transported to La Hague for reprocessing, initially it has to be cooled in pools. These spent-fuel pools are highly vulnerable to attacks according to a report published by Greenpeace. The pools have not been designed to withstand an attack. An attack which leads to a loss of cooling water could spark a spent-fuel fire which could contaminate areas as far as 250 kilometres away.[36]

Greenpeace illustrated the vulnerability of spent fuel ponds by crashing a Superman-shaped drone into EDF's Bugey nuclear plant, near Lyon in France. The drone was flown into the no-fly zone around the power station, and crashed into the wall of the plant's spent-fuel pool building.[37]

DECOMMISSIONING

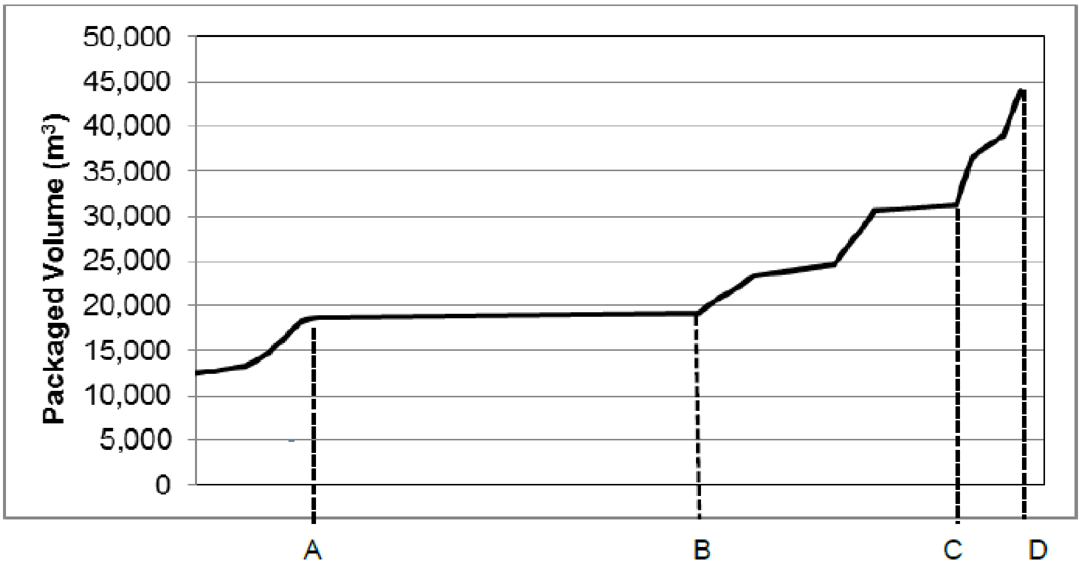
The oldest nuclear power plant in the United States, which opened in 1969, will shut down on 17th September 2018, but Oyster Creek New Jersey, will stay right where it is for the next 60 years. According to the Nuclear Regulatory Commission the plant's owner – Exelon - expects to remove the remaining spent fuel from storage pools and put it into dry storage within 5½ years of the shutdown date. All told, it will cost $1.4 billion to shut down the plant but Exelon currently only has $982.1 million of that set aside in a decommissioning account. Although the plant will stop producing electricity just before summer ends, radioactive material could be on site until the late 2070s, if not later. The reactor will be put it into so-called "safe store" condition until 2075 and dismantling should take place between 2075 and 2078. This will allow radioactivity levels time to decay.[38]

It's a similar story in the UK. Hunterston A, for instance is located on the coast 30 miles south west of Glasgow. The two Magnox reactors also opened in 1969 but ceased operations in 1989, after only 20 years of operation. The spent fuel has already been removed and transferred to Sellafield for reprocessing. Work is still ongoing to put the site into its care and maintenance phase. This involves developing some complex techniques to retrieve and package solid Intermediate Level Waste – mainly metal cladding stripped off spent fuel before it was despatched to Sellafield - stored in 5 bunkers.

This process will take around six years. The 5 bunkers contain around 2,200m^3 of solid waste. Another project - the Wet ILW Retrievals and Encapsulation Plant (WILWREP) is dealing with 180m^3 of sludge; 11m^3 resins and 141m^3 of contaminated acid. WILWREP is developing new robotic techniques. The two reactors will be clad in aluminium and by 2024 all the intermediate level waste will be placed in an above ground store. The site will then enter a period of care and maintenance for the next sixty years. Final decommissioning is not expected to start until after 2070.[39]

Currently most countries are planning a period of care and maintenance for old reactors to allow radioactivity to decay to reduce the radiation dose to the workforce before final decommissioning takes place. However, advances in robotics and concern about whether the necessary skills will be available in 50 years' time may change this.

A profile of how volumes of intermediate level waste are expected to arise over time in Scotland illustrates the long timescales involved. Around two thirds of this waste will not arise until final site clearance after 2070. The Scottish Government has a policy of refusing to allow the construction of new nuclear power stations.



A = around 2030. Operational and decommissioning waste continues to be produced until around 2030.
B = 2070 – 85 Decommissioning begins on Scotland's two oldest nuclear stations which stopped generating in 1989 and 2004.
C = 2115. Decommissioning begins of Scotland's two newest nuclear stations still operating today, which are expected to close in 2023 and 2030
D = 2120. All decommissioning expected to be completed by now. No further arisings of ILW.

Source : https://www2.gov.scot/Resource/0051/00511782.pdf

The UK built 26 Magnox reactors at 11 sites (including the two in Scotland) between 1956 and 1971. These are all now closed and the job of decommissioning them has fallen to a public body known as the Nuclear Decommissioning Authority (NDA). In 2014 the NDA awarded a 14-year contract to decommission these reactors (plus a site with two unique experimental reactors) to an international consortium - Cavendish Fluor Partnership. However, two US companies that lost out on the £6.2bn contract brought a legal challenge over the tender process, and in 2017 in an out of court settlement were awarded £97.3m. The NDA also spent £13.8m on legal and external advisers, while in-house staff time cost £10.8m – so the total cost to the taxpayer of the botched tendering process was £122m. Ministers have now terminated the contract with Cavendish Flour early, and will bring the decommissioning work back into public hands.

One of these Magnox stations (with two reactors) at Bradwell in Essex, just outside London, is now in the final stages of preparing the site for an 80 year period of care and maintenance. The power station stopped generating electricity in March 2002, after running for 40 years. So a baby born today in the maternity ward at Colchester Hospital could end up with grand-children or great grand-children who work on the job of final decommissioning and packaging the waste generated by dismantling the plant.

The European Commission estimates that Europe is facing a €253bn bill for nuclear waste management and plant decommissioning which outstrips available funds by €120bn. The sum breaks down into €123bn for the decommissioning of old reactors and €130bn for the management of spent fuel, radioactive waste and deep geological disposal processes.[40] France, which operates Europe's largest fleet of nuclear plants, is heavily underfunded. It has earmarked assets only worth €23bn, less than a third of €74.1bn in expected costs. In Germany, an extra €7.7bn is needed on top of the current €38bn.[41]

FUTURE STOCKS OF NUCLEAR WASTE

In 2003 the UK Government set up a new independent committee – the Committee on Radioactive Waste Management (CoRWM) to review options for managing radioactive waste and make recommendations. Three years later the Committee made a series of recommendations many of which the Government ignored. Although it recommended that geological disposal was the best available option for existing and committed waste arisings, it also said *"… the political and ethical issues raised by the creation of more wastes are quite different from those relating to committed – and therefore unavoidable –wastes".*

Later the Committee elaborated saying: *"To justify creating new spent fuel from an ethical point of view, there must be a management solution that is ethically sound, not just least bad. … In short, a solution that is ethically acceptable for dealing with existing spent fuel is not necessarily a solution that would be ethically acceptable for dealing with new or changed materials."*

In 2008 the UK Government launched yet another search for an underground site for a nuclear waste dump. The West Cumbria Managing Radioactive Waste Safely Partnership was set up by three municipalities in North-west England to look at the issues that would be involved in West Cumbria taking part in the search for somewhere to build a repository for higher activity radioactive waste. The Partnership's final report was published in 2012. Although Cumbria County Council rejected the Government's plans to undertake preliminary work on an underground radioactive waste dump at the beginning of 2013, the final report of the Partnership listed a set of principles about the nuclear waste inventory which show the importance of a community considering hosting a nuclear waste facility knowing the inventory of waste it is expected to house. Any *"changes to the inventory would be subject to an agreed inventory change process."*

The UK nuclear programme illustrates perfectly the need for communities considering playing host to nuclear waste stockpiles to have access to information about nuclear waste inventories.

The UK Nuclear Industry Association, for instance, claims that a *"new fleet of nuclear power stations would only add 10% to the volume of existing waste over their 60-year lifespan."* This implies the additional amount will not make a significant difference to finding a site for an underground dump for the wastes the UK's nuclear industry has already created. The use of volume as a measure of the impact of radioactive waste is, however, highly misleading. Volume is not the best measure to use to assess the likely impact of wastes and spent fuel from a new reactor programme, in terms of its management and disposal. The new reactors proposed for the UK, such as the EPR under construction at Hinkley Point C will use 'high burn-up fuel' which when spent will be much more radioactive than the spent fuel produced by existing reactors like Hinkley Point B. Rather than using volume as a yardstick the amount of radioactivity in the waste would be much more appropriate. This will affect, for instance, how much space will be required in a deep geological repository.

According to Radioactive Waste Management Ltd, the radioactivity from existing waste (i.e. not including new reactors) is expected to be 4,770,000 Terabecquerels (TBq) in the year 2200. The radioactivity of the spent fuel alone (not including other types of waste) generated by a 16GW programme of new reactors is expected to be around 19,000,000TBq. The amount of radioactivity in the spent fuel from Hinkley Point C alone in the year 2200 would be 3,800,000TBq – or about 80 % of the radioactivity in existing waste.

USING SCENARIOS TO ESTIMATE FUTURE STOCKPILES

With the aim of estimating the volumes of waste expected to be generated as a result of the operation of the current fleet of nuclear facilities, the Spanish submission to the 5th Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, developed a scenario which had the then current fleet of six nuclear power plants (eight reactors - 7.7 GWe) operating for a 40-year life.

Several other countries have done this too, either in submissions to the IAEA Convention or in other reports. The table below gives the information currently available.

	Assumptions	**Short-lived low and intermediate level waste**	**Long-lived low and intermediate level waste**	**High Level Waste incl spent fuel**
Belgium	7 reactors all closing between Oct 2022 and December 2025.[42] (From National report Oct 2017)	70,500 m^3	11,100 m^3 – 10,430 m^3	600m^3 – 4,500m^3 (depending on the future management of commercial spent fuel)
Canada (estimated 27th Nov 2015)[43]	Projected radwaste inventory 2050 forecasted as the end of operation for the last constructed power reactors - assumes that no new nuclear commissioned.	LLW 2,570,000m^3	ILW – 79,000m^3	21,300m^3 (104,000tHM projected Dec 2016) [44]
Finland[45]	Projected radwaste inventory incl OL3 & Fennovoima operating for 60yrs			8.300tHM
France[46]	Waste produced by all the facilities authorized at the end of 2013 until their end of life, including dismantling – two scenarios (1) 50yr reactor life; all Pu recycled. (2) 40yr reactor life; reprocessing ends 2019.	(1) 1,900,000 m^3 (2) 1,800,000m^3	(1) 252,000m^3 (2) 245,000m^3	Vitrified waste (1) 10,000m^3 (2) 3,900 m^3 (Under scenario 2 there would also be about 89,000m3 of packaged spent fuel and MoX)
Spain	8 reactors - 7.7 GWe) operating for a 40-year life. (Estimated Dec 2013)	181,091m^3 (incl VLLW)	855m^3	6,704m^3 spent fuel plus 12m^3HLW.
Sweden[47]	Remaining nuclear stations assumed to operate for 60 years until 2040-45	153,200m^3	16,400m^3	11,404tHM

	Assumptions	Short-lived low and intermediate level waste	Long-lived low and intermediate level waste	High Level Waste incl spent fuel
Switzerland[48]	5 plants 47yrs life - Mühleberg; 60yrs others. Results in around 4100 tons of spent fuel of which. 1140 tons reprocessed Packaged spent fuel assemblies and high-level waste will have a volume of around 9400m^3	L&ILW packaged – 81,760m^3 (incl industry and medicine)	Alpha toxic 1,072m^3	9400m^3
UK[49]	New build assumes a 16GW programme	11,800m^3 LLW	Legacy ILW 415,000m^3 New Build ILW 41,000m^3	9,290m^3 HLW and 14,800m^3 legacy spent fuel. 39,400m^3 new build spent fuel
US				140,000tHM HLW generated by defense activities 90 million gallons of high-level waste liquids, sludges, and solids[50]

CONCLUSION

Currently worldwide it can be estimated that there are nuclear waste stockpiles of:

2.4 billion tonnes of Uranium Mill Tailings:
1,188,200 tonnes (tU) of depleted Uranium: (in 1999 increasing at 60 000 tU annually), rising to an estimated 2 million tons as of 2020. Spent Fuel in only 14 countries 246,686 tHM; the IAEA estimates that around 370,000 tHM) of spent fuel has been produced since the advent of civil nuclear power production, of which 120,000 tHM has been reprocessed 373,313m3 of High Level Waste and a global stockpile of plutonium of 520 tonnes.

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2

BELGIUM

GEOLOGICAL DISPOSAL PROJECT — BELGIUM

Bertrand Thuillier

INTRODUCTION

Deep geological disposal of nuclear waste is an imminently complex issue due to the scientific, technical, ethical, political and sociological factors involved, as well as time-related ones, given the operational time of hundred years of a site as well as its closure for a period of hundreds of thousands of years at least during which time the waste is still dangerous.
This paper aims to shed light on the current state of the deep disposal project in Mol, in north-east Belgium, which involves using a layer of 'Boom' clay, and describes the project's three major components: a) the waste to be managed, b) the host rock, and c) the planned underground infrastructure.

This description will then be used to address how these factors combine and interact to influence both safety risks and consequences, and the migration of radioactive elements to upper aquifers. Lastly, a summary of risks and unknowns will be used to provide constructive insight on this complex issue.

DESCRIPTION OF THE DEEP DISPOSAL PROJECT IN MOL

NUCLEAR WASTE TO BE MANAGED

— VOLUMES

This project deals with two types of waste: Type B – intermediate-level waste, and Type C – high-level waste.

Due to Belgian legislation banning the construction and use of new commercial reactors (Law of 31 January 2003), and the closure of the seven existing ones after a 40-year period of activity[1], it is possible in this case (unlike in France) to establish a preliminary but relatively clear inventory of the volumes of waste which will need to be managed:

• 10,430–11,100 cubic metres of Type B waste (around 2% of total waste radioactivity) – It should be added, however, that part of the 85,000 cubic metres of unconditioned radium waste stored in Olen (Umicore 2011) could increase the volume significantly.3

• 4,500 cubic metres of Type C waste (around 98% of total waste radioactivity) — It should be noted that in these volumes we include spent fuel, which must now be classified as waste due to: the suspension of Belgium's nuclear programme (see above), Belgium's decision to no longer reprocess its waste in 1993[4] (a decision confirmed in 1998)[5], and, lastly, the European Directive of 19 July 2011 on nuclear waste and its consideration of spent fuel as 'waste'.[6]

— PROPERTIES

Depending on the Type (B or C) and category of the waste, four properties will play an important role in how the site evolves – particularly in an underground environment:

The presence of bitumen

Only Type B waste has this property[7]; 47% of this waste is contained in stainless steel drums in a bitumen matrix (16,600 drums of a total of 35,000 approximately). This coating method (containing 60% pure bitumen)[8] is no longer used; not only is bitumen highly flammable, **with 3,200 tonnes of pure bitumen presenting a fire risk, in the presence of salts and radiation (a dose rate ranging between 400 and 5,000 Gy/h), this matrix can expand to up to 70% its initial volume.**[9] This expansion is linked to the bubbles of hydrogen generated by the radiolysis of organic matter in the matrix.

Hydrogen production

The same Type B waste can also generate significant amounts of hydrogen and release radioactive gases such as tritium, krypton-85, carbon-14, and chlorine-36, as indicated in reports by Andra, France's national radioactive waste management agency.[10] In Andra reviews of these standard drums (Eurobitumen), it is noted that these can emit – per package and per year on average – 10L H2, **a total of 150 to 200 cubic metres of hydrogen per year**. Emission from certain packages, however, can be as high as 500L H2/drum/year[11] due to radiolysis in the presence of water and organic matter.

Decay heat

This characteristic concerns Type C wastes, which for the most part are made up of ZAGALS and UOX spent fuels (10,250 out of 11,000 of them, approximately)[12]; these packages, highly exothermic, are veritable small radiators. Their thermal power (in Watts per package) decreases over time, to 1,000–1,400 W after 20 years, and 400–600 W after 60 years. Attention must also be paid to the plutonium and americium content of these wastes, the thermal power of which decreases more slowly.[13] It can also be noted that MOX packages (144) listed in the Andra reports (CU2/MOX) retain a thermal power of 1,100 W after a storage period of 90 years after leaving the reactor.[14]

Fissile material

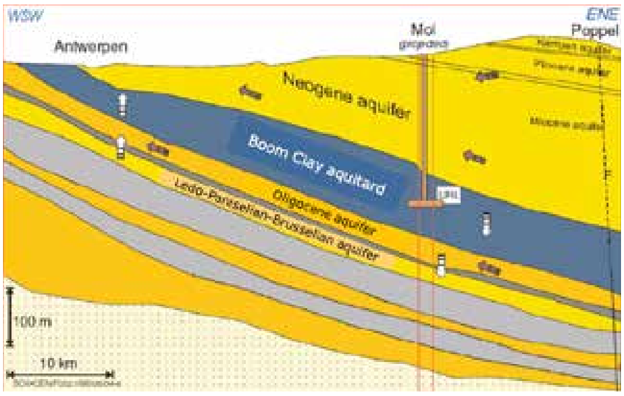
Also based on the descriptions in Andra reports, the mass of residual fissile material on leaving the reactor is approximately 10 kg, including four to five kg of uranium-235 and less than four kg of plutonium-239 per package of UOX spent fuel. This can be as much as 20 kg in mass, with nearly 12 kg of plutonium-239, also per package of spent fuel.[15] It is important to note that plutonium-239 has a critical mass of 510g. It is therefore essential that burn rates be taken into account when assembling packages to ensure that criticality – and nuclear chain reactions – are avoided.

HOST ROCK (BOOM CLAY)

— SITUATION

Boom clay is a sedimentary formation deposited approximately 30 million years ago, with a 1–2% dip to the north-east and about 100 metres thick, located between 190 to 290 metres below the surface of Mol-Dessel. Its thickness and depth grows closer to the border with the Netherlands.[16]

This impervious layer is therefore located just below a layer of Neogen sand, the second largest aquifer used for the abstraction of drinking water in Belgium, and the main one used in the country's north-east region (see Figure 45).[17]



— CHARACTERISTICS

Plasticity

This clay is a very plastic type of rock; it is not self-supporting (unlike granite, for example). To prevent retractions and landslides during its excavation, significant supports are required, including very large quantities of concrete and very large metal structures (e.g. hundreds of thousands of tonnes for the Cigéo Project in France — five times the volume of waste for burial).

Presence of water

Between 19% and 24% of the rock's weight is made up of water.[18] This is key for two reasons: firstly, such a level of saturation causes withdrawals and crevasses depending on the degree of desaturation in relation to ventilation in particular. Secondly, the presence of powerful radiation causes radiolysis, in which water molecules are broken down into two radicals: H+ and OH-, which will then re-combine haphazardly to form different molecules, such as hydrogen gas (H2), and hydrogen peroxide (H2O2) to form highly oxidizing and reductive compounds. These compounds will then heavily attack metals, which react by also producing hydrogen gas (H2) during this intense corrosion process in the metallic structures.

Temperatur

Two temperature-related restrictions must be respected: one, the rock must never reach a temperature exceeding 90°C / 100°C due to the obvious risks of structural change and permeability (water vapour and cooking), and two, the temperature limit for sands and clays is currently established at 14–15°C; a 10-degree increase would severely damage the quality of drinking water (a regulatory limit is set at 25°C to prevent the development of legionella bacteria.[19]

STORAGE INFRASTRUCTURE

— DESIGN

Facilities will be located at a depth of around 240 metres and have three access and ventilation shafts six metres in diameter, including a central well specifically dedicated to lowering down packages. These shafts, which pass through the sand aquifers mentioned above, must remain waterproof for the entire period during which the site is filled and sealed.
Underground, the shafts are connected by a central access tunnel to the storage galleries (see Figure 14).[20]

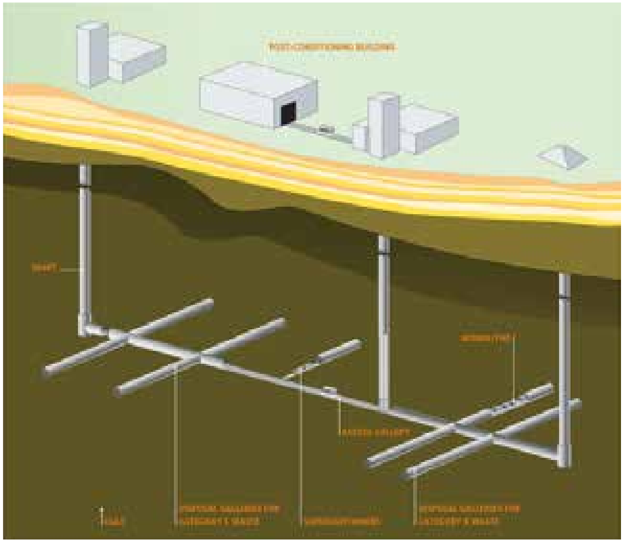


Figure 14 — Indicative diagram of the geological repository envisaged for B&C waste and of the surface facilities for the production of supercontainers and monoliths B. The waste shaft has a central position.

This access tunnel is a rectilinear single-pipe system approximately six metres in diameter and one kilometre long. The storage galleries, three metres in diameter and no more than one kilometre in length, are connected perpendicularly to the central tunnel and spaced 50–20 metres apart. Concrete flooring and rails are planned, on which packages will be transported in super-containers. The ends of the storage galleries opposite the central tunnel are closed off.[21] The cumulative total length of these galleries is around 30 kilometres over a total area of 3.1 square kilometres. Once completed, they will be used to store the super-containers, built above ground. See figure 14 for the diagram of this repository [22].

Assembled super-containers contain waste packages 2.1 metres in diameter and 4 – 6.2 metres long; the mass of the largest ones can reach 70 tonnes.

• Type B super-containers are made up of primary packages (of 1 to 12 packages or drums) suspended in concrete (Figure 13).[22]

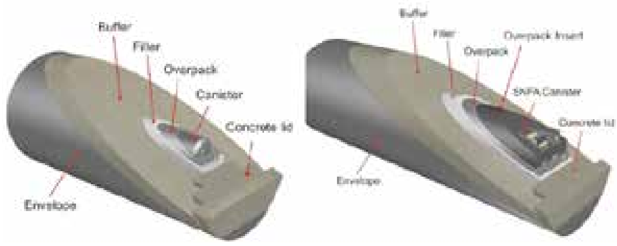


Figure 11 — Supercontainer for vitrifed high-level-waste (left) and UOX irradiated fuel (right)

• Type C super-containers contain one to for primary packages (one MOX package, two vitrified packages, or four UOX packages) inserted into a 30-millimetre stainless steel shell which is then coated in bentonite clay, one layer of concrete, and a second steel shell (see Figure 11).[23]

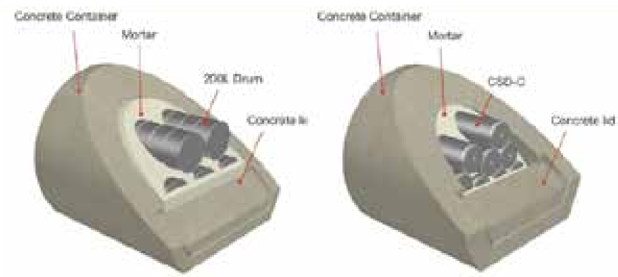


Figure 13 — Monolith B for category B waste (200 L drums) (left) and CSD-C (right)

The above described design does not provide for the removal of these super-containers, which are non-recoverable: the galleries are sealed once they are filled.

— OBSERVATIONS

This approach involves the introduction of four foreign elements into an underground environment: concrete, steel, ventilation air, and – in the event of a loss of water-tightness in a shaft – water, which will have to be removed during the operational phase of the site.

Water-tightness:

This is a complex problem linked to the presence of sand aquifers, resulting in the need for a double concrete structure with an inserted hermetic layer of polyethylene reinforced with asphalt and steel in the second shaft of the HADES laboratory (located 225 metres below ground and established in 1980 for the purpose of studying deep disposal in this clay environment). Asphalt leaks have already been observed in the second shaft and frequent re-injections of the impermeable polyethylene are needed to preserve water-tightness.[24] Without a recovery pumping system, such a breach could lead to the complete flooding of the site with water if the underground sections weren't drained due to the permeability of the clay.

Handling:

Barring design changes, it appears that the planned diameter of the access shaft for packages is incompatible with the diameter and length of the super-containers and precludes direct, horizontal loading on down-hole conveyors. As a result, it is essential that there be a sufficiently large down-hole receiving chamber to handle directional changes made difficult by the mass involved (70 tonnes). Likewise, it is unclear how right-angle turns (to access storage galleries) will be made on these rail-mounted conveyors without the presence of platforms and, therefore, additional large chambers for each intersection.[25]

Safety:

Albeit without the most recent project diagrams, it is surprising to note a single-, rather than a double-pipe system in the galleries: in the event of a fire or landslide, an escape route is vital. Examples include underground highway tunnels, the Channel Tunnel, and design changes in Cigéo project.

Criticality:

It is also surprising that Type C high-level and spent fuel packages are lowered down through a shaft; if a package were to fall in a shaft, the reconfiguration of assembled packages could lead to a criticality event. It is noteworthy that this method of lowering packages down a shaft has been abandoned in the case of the Cigéo project for the same reason, in favour of a way shaft, or winze, system.

Co-activity:

Not being specified, it is difficult to imagine how construction and storage activities will be co-managed in areas that are not physically separated. It will be necessary to manage the co-existence of dust extraction, exhaust from equipment used to dig and convey debris (an estimated 1 to 2 million cubic metres), engine oil storage areas, battery charging stations, hydrogen and radioactive gases (in limited, but nonetheless definite quantities).

Ventilation:

There is no doubt – particularly during the co-activity phase (see paragraph above) – that powerful ventilation will be needed; as an example, Cigéo project plans call for between 500 and 650 cubic metres per second in a ventilation shaft that is 11 metres in diameter.[26] It is also difficult to understand how appropriate ventilation (exhaust versus extraction) can be installed without differentiating between the three planned shafts, and without separate conduits at the gallery level. No mention appears to be made of the presence of non-return valves or smoke management protocols in the event of a fire. It is also unclear how the necessary task of air renewal is ensured (in order not to reach the Lower Explosive Limit of 4%) in the closed-off galleries, or how HEPA (high-efficiency particulate air) filters could be effective and feasible in such an environment in the event of a nuclear accident.

INTERACTIONS BETWEEN ELEMENTS AND ASSOCIATED RISKS

— TEMPERATURE AND INCREASES IN PERMEABILITY

If storage of Type C waste were to begin after a period of 60 years, the thermal power of the super-containers could reach levels far exceeding 1,000 W (4 x 500 or even 1,110 W); the Praclay experiment[27] has demonstrated that 350 to 450 W/m of thermal power is enough to make temperatures in the rock reach 80°C. Beyond this threshold, mineralogical transformations will definitely lead to **structural changes in permeability.** The same experiment showed that these temperature impacts increased steadily over the period of the experiment (42 months) and affected areas up to 15 metres away from heat sources.[28]

— VENTILATION (DESATURATION) AND RISKS OF COLLAPSE

A 2011 study on the impact of gas transfers on the pro-mechanical properties of clay materials[29] confirmed not only that the permeability of clay to gases depends heavily on its degree of saturation[30]; in the presence of powerful ventilation, combined with large amounts of heat, significant wall evaporation can even lead to fracturing and significant damage to the rock. Links can even be made to observations of crevasses in clay soil generated by water evaporation. This evaporation creates preferential flow paths[31] and the potential migration of radioactive elements; it could also go as far as to create serious fissures and cracks in the massif [32] (see Figures 5-14), with changes in density of as much as 8 to 11%[33], and as a result create a risk of instability in the infrastructure.

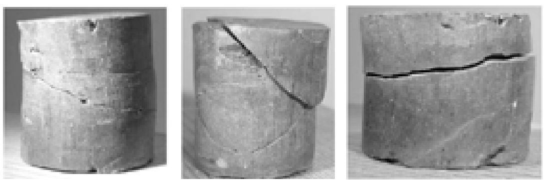


Figure 5-14: Macroscopic observations of cracks on boom clay samples under desaturation

— OFF-GAS (HYDROGEN) AND FRACTURING OF THE ROCK

Concerning Type B, bitumen matrix-sealed waste, the insertion of these packages into concrete, leaving only 20% of the space unfilled[34] in order to handle swelling of up to 70% (as mentioned above), will eventually lead to the bursting of the super-containers (as pressure can reach 43 MPa under strain35) and the release of this concrete, which can result in pressure-induced rock deformation. It should be noted that the pressure threshold equivalent to an initial fracture in Boom clay begins under very low amounts of pressure (0.9 to 2.9 MPa)[35], which can of course lead to preferential flow paths, as seen above.

— DESIGN (SHAFTS AND CLOSED-OFF GALLERIES) AND THE RISK OF EXPLOSION

The principal risk of nuclear explosion lies in the lowering down of packages (of spent fuel) via a shaft; the 2005 Andra reports clearly mention, in relation to the way-shaft project: “Events likely to induce a risk of criticality correspond to the combination of significant accidental damage to a spent fuel package caused by dropping it, and the sudden presence of water”.[36]

The second risk lies in the fact that any space in which hydrogen may be present must imperatively be ventilated to prevent an explosion: it should be noted that such an explosion can occur when hydrogen levels reach 4%, and one cubic metre of hydrogen is equal to the explosive power of approximately 2 kg of TNT. In view of this, it is quite difficult to see how such long galleries, nearly one kilometre in length, can be ventilated if they are closed off at one end, without any air ventilation during the time the site is in use.

SUMMARY

— DIGGING ZONES (FRACTURING) AND RADIOACTIVE ELEMENT MIGRATION

The mechanical constraints of digging in a plastic rock such as clay create what is called an excavation damaged zone, or EDZ, which can grow to around 2.1 times the radius of the space depending on the digging method used[37]; this zone is particularly sensitive, given that galleries are six metres across (useful surface area) and require digging at least eight metres down to insert supports. This results in 4–5 times greater[38] permeability in a space about 16 cubic metres in size, for a resulting **blank layer only 40 metres from the aquifers.**

— PERIOD OF OPERATION AND FIRE RISKS

As mentioned above, clay is very sensitive to increases in temperature. This means that a fire underground, which produces an 'oven' effect and dissipated heat, very quickly causes an increase in temperature. One possible outcome is the ignition of a conveyor following a maintenance problem (oil, diesel, battery), as occurred at the Waste Isolation Pilot Plant (WIPP), a storage site in the U.S.; another is a chemical reaction between components (examples include an explosion, also at WIPP, and the Stocamine fire). These examples show that the thinness of the layer would allow no drift or landslide associated with this type of incident.

PROJECT STRUCTURE

It is clear that the very structure of the project still presents inherent, significant and multiple risks. Essential among these are:
• the choice of a clay matrix for deep disposal, a rock that is saturated in water and not self-supporting,
• the depth of the site, too close to the surface and a few dozen metres from important drinking water sources that are already in use,
• the insufficient thickness of the layer, which furthermore dips (by a small percentage, equivalent to a 40 metre drift for a 2% dip over 2 kilometers). Infrastructure of this kind could require a strictly horizontal design for reasons of traffic and branching.

Also noteworthy are the many operational risks associated with co-activity and significant disturbances from powerful ventilation nearby residential areas.

We must also not forget the lengthy period of time involved with this type of site; what state will this infrastructure be in after a century, in terms of shaft water-tightness? How can maintenance be carried out in galleries which may have collapsed? How will the waste evolve? A perfect example is the appearance of gel on certain drums in 2014, or imperative stability issues in these drums over time[39].

PROJECT COSTS

Project costs have clearly fluctuated, due to uncertainties surrounding inventories (related to re-processing or otherwise), due to as-of-yet unprocessed waste (at Olin), and, above all, due to design and structural issues concerning the site. Total costs, including a margin for unplanned events, were estimated at 3 billion euro in 2011 (!)[40], and now stand at 8 to 10 billion euros[41].

INSIGHT

Given these well-identified risks and remaining uncertainties inherent to the complexity of phenomena and their occurrence over a long period of time, the immediate and imposed choice between a medium-term solution (long-term storage) and a definitive long-term one (deep disposal) for waste management does not seem appropriate. In order to not leave this burden to future generations, and in light of waste dumped overboard in the sea due to a lack of knowledge on the part of the generation before us, it might be better to choose a solution combining both options.

THIS INVOLVES:

1.
Safely storing waste in long-term storage facilities for at least 100 years to allow the thermal power of packages to decrease, along with degassing, but also

2.
Providing future generations with two endowments, allowing them to solve the issue of this waste in an informed manner;

3.
Ensuring sufficient funding during this period (based on a more definitive cost assessment), and

4.
Acquiring, by way of long-term and representative testing of properties of underground storage based on different matrixes, all the data needed to choose a definitive, long-term solution in a well thought-out manner.

1 ONDRAF/NIRAS Research, Development and Demonstration (RD&D) Plan 2012 (NIROND TR 2013-12E), page 59

2 NIROND TR 2013-12E, page 60 (in French)

3 NIROND TR 2013-12E, page 66 (in French)

4 Chamber of Representatives Resolution 541/9-91/92 on the use of fuels containing plutonium and uranium in Belgian nuclear plants and on the advantages of reprocessing fuel rods, adopted on 22 December 1993

5 ONDRAF Plan déchets, septembre 2011 (NIROND 2011-02 F), page 24 (in French)

7 NIROND-TR 2013-12 E, page 350 (in French)

8 NIROND-TR 2013-12 E, page 190 (in French)

9 Thesis of M. Mouazen, 2011 – Evolution des propriétés rhéologiques des enrobés bitume, page 179 (in French)

10 ANDRA – Dossier Argile 2009, concepts d'entreposage, page 282 (report on clay, section on waste management concepts, in French).

11 ANDRA – Dossier Argile 2005, Architecture du stockage, page 456 (Idem, section on storage architecture, in French)

12 NIROND-TR 2013-12 E, page 350 (in French)

13 ANDRA – Dossier Argile 2005, Evaluation faisabilité, page 47 (feasibility assessment, in French)

14 ANDRA – Dossier Argile 2005, Architecture du stockage, page 146 (Idem, section on storage architecture, in French)

15 ANDRA – Dossier Argile 2005, Architecture du stockage, page 144 (Idem, section on storage architecture, in French)

16 NIROND 2011-02 F, page 140 (in French)

17 NIROND 2011-02 F, page 140 - NIROND TR 2013-12 E, page 135

18 NIROND-TR 2013-12 E, page 89 (in French)

19 NIROND-TR 2013-12 E, page 253 (in French)

20 NIROND TR 2013-12 E, pages 69 and 76

21 NIROND TR 2013-12 E, page 69

22. NIROND TR 2013-12 E, page 71

23 NIROND TR 2013-12 E, page 74

24 Id.24 NIROND TR 2013-12 E, page 212

25 NIROND TR 2013-12 E, page 221

26 ANDRA – Dossier Argile 2005, Architecture, page 281 (Idem, section on architecture, in French)

27 The Praclay heater test, EURIDICE Report, 2017, page 24

28 The Praclay heater test, EURIDICE Report, 2017, page 33

29 Thesis of Pierre Gérard, Impact des transferts de gaz sur le comportement poro-mécanique des matériaux argileux, May 2011 (TPG) (in French)

30 TPG, page 26

31 TPG, page 56

32 TPG, page 137

33 TPG, page 141

34 NIROND TR 2013-12 E, page 169

35 TPG, page 58

36 ANDRA – Dossier Argile 2005, Evaluation de la faisabilité, page 30 (feasibility assessment, in French)

37 TPG, page 170

38 ANDRA – Dossier Argile 2005, Evolutions phénoménologiques du stockage, page 352 (Phenomenological changes and storage, in French)

39 ONDRAF – 26/09/2014 Press release

40 NIROND TR 2013-12 E, page 133

41 Les échos.be – Des milliards supplémentaires pour stocker les déchets nucléaires – 22 August 2018 (in French).

3

FRANCE

HIGH-LEVEL NUCLEAR WASTE STORAGE IN FRANCE

Bernard Laponche

SPENT FUEL AND RADIOACTIVE WASTE

SPENT FUEL PROCESSING

After it is used in a nuclear reactor (for approximately three to four years), spent fuel is stored underwater, in 'pools' located near the reactors. They are continually cooled with circulating water to eliminate heat produced by the radioactive fission material and transuranic elements (primarily plutonium) they contain.
The solution adopted in most countries where nuclear plants are in operation (e.g. the United States, Germany, Sweden, Japan, South Korea) is to keep spent fuel, as is, in storage pools, and in some cases, after a few years, in dry storage facilities, when radioactivity and heat levels have dropped. In France (at La Hague) and the United Kingdom (Sellafield) however, plutonium is extracted from spent fuel at what is called a "re-processing facility". Here, spent fuel is transferred from the reactor pools to pools in La Hague for the plutonium to be removed.[1]
Reprocessing involves extracting uranium and plutonium from spent fuel using chemical methods. Fission products and transuranic elements other than plutonium, also called "minor actinides", are kept together, as is, in liquid form[2]. Historically, this technique was developed during the Second World War for the production of military-purposed plutonium. Production of plutonium later continued and expanded to supply fuel to the 'breeder' reactor sector: Phénix and Superphénix in France, are now indefinitely closed.

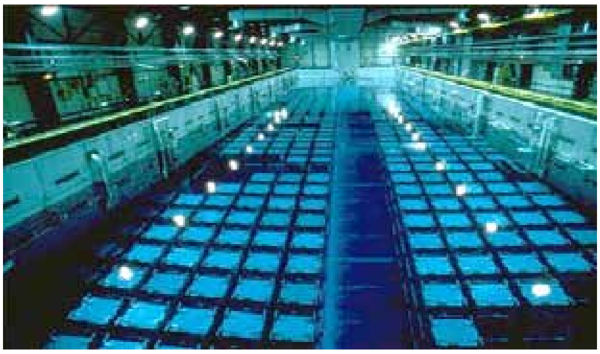


Figure 1 – Main spent fuel pool in La Hague

To replace this method, a new fuel was designed as a substitute for traditional, uranium-enriched fuel in water reactors. Known as MOX[3] (mixed uranium and plutonium oxide), it contains uranium that is depleted in uranium 235 and 7–9% plutonium.
Spent MOX fuels are not re-processed. As such, in France, re-processing only reduces around 15% of the plutonium produced in currently used reactors, some of which is 'stocked' at La Hague[4]. Fission products and minor actinides are kept in liquid form in tanks which require continual cooling and shaking to prevent matter from becoming concentrated.
The last step involves manufacturing glass blocks out of fission product and minor actinide solutions which are placed in dry storage at La Hague in silos. These facilities are constantly cooled due to the radioactivity emitted by the glass and can only be moved after several decades (at least 60 years).

This system leads to an accumulation of very different types of waste. Clearly, the real goal of re-processing is not to correctly manage waste but to produce plutonium (the La Hague plants are named UP2 and UP3, for "usine plutonium" or "plutonium plant").

Figure 2 – Vitrified high-level metallic waste container

RADIOACTIVE WASTE IN FRANCE

— WASTE MANAGEMENT

The French national radioactive waste management agency (ANDRA) is a public body under the authority of the French energy, environment and research ministries, tasked with managing the waste produced by nuclear activities in French territory.

Created in 1979 as part of the French Atomic Energy Commission (CEA), the ANDRA became independent with the Bataille Act of 1991. It carries out several missions. It takes inventory of, and collects radioactive waste generated by nuclear plants for energy production, and also by research institutes, the defence sector, and hospitals. It is also tasked with finding solutions to manage and store 'ultimate waste', which cannot be processed with existing technology.

ANDRA operates three storage sites (in Soulaines, Morvilliers and La Manche), as well as an underground research laboratory located in the towns of Bure (in the Meuse region) and Saudron (Haute-Marne).

— CHARACTERISTICS OF RADIOACTIVE WASTE

Different types of waste are divided into categories primarily based on their life cycle and level of radioactivity. Based on this criteria, the following classification system is used in France:

• D- life span: 100 days and 31 years (very short lived: less than 100 days; short life: between 100 days and 31 years; long-lived: over 31 years);

• Four levels of radioactivity: very low-level (VLL: less than10^2 Bq/g) ; low level (LL: between 10^2 and 10^5 Bq/g); intermediate level (IL: between 10^5 and 10^8 Bq/g); high-level (HL: over 10^8 Bq/g).

These two criteria are combined to define waste categories:

• VLL: very low-level, including: VLL-SL: very low-level, short-lived; VLL-LL very low-level, long-lived.
• LIL-SL: low and intermediate-level, short-lived
• LL-LL: low-level, long-lived
• IL-LL: intermediate-level, long-lived
• HL: High-level.

Table 1 – Total volume and content of radioactive waste by economic sector and management sector in 2013[5]

**'Non-sector' category waste does not fit into any existing or currently planned categories, notably due to the waste's chemical and physical properties. Studies on the subject of this waste are under way.*

These volumes correspond to conditioned waste that is placed in "primary" packages for storage and transportation to storage centres.

In some specific cases, such as sub-surface dry storage or deep disposal, additional preparation is needed before the waste can be stored.

The table shows that high-level waste comes nearly exclusively from the electronuclear sector – in other words, spent fuel. France currently has an operating nuclear fleet of 58 enriched uranium and pressurised water reactors producing between 900 to 1,450 MW in electrical power, spread over 19 nuclear plants.

cubic metres	Electronuclear	Research	Defence	Industry	Medical	TOTAL	%	Elec./Total
HL	2,700	190	230			3,120	0.22	0.865
IL-LL	26,000	10,000	6,200	170		42,370	2.93	0.614
LL- LL:	42,000	20,000	17,000	12,000	2	91,002	6.3	0.462
LIL-SL	580,000	200,000	61,000	22,000	8,500	871,500	60.32	0.666
VLL	220,000	160,000	42,000	11,000	3	433,003	29.97	0.508
Non-sector	2,400	740	650	4	1	3,795	0.26	0.632
TOTAL	873,100	390,930	127,080	45,174	8,506	1,444,790	100	0.604
Percentage (%)	60.4	27.1	8.8	3.1	0.6	100		

Source: ANDRA, inventaire 2015 (in French).

— RADIOACTIVE WASTE BY RADIOLOGICAL CONTENT IN 2013

The becquerel (Bq) is a unit of activity to measure the number of disintegration per second in radioactive materials. The Tera-becquerel (TBq) – 10^{12} Bq or one thousand billion Bq.

Radioactivity is detected by the emission of radiation:

• particle emissions: 'alpha' (helium core), 'beta' (electron), or neutrons.

• photon emissions: 'gamma' or 'X' radiation.

HL waste, primarily produced by the electronuclear industry, represents 98% of total waste radioactivity.

Table 2 – Total activity, by type of emission, as at 31 December 2013

Unit: TBq	Alpha	Beta and Gamma Short-lived	Beta and Gamma Long-lived	Total Radioactivity
HL	3,500,000	210,000,000	350,000	220,000,000
IL-LL	44,000	4,300,000	1,100,000	5,500,000
LIL-LL	720	16,000	2,800	19,000
LIL-SL	910	27,000	8,300	36,000
VLL	3	4	1	8

Source: ANDRA

THE CIGEO PROJECT FOR DEEP GEOLOGICAL DISPOSAL

DEEP GEOLOGICAL DISPOSAL

Deep geological disposal of nuclear waste, in addition to surface-level storage, is viewed as a solution in many countries, in particular for high- and intermediate-level long-lived waste. It consists in processing this waste and storing it in a geologically stable repository in which natural and artificial barriers are created between the waste and the surrounding environment. This method is based on the theory that waste can be stored long enough to ensure radioactive decay (up to one million years).

Different host rock formations are currently under study or used around the world: tuf, granite, salt, clay, etc. The behaviour of these different materials in relation to storage constraints (temperature and the presence of water, in particular) determines the type of barrier required. Following legislation to explore the feasibility of deep storage in a granite or clay site, the French authorities abandoned the idea of granite – rejected by the public – and research focused on clay, with the construction, in 2011 in Bure – a sparsely populated and relatively poor area at the edge of the regions of Ardenne and Champagne – of a research lab operated by ANDRA, the French national radioactive waste management agency.

From this research was developed the CIGEO Project (for 'industrial centre for geological storage'), which was submitted to two public debates: the first one on the overall problem of radioactive waste management (2005) and the second on the CIGEO Project itself (2013). These debates, which highlighted the numerous safety issues connected to the operating phase (the hundred years or so during which the waste is stored), raised the question of whether this was the best storage method possible, and voiced a desire to explore alternative solutions.

RADIOACTIVE WASTE TO BE STORED

The reference scenario for sizing the project is the continuation of electronuclear production with existing reactors operating for another 50 years. Waste produced by any future reactor fleets is not taken into account.

Two types of waste will be stored at CIGEO:

- "High-level, long-lived" (HLLL) waste: around 10,000 cubic metres (non-conditioned volume) and approximately 30,000 cubic metres of conditioned waste for deep deposit (60,000 packages).
- "Medium-level, long-lived" (MLLL) waste: around 70,000 cubic metres (non-conditioned volume) and approximately 350,000 cubic metres of conditioned packages for 180,000 packages, including 75,000 asphalt packages.

It should be noted that these figures do not include waste products classified as "nuclear materials", which should eventually be classified as waste and which, in the case of high- or intermediate-level, long-lived waste, involves processing similar to that currently planned within the CIGEO Project. One example is spent fuel, not destined for processing (including spent MOX fuels). Similarly, neither have provisions been made for the plutonium currently stored at La Hague.

THE CIGEO PROJECT

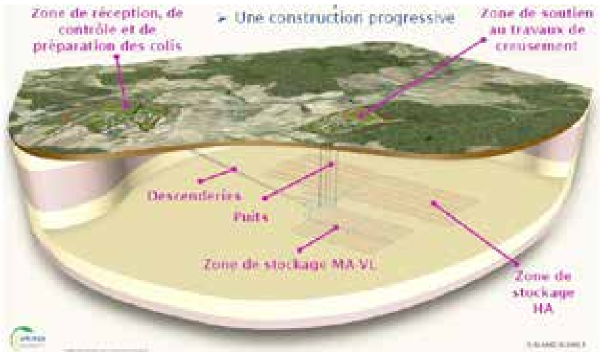


Figure 3 – The CIGEO Storage Project

— PROJECT LOCATION

Radioactive waste will be stored in a layer of Callo-Oxfordian clay around 130 metres thick, about 500 metres deep, in the town of Bure, in the Meuse region. Construction of the storage site involves digging four access shafts and around 265 km of underground passages for the way-shaft system, cells and galleries, and a total underground surface of around 15 square-kilometres. As a result, the structure calls for the removal of 7–8 million cubic metres of rock, the insertion of several hundred thousands tonnes of steel, and the production of 275,000 cubic metres of concrete to built the site's supporting elements.

— PROJECT STRUCTURE

CIGEO will be composed of an underground structure in which radioactive waste packages will be stored. During the operating phase (construction + filling with waste), two different – above-ground – sites will be operational for the reception, inspection and preparation of waste packages prior to their transfer to the underground repository (building the way-shaft area), and to ensure the logistics of underground work (building the shaft areas). The underground structure will be expanded upon as the operating phase progresses. After one hundred years in operation, the total surface area of the structure will be around 15 square-kilometres.

Two types of cells exist for waste to be stored:

• **'HLLL cells'** (approximately 1,500), connected horizontally by access shafts, are composed of jointed, seamless steel pipes of about 100 m in length and around 70 cm in diameter, used to push the HLLL packages to the end of the cells for storage.

• **'ILLL' cells** (approximately 50), 9 metres in diameter (excavated 65 square-metre section) 375 to 525 metres in length, ventilated with air from the connecting galleries; these tunnels, equipped with rail-mounted maintenance equipment, will be used to store different concrete coated, parallelepipedal-shaped waste packages.

In order to optimise the space underground, it was decided that these cells would not be equipped with an anti-radiation barrier, and will therefore emit radiation.

— THE COST OF CIGEO

The final radioactive waste generated by the electronuclear sector comes from several sources: the operation of nuclear facilities, their dismantlement, and the recovery and processing of older waste and spent fuel, be it reprocessed or not.

It's highly complicated to assess the total cost of waste management, particularly since it increases over the time. According to the Court of Auditors, in 2013, the total gross costs for long-term waste management was €32 billion (of which €26 billion to be financed by EDF (81%). This number does not include costs of spent fuel management which was estimated at €16 billion by EDF on 31 December 2013. Lastly, regarding the cost of the Cigeo project for the deep geological disposal of high-level and medium-level waste: in 2015, ANDRA estimated that the project would cost €35 billion. But in 2016, a governmental decree decided it would cost €25 billion.

RISKS

The French Nuclear Safety Authority (ASN) issued an opinion on the safety options file (DOS) submitted by ANDRA for the CIGEO Project[6]. This opinion was based on an assessment by the IRSN (*Institut de radioprotection et de sûreté nucléaire*)[7] and an international review of ANDRA's "Safety Options File", carried out by regulators of different nationalities (an "international review team") at the request of the ASN and organised by the IAEA[8]. Negative feedback in these different reports confirm the findings of independent experts and in particular those of Bertrand Thuillier[9], upon whose analysis the following elements are based. Of particular note, workers involved in the construction and operating phase of the site are likely to be exposed to considerable risk resulting from a combination of construction-related risks, underground operational risks, and risk related to the radioactivity of waste packages to be stored.

EXPLOSION-RELATED RISKS

A risk of explosion exists due to the uninterrupted production of hydrogen. If the concentration of this gas exceeds 4% in any area that is not correctly ventilated (cells, galleries, hoods, packages), the slightest spark, from a faulty or leaky battery, broken lighting, oil on an overheated engine, friction, or even inspection and monitoring systems themselves, can cause an explosion. ANDRA design files show that these risks are significant, especially in ILLL cells with the radiolysis of organic matter in certain packages. Ventilation is therefore key, and cannot be interrupted for more than 10 days or so.

Is it possible, however, to imagine that such an interruption – lasting weeks – would never occur in any of the storage areas in the wake of a landslide, flooding or even a minor electrical problem?

In a project that involves so many vehicles, handling machines, lighting equipment and radio control systems, how can a small but fatal spark be avoided in non-ventilated areas where hydrogen is ever present and may accumulate at any moment?

Packages would be considerably damaged, and the ANDRA admits that *"an explosion could lead to a loss of confinement"*[10]. A loss in confinement, of course, would mean the potential release of radionuclides into the repository.

The report also says that *"potential consequences of an explosion may include worker injuries and damage to, or destruction of, material and equipment – in particular damage to a confinement or anti-radiation barrier, leading to a risk of external leaks and/or exposure"*[11].

IRSN recommendations are more specific; they point out that *"ANDRA must assess the consequences of an explosion and, if required, submit information regarding planned measures for monitoring, prevention, damage control and/or interventions".*

FIRE-RELATED RISKS

The most serious risk is that of a fire, given the co-existence in ILLL cells of hydrogen, flammable packages (around 10,000 tonnes of pure bitumen in total, with 100 – 500 tonnes per cell) and the powerful ventilation (hundreds of cubic metres/second in total in storage areas) needed to evacuate said hydrogen as well as radioactive gases.

Controlling a fire in this type of underground environment would be particularly difficult to manage, due to:

• Firstly, the time it takes to detect the fire (the underground structure is spread over 265 km),

• the challenges faced by firefighters needing to enter the area (radiation-emitting cells and anti-radiation equipment that is very heavy and uncomfortable),

• the intricate management of powerful ventilation systems (necessary, gradual stopping, but also blocking of filters; the presence of check valves but also the need to extract smoke), and

• the need to limit the use of water in an underground, clay environment and due to the potential criticality of certain packages (mirror effect with neutrons).

The IRSN has demonstrated that this storage weakness is real and that a risk exists for a full-blown blaze in a storage cell; simulation studies carried out by the institute show that a heat wave from a fire started in one package can spread to a target package in a matter of hours.

It is therefore difficult to imagine that it would be possible, in just a few hours and in a series of galleries and/or cells spread over a hundred kilometres, to detect and contain a fire outbreak, evacuate staff, bring in emergency teams, stop the ventilation system and bring the fire under control without damage to the infrastructure. Here too, the IRSN finds that *"planned detection and extinction measures are insufficient in the active part of ILLL cells to the extent that they cannot guarantee that a fire would be brought under control within one hour in the event of a system failure."*

POTENTIAL FOR OPERATIONAL SHUTDOWN

It would be impossible for 'normal' operations to resume after such an accident. By design, CIGEO cannot operate with contaminated cells or galleries due to the need for ventilation; following an incident, the contamination would be directly pumped into the environment. This too was highlighted by the IRSN, which "regrets that ANDRA has not considered, at the safety options file (DOS) stage, any special measures for the resumption of activity at the site after an accident," that ANDRA "does not demonstrate that intervention would be possible in the event of a breakdown. ". As a result, it is clear that the principle of reversibility could not be applied in this case: it would be impossible to continue operations, and, of course, impossible to recover damaged packages.
Understandably, ANDRA technicians admit that a problem exists concerning repair and the presence of hydrogen: "Estimates are needed of the time required for a major intervention in a hard-to-access and confined environment in various scenarios, in order to assess the feasibility of controlling a risk of explosion".

RISK OF WATER FLOW IN THE ROCK

The issue of water flow in the rock was a key issue in the ERI review of the ASN opinion. We have noted the following elements:

Except from observation No. 12:

"While the ANDRA has argued, following a detailed study of the site, that the likelihood of the appearance of inconsistencies contributing to the flow of water (fissures, for example) in the ZIRA (zone of interest for deepened investigation) is negligible, the ERI review recommends that ANDRA take into consideration fissuring in the 'Cox' rock (from 'Callovo-Oxfordian' – the exact term for the mudstone found in the geological layer chosen for the deep deposit of waste) in the context of the identified scenarios".

"Calculating the scope of the spatial and hydraulic characteristics of inconsistencies which favour water flow would allow the ANDRA to illustrate: the elevated location of the Cox rock, which contributes significantly to the overall robustness of the storage system in the post-closure phase; the impact, in terms of safety, of these inconsistencies in the Cox rock in the ZIRA, which would make it possible to assess the robustness of the design".

Excerpt from recommendation No. 4:
"The ANDRA must include water flow mechanisms in the Cox in its simulations to enhance the demonstration of storage system robustness, and in particular Cox rock behaviour in terms of safety."

SAFETY AND EXTERNAL ATTACKS

Added to the site's design, construction operational risks are safety concerns in relation to external attacks. One such concern are entirely possible climate-related phenomena occurring during the century or more in which the site is operational – events which could interrupt the power supply and therefore ventilation in the underground infrastructure (violent storms, torrential rains, flooding, snowfall that closes off roads, etc.). Another are malevolent external attacks, during the construction of an immense labyrinth of galleries and cells spread over a minimum 15 square-kilometre footprint, equipped with air vents installed throughout the site, where radioactive waste will be received and stored. This is comparable to operations at two standard nuclear plants; one above ground and the other 500 metres below. The vulnerability of such a site is obvious.

STORAGE AND REVERSIBILITY

Legislators imposed the concept of reversibility in the Law of 28 June 2006: Article 5 states: “Deep geological disposal of radioactive waste involves the storage of these substances in underground facilities specially designed for this purpose and in compliance with the principle of reversibility.”
A detailed definition of this principle is found in the Law of 25 July 2016:

> “ ***Reversibility is the ability, for future generations, to either pursue the construction and use of successive levels of storage, or re-assess previous choices and re-orient management solutions.*** ”

In reality, reversibility is restricted to the period of operation (equivalent to few future generations), and it is now known that the recoverability of one or more packages – the actual application of reversibility– is only obligatory in the pilot industrial stage, early in the site’s period of operation.
In truth, the issue of reversibility arose with the decision to deposit waste in clay: it would be impossible to “go back” or adopt a different waste management strategy once the site were definitively closed. The option of irreversibility when construction is completed, coherent with the notion of “indefinite” storage, should in no case apply to the long construction phase of over 100 years which would precede the closure of its site and its ‘oblivion’. Reversibility is essential throughout this period as a counterweight to unplanned and risk-laden construction problems, and to recover defective waste within time frames that are compatible with the safety of the site and nearby populations. Project developers themselves admit (a fact that was highlighted in particular by the ERI review) that the presence of a defective package and the need to recover it cannot be excluded, similarly to the need to intervene in the event of even a mundane accident during the waste deposit phase. If a problem arises on-site, reversibility must be compatible with the method of intervention following an accident. This does not apply, of course, in the event of a fire deep within a gallery containing a series of packages, the removal of which would take months. Despite these considerations, ANDRA does not specify any time frame with regard to the pace of reversibility in normal situations or in the event of an accident.

IS THE DEEP DISPOSAL OF RADIOACTIVE WASTE IN THE EARTH'S CRUST ACCEPTABLE?

The idea that future generations are spared the problem of radioactive waste because we make it 'disappear' is deeply hypocritical: burying such waste in a completely irreversible manner in the Earth's crust, without any hope of changing strategy, inflicts upon these generations a problem of underground pollution that they will discover and suffer from, with practically no ways of solving it.

It is bold to suggest, as did ANDRA's former director, that the 'unimaginable' has been imagined when the task at hand is to "guarantee" the trouble-free storage of waste for over 100,000 years. While testing of the geological layers will no doubt permit the calibration of complex models, no guarantees can be made with regard to geological events that are unexpected and most likely unimaginable today.

More specifically, the risk of water infiltration in the geological layers is probably the biggest 'technical' – and unpreventable – long-term risk: after how much time could water containing radioactive elements rise to the surface? This can occur in any type of rock layer, though clay is a better choice over granite in light of this issue.

The second problem is that of forgetting that this underground storage site exists. Admittedly, the problem is being studied, and ideas are not short in supply. For some, the goal of deep disposal is to "make waste disappear": as such, the best solution is to not tell future generations, and instead let geology take care of this carefully hidden and ignored waste. For others, efforts must focus, to the contrary, on signalling the long-term presence of this high-risk underground site. The subject concerns centuries and millennia: what will this region look like in the very long term? Regardless of precautions and information provided, any kind of change or upheaval can lead to the persistence of only one memory, that "something possibly special is down there", that needs to be brought up.

If France, 'the world's nuclear champion', adopts the solution of deep disposal, the short- and medium-term risk is that other States and companies will rush to "do the same". This perfect model would be adopted abroad to make other types of toxic waste disappear as well, in conditions that have not been tested. In less than a century, the Earth's crust would be riddled with carefully covered holes containing extremely dangerous waste.

After polluting the air and the oceans, a problem so difficult to stop and solve, humankind is now digging downwards, into ground that rich in raw materials, energy resources, and, above all, through which water – essential to life on Earth – flows and is stored.

Just as international conventions (e.g. climate conventions, Montreal protocol, and the OSPAR Convention) try to improve our air and water, it is possible to imagine that future generations will be less destructive than current ones, and that an international convention will be signed soon to ban the deep deposit of any toxic or radioactive waste, similarly to the 1993 London Convention banning the dumping of radioactive waste.

Lastly, a sealed deep disposal site – an irreversible choice in practice – is a choice forced upon future generations. The decision in favour or against deep disposal is not simply a scientific or technical one: it is an ethical, political and civic choice, too.

RECOMMENDATIONS

Three possibilities are recommended: continued research to reduce the toxicity of radioactive waste in volume and over time; safety improvements to current storage and disposal sites; and sustainable, sub-surface disposal.

Partitioning and transmutation, one of three avenues explored in the Law of 1991, will not 'solve' the waste problem. Transmutation involves 'overradiating' the waste with neutrons. The energy in these neutrons depends on the elements present in the waste. Therefore all waste must be fully separated (technically speaking, a nearly impossible task, and a financially burdensome one as well), and, in any case, this does not "eliminate" waste: it simply shortens the life span of some waste, from 10,000 to a few hundred years). Transmutation is still under study by the CEA, but only concerns a tiny proportion of the waste. 2006 discussions concluded that this could not be an industrial solution for the tens of thousands of tonnes of existing waste. Shortcomings in this possible solution are not a reason to abandon efforts to reduce the toxicity of radioactive waste, however. Pursuing this field of research should be a priority.

Surface (or 'indefinite') disposal already exists for low-level waste (e.g. the ANDRA disposal site in Soulaines, Morvilliers, La Manche.) This disposal must be 'inspected' for at least 300 years and up to 800 years in the case of La Manche, due to the presence, in certain cases, of plutonium.

At this time, no satisfactory solution exists for the management of this waste. The best one so far would appear to be 'sub-surface dry disposal'.

The CIGEO project, base on oblivion and trust in nature and technology as a guarantee of safety, attracted much controversy in the national debate on radioactive waste management which occurred in 2006. At this time appeared the notion of monitored and sustainable storage, based on a very different approach which rejects oblivion as a current and future solution. In addition to monitoring, this storage approach calls for real technical means to exact waste drums at any moment and dispose of them in another way. The notion of evolution – of science, technology, mindsets and societies – is at the heart of this alternative concept, which won widespread approval in public debate led by a national committee on radioactive waste management organised in 2005–2006.

There is also reason to believe that major progress can be made in packaging and container techniques, which would of course be made impossible with indefinite deep disposal. Dry disposal already exists in France for several types of waste, including glass produced at La Hague containing fission products and minor actinides (elements other than plutonium which are heavier than uranium) from spent fuel from reactors and separated during reprocessing. This very hot waste is stored in La Hague in vertical silos and cooled by powerful natural and forced ventilation. It is HLLL (high-level, long-lived) waste. In Germany, and the United States in particular, where spent (or irradiated) fuel is viewed as waste since it is not reprocessed (France is practically the only country to do so on a large scale), solutions have been and are being developed for long-term storage on-site at nuclear plants (thus eliminating the need for transport): dry storage, for spent fuel, after remaining approximately five years in cooling pools located next to nuclear reactors. 'Sub-surface' storage involves storing spent fuel from reactors without any reprocessing in low-depth underground galleries, or in the side of granite mountains. This facilitates monitoring and ensures that the fuel can be extracted if a better technical solution is found. This method can also be used for (well-conditioned) containers of existing ILLL waste, as well as existing HL glass stored at La Hague after the necessary cooling period.

CONCLUSION

1.

The vulnerabilities, shortcomings and obstacles identified by three official opinions – that of the ASN, the IRSN and the peer review – raises serious questions about the CIGEO Project presented by the ANDRA. The many comments in response to the ASN consultation process further confirm these findings.

2.

In light of such significant problems, the French government and parliament must re-examine this project, which will inevitably lead to a dead-end, and incur necessarily considerable costs that would ultimately fall to French citizens.

3.

The option of the deep geological disposal of radioactive waste is unacceptable: it does not make waste 'disappear'; it hides it and inflicts upon future generations an irreversible pollution of the Earth's crust over an unlimited amount of time at the human level. It also imposes the creation and management of a construction site that exposes local populations to considerable risk for over a century. Applying the same solution in unmonitored conditions would no doubt lead to the wide-scale contamination of underground water in numerous regions around the globe.

4.

In line with legislation on radioactive waste management, recommended in public consultations, sub-surface dry storage should be thoroughly studied, with one or more pilot projects tested.

5.

A complete overhaul is needed of the current management strategy for radioactive waste, developed after a long period of disinterest and based on a choice of either fuel reprocessing, plutonium production or the (questionable) differentiation between high-potential materials and waste – dictated by those producing the waste.

1 The volume of spent fuel contained in La Hague pools is equal to one hundred 1,000-MW reactor cores.

2 Spent fuel, initially composed of enriched uranium from a traditional pressurised water reactor, and enriched uranium, contains approximately 95% uranium, 1% plutonium and 4% fission products and minor actinides combined.

3 MOX: “mixed oxide”, a mix of uranium oxide and plutonium oxide. Breeder plants also use a plutonium fuel with a much higher (>20%) Pu content than that of MOX.

4 Significant amounts of plutonium remain in storage at the La Hague re-processing plant, however: of the 56 tonnes present there at the end of 2013, 39.5 belonged to France.

5 Source: ANDRA, inventaire 2015 (in French).

6 https://www.asn.fr/Reglementer/Bulletin-officiel-de-l-ASN/Installations-nucleaires/Avis/Avis-n-2018-AV-0300-de-l-ASN-du-11-janvier-2018 (in French)

7 http://www.irsn.fr/FR/expertise/rapports_gp/Documents/Dechets/IRSN_Rapport-2017-0013_GPDOS-Cigeo_Tome-1.pdf (in French)

8 https://www.asn.fr/Informer/Actualites/CIGEO-revue-internationale-du-dossier-d-options-de-surete (in French)

9 https://www.encyclopedie-energie.org/les-risques-dexploitation-du-centre-industriel-de-stockage-geologique-cigeo/

10. Andra : https://www.andra.fr/sites/default/files/2018-01/392.pdf — page 143.

11. Ibid

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JAPAN

THE SITUATION ON HIGH-LEVEL RADIOACTIVE WASTE IN JAPAN

Hideyuki Ban

Japan has adopted a policy of permanent geological disposal for high-level radioactive waste (HLW). However, as of today and for a long period, there is insufficient public consensus for this policy because citizens deeply doubt the safety of the system. The disposal site has not yet been selected.

FROM DEEP UNDERSEA DISPOSAL TO GEOLOGICAL DISPOSAL

In the 1960s, Japan's policy for HLW was to dispose of it deep undersea because of earthquakes and limited available land. This policy was changed to geological disposal as a result of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, London Convention 1972. Geological stability in Japan is poor, so technical barriers are more important than natural barriers in ensuring the safety of geological disposal in Japan.

VITRIFIED HIGH LEVEL WASTE AND LONG-LIVED LOW HEAT RADIOACTIVE WASTE (LLHW)

The government stipulates that all spent nuclear fuel must be reprocessed as Japan has adopted the nuclear fuel cycle policy. That's why spent nuclear fuel is not categorized as a high level radioactive waste. This policy however will be reversed sometime in the future because reprocessing all spent fuel is impossible.[1]

NUCLEAR WASTE DISPOSAL RESEARCH FACILITY – HORONOBE, HOKKAIDO, JAPAN

Citizens protest at Horonobe nuclear waste facility, Hokkaido, Japan, November 2016, photo: Mihoko Inagaki

In Horonobe Town, Hokkaido, located in northern Japan, the underground disposal of high-level radioactive wastes resulting from the reprocessing of spent fuel generated by nuclear power plants, is being studied. Horonobe, a small town with a population of slightly more than 2,600, is the only place in Japan that hosts such a study. In the early 1980s, the town initiated efforts to invite nuclear-related industry to the area to halt the decline in population and revitalize the town.[2] The town succeeded in inviting the research and storage facilities for high-level radioactive wastes in 1984. However, the project was frozen due to strong opposition from municipalities around the town and the Hokkaido population. As a product of compromise, the Underground Research Project started in April 2001 under the condition that no nuclear material would be brought in and only research would be conducted. In the municipalities around Horonobe, many citizen groups were established in the year when the nuclear waste issue became a serious controversy, and in January 1985, the Northern Hokkaido Network against the Invitation of Nuclear Waste Disposal Facilities was established as an organization networking those groups. (Several such organizations were formed across Hokkaido.)To determine the site for the disposal of nuclear wastes and thus enable a swift restart for nuclear reactors, the government shifted the disposal-site nomination system from a voluntary municipality self-nomination system to a government designation system.

The deep underground research project in Horonobe Town has been conducted based on an agreement that the research would be discontinued in about twenty years. However, the Independent Administrative Institution Japan Atomic Energy Agency (JAEA), which oversees the project, has been attempting to extend this period, and has begun to deny the agreement confirmed with local municipalities that the land hollowed out for the underground facilities would be reclaimed after the research had ended. There are still some people in Horonobe Town voicing the opinion that nuclear waste disposal facilities should be invited to the town. Concerns are growing that the town might be designated to host the disposal facilities as a result of unreasonable maneuvering of the project.

In Japan, there are many active volcanoes, earthquakes are frequent, and underground water is abundant. Scientists seriously question the viability of the underground disposal method. Geologically speaking, the geological structure of Hokkaido is rather new, having been formed only about 100,000 years ago. The area around Horonobe Town is still experiencing deformation and tectonic activity. Below the surface in the area around Horonobe lie mudstones, which contain large numbers of fissures and great amounts of underground water. (The water includes both water from the ground surface and fossiliferous seawater. The daily average drainage volume from the underground research facilities between April 2012 and March 2013 was 310.4 cubic meters.) There are also gaseous emissions. That research into the disposal of high-level radioactive wastes, which need to be isolated for as long as 100,000 years, is being conducted in such a place, indicates a fundamental problem with Japan's nuclear power policy.

SPACE AND CAPACITY OF A PLANNED PERMANENT DISPOSAL SITE

The Act of Permanent Disposal of HLW passed in 2000. The Act states that the waste should be buried underground at a depth of more than 300m. The Nuclear Waste Management Organization of Japan (NUMO) was established by law for finding the permanent disposal site and carrying out the deposit of HLW.

Surface facility: 1-2km
Underground facility (deeper than 300m): 6-10km

Diagram reference [3]

The planned disposal site will be about 1-2 km^2 on the surface and 6-10 km^2 underground. Around 40,000 canisters will be buried there which contain high level radioactive waste produced by the planned reprocessing of 32,000tHM of spent fuel at the Rokkasho reprocessing facility. Long-lived low heat radioactive waste (LLHW), which consists of transuranic waste and iodine 129, produced by the reprocessing also will be buried at the same site. If Japan continues to generate nuclear power for a longer time, for example over the next 30 to 50 years , another disposal site will be needed. But after the Fukushima disaster, this seems unrealistic.

A bottle of vitrified high-level waste should be put into a 19cm thick carbon steal canister, a so-called 'over pack,' which is surrounded by 70cm thick bentonite. LLHW should be disposed of in a 5cm thick carbon steal square box. According to NUMO, the total tunnel length will be 200-300km comprising the access tunnel, main tunnel and disposal tunnel. These tunnels will be closed by rock with bentonite. NUMO aims to maintain water permeability factors in these tunnels as they were. However, this is impossible and these tunnels could be a way for radioactive materials to reach areas where people live.

REPORT ON THE TECHNOLOGICAL RELIABILITY OF GEOLOGICAL DISPOSAL[4] (1999) AND THE PERMANENT DISPOSAL LAW (2000)

The Nuclear Cycle Development Institute (JNC), now the Japan Atomic Energy Agency (JAEA), released a report in 1999 that evaluates the safety case of geological disposal. It shows a design ofthe disposal site, facilities and equipment based on an idea of combined technological natural barriers. The report says "generally, there are reduced oxygen conditions (reduced environment) deep underground and water flow is so slow that there will be enough area in Japan to maintain isolation of the waste from human living zones for around 100 thousand years utilizing technological barriers". However they examined water flows in deep underground by boring only two or three samples. In the Mizunami case where JAEA conducted research at depths of 100m, 300m and 500m, 700 to 1000m^3 of water a day keeps leaking from the soil over 20 years. And JAEA hasn't yet discovered where the water comes from and goes to. That means they have less knowledge about the deep underground environment such as water flow or rock cracks. NUMO however hasn't announced, as of today, that a site like Mizunami is not suitable for permanent disposal.In addition there is no regulation yet on the design of the disposal site and on safety standards of disposal. NUMO also has no regulation that allows it to abandon the site even if it finds bad conditions through later detailed research. In such cases, NUMO may carry out so-called comprehensive evaluation and as a result, the site will be declared suitable for disposal.

ENVIRONMENTAL IMPACT ASSESSMENT

Environmental Impact Assessment (EIA) reports on VHLW consist of a basic scenario and variation scenarios. In both scenarios, underground water delivers radioactive materials to the human living environment. Preconditions of the basic scenario are: flat land, river water, granite rock, 70% bentonite + 30% silica sand as a blanket, 1000m depth and 100m away from cracks with high permeability. An over pack is expected to keep radioactive materials for 1000 years. And glass is supposed to dissolve completely 70,000 years later. During this period, radioactive materials slowly diffuse with water through 70cm thick bentonite/silica sand and into the near field assumed to be 100m. Then materials enter into the human living environment. The calculated dose rate is 0.005 micro-sievert per year at the peak point, which is 800,000 years after closure of the facility.
The fluctuation scenarios of the EIA contain 36 patterns. 30 of the 36 patterns are a combination of water, surface water or seawater, groundwater flow and the nature of the soil. Other patterns vary the thickness of the over pack, the dissolving speed of the glass, colloidal status, uplift and subsidence and mal-construction of shields. Maximum dose given by these scenarios is calculated at below 100micro Sievert per year.

In the fluctuation scenarios, however, variation of only one condition is considered. If two or more factors change at the same time, the dose will increase up to 1mSv/y or more. For example, if an earthquake makes the cracks in the rock wider, corrosion of the over pack will occur more quickly, the water flow route from the blanket to the earth's surface will also change and radioactive materials unexpectedly rapidly appear to our living environment, then internal exposure to radiation will become more severe than 1mSv/y.

A report on the EIA about LLHWs going to geological disposal was released in 2005 by the then JNC. It says that maximum dose is estimated at 2 μ SV/y at the peak point of 10,000 years later based on the similar geological conditions as the case of VHLW. The main nuclide is iodine 129 , which has a half-life of 15.7 million years, and which easily dissolves in water.

PROCEDURE OF SITE SELECTION

The provisions in the law about site selection set out a step-by-step procedure: Firstly preliminary research of the region such as earthquake, flood risks, volcanic eruptions and so on, is carried out by using documents of the region. Secondly outline research is conducted by boring holes for samples, and finally detailed research on the site underground is conducted. In each step NUMO has to makean evaluation report and release it to local residents. Local authorities and local governments opinions must be 'respected.' NUMO insists that if the authority or the local government refuses to enter the next step, they will stop the research. NUMO releases no announcement about abandoning the site, but just stop their research. People are critical of this because they are concerned that NUMO will wait for the next election and try to influence the new governor or mayor, which is why they keep the project 'on hold' instead of abandoning it.

NUMO AND "INVITING" APPLICATION SYSTEM

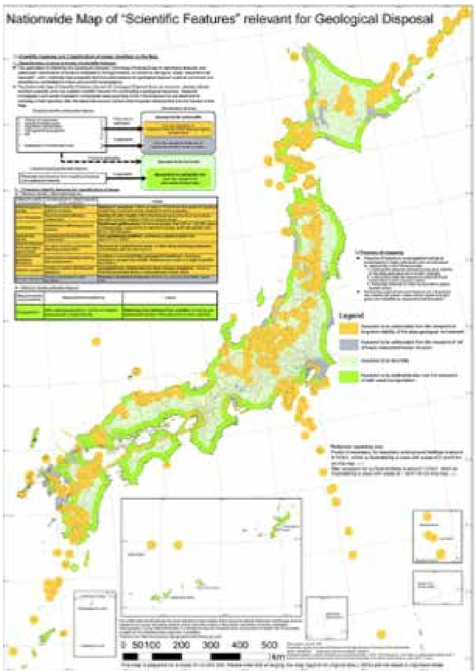
NUMO, founded by the permanent disposal law, introduced the so-called "inviting application procedure" in 2002 and asked all local authorities to submit acceptance papers for entering document research. NUMO insists the procedure is a very fair method because all authorities have equal opportunities to accept the preliminary research. Five years later, the mayor of Toyo town in Kochi prefecture applied for research to be conducted, but without discussions either in the assembly or notice to the town's people. This mayor's decision created a strong movement against accepting the research for becoming a radioactive waste dump, and the movement managed to challenge the mayor. Finally a new mayor, who was against the research application, was elected and he withdrew the application. As soon as the mayor showed an interest in the subsidy by accepting the first step of the research, movements against it rose rapidly and all the experimental trials were abandoned. These events occurred in eight municipalities in addition to Toyo town. After the Toyo town incident, there were voices demanding a new approach to the site selection from the promoting side, and a system where the central government takes the initiative in approaching municipalities was introduced in the same year.

When preparation for the request by the government to several municipalities was just completed, the Fukushima Daiichi disaster occurred. The subsidy to local governments, including municipality costs, is a maximum 2 billion yen in the first step and maximum 7 billion yen in the second step. The amount of the further subsidy in thefinal step is not decided yet.

GEOSCIENTIFIC CHARACTERISTIC MAP RELEASED

Former Prime Minister Koizumi, just after he visited "Onkal" in Finland, said that Japan should phase out nuclear power because geological disposal is impossible for Japan due to such unstable geography. The Government of Japan was very afraid of activating anti-nuclear movement and made the approach introduced in 2007 concrete for site selection of geological disposal. In December 2013, the Government announced the approach consisting of 3 steps which are firstly, designating suitable areas based on scientific information and data, secondly getting acceptance in the areas through dialogues, and finally requesting municipalities in these areas for document research.

On July 28, 2017,[5] the Japanese government released a geoscientific characteristics map to provide a basis for selecting locations for high-level nuclear-waste disposal sites. The map, on a 1:2,000,000 scale, shows the entire Japanese archipelago, accompanied by five aerial maps. The explanations of the standpoints used to evaluate aerial favorability for site construction are provided, along with the criteria for those standpoints, accompanied by the maps, which use color-coding to indicate individual standpoints.



Map reference: [6]

The map for showing suitable areas categorizes the whole nation into 3 areas which are 'advantageous,' 'suitable' and 'unsuitable' based on eleven disqualification conditions such as volcanic activity, fault activity, upheaval or land erosion, presence of mineral resources, temperature in deposit area and so on. For this, nationwide data or documents were used not specific regional data nor documents for classification of areas. The map divides 'advantageous' areas, named green coastal areas, from 'suitable' areas based on transportation conditions. A cargo with VHLWs weighs more than 100 tons therefore it can't use public roads but requires specific private roads. The green coastal area means within 20km away from the coastal line NUMO is planning and carrying out dialogues in the green coastal areas. However as soon as the map was released by METI and NUMO, 21 of 46 local governors clearly announced not to accept the document research. In every meeting organised by NUMO, participants also insisted that generating any more radioactive waste must stop prior to discussion of the disposal.

The geological conditions specific to each area will be examined in the literature survey, with reference to geological records, while the characteristics map shows the divisions based only on the information available nationwide. Therefore, while the map is called a geoscientific characteristics map, the characteristics specific to individual areas are not always reflected. As an example, the map is supposed to exclude areas having pyroclastic flow deposits younger than 10,000 years as not favorable, but the map does not consider the range of influence of the pyroclastic flow from a possible eruption of the Kikai Caldera Volcano, Kagoshima Prefecture, the most recent eruption of which was 7,300 years ago. This influence will be considered in the literature survey. Many areas in Tokyo are classified in the green coastal areas, but because the Kanto Plain was formed during the Quaternary period, the bedrock is still soft deep underground, and there may be many unlithified rocks. This should also be considered in the literature survey. This geoscientific characteristics map does not consider restraints in the use of land due to legislation or international treaties, nor social conditions such as population density and the number of landowners.

NUMO's conventional conditions for the acceptance of survey applications were only volcanic activity and fault activity. The other standpoints are included in the social characteristics map scheduled to be examined in the literature survey. Therefore, the release of the map is a step forward for the government. NUMO is modifying the acceptance conditions in order to be consistent with the conditions described in the map.

The Japanese archipelago lies in the tectonic movement zone, where four plates meet. Even if all the conditions presented in the map are satisfied, it would still be difficult to isolate wastes from the environment for more than 100,000 years. Especially, information on relatively large amounts of deep underground water, which should essentially be considered for long-term stability, is limited. The government intends to ensure the long-term safety of HLW by using engineering methods, and this governmental intention remains unchanged.

After the release of the geoscientific characteristics map, the government and NUMO intend to promote activities to gain public understanding, mainly in the areas whose characteristics have been judged favorable (green coastal areas). However, of the 47 prefectures nationwide, 20 prefectures have already turned down the survey. Citizens' movements against nuclear power generation have been powerful since the Fukushima Daiichi accident, and the movement strongly demands that all nuclear power plants be shut down first in order to halt the accumulation of HLW. The Science Council of Japan also stated that the upper limit of HLW should be determined (2012).

The government's stance concerning the new characteristics map is that its release is not intended to persuade municipalities to accept a survey for disposal site selection; the government says that it will not initiate any survey unilaterally without gaining the agreement of the locals. According to the government, "this is the first step in a long road to realize final HLW disposal." NUMO plans to begin the first step by organizing dialog gatherings with a small number of people in the areas judged favorable from all the standpoints including transportation. However, the government and NUMO intend to promote the conventional concept and plan of geological waste disposal, separating the disposal site issue from the controversy of nuclear power plants. This head-on disagreement is expected to continue.

The government does not make efforts to form a participatory consensus concerning the treatment of HLW. As an example, consensus meetings or deliberative polls have not been conducted and are not planned. The government councils did not discuss ways in which to obtain social agreement. What the government has attempted to do thus far is to try to earn public agreement for its geological disposal policy. However, what it has actually been engaged in is organizing gatherings that attempt to obtain public agreement for the government's plan, under the name of explanatory hearings.

THE SCHEDULE FOR HIGH LEVEL WASTE MANAGEMENT

In 1995, the first shipment of VHLWs arrived from France. VHLW shipments arrived at the private port of Japan Nuclear Fuel Limited (JNFL) and are to be stored in the Vitrified Waste Storage Center at Rokkasho-mura for 30-50 years by the agreement between JNFL and the Aomori Governor. Therefore NUMO has to start its operation before 2045. It needs roughly 30 years for reaching its operation, 2 years for document research, 4 years for outline research, 14 years for detail on-site research and 10 years for construction.

NUMO is behind schedule by 3 years already and is unlikely to find a municipality to accept the research in the near future. But it can't change its schedule because of the agreement with the Aomori Governor.

ESTIMATED DISPOSAL COST

The total disposal cost including LLHW is estimated by the Ministry of Economy Trade and Industry (METI) as 3.8 trillion yen (about 29,4 billions of Euros) of the total disposal cost including LLHW.[7] If the schedule is delayed for 20 years or more, which is likely, the price will increase. In addition, the running cost of NUMO is also excluded from this calculation, which will further increase the disposal cost.

COLLECTING DISPOSAL FUND

METI and electric utilities collect the fund through the electricity price but only half of the 3.8 trillion yen will be collected directly because of discount rate of 2%. Each year METI demands from utilities the amount towards the final disposal cost based on last year's nuclear power generation and reviewing the cost of geological disposal. They are accounting for the discount rate but the cost will increase by many factors. Future generations will face serious problems of funding shortfall, but they will be presented with the final bill even after the nuclear age has ended.

CONCLUSION

The March 2011 Fukushima Daiichi accident has increased the public opposition to nuclear power in Japan. Whereas there were 54 commercial reactors available in 2011, in 2018, there are nine reactors in operation. While the government plans are for as many as 35 reactors to operating by 2030, this is almost certainly not possible. The prospects for the nuclear power in Japan are not good. At the same time, as a consequence of Japanese energy policy, the country has large volumes of high level waste – both spent fuel and vitrified high level waste from reprocessing. To date, efforts to secure underground repositories for this waste have failed and there are no prospects in the near or even distant future. The Japanese people have a feeling of moral duty that nuclear waste produced for electricity generation should be managed safely, including finding a long term solution. However, from a 2017 polling conducted by the Japan Atomic Energy Relations Organizatio, it is clear that while there is considerable support for research on nuclear waste disposal, there is little confidence that this can be done safely. Opinion on underground disposal according to this poll is split - with 20 percent each opposed and in favor. But in reality, when proposed sites have been suggested to communities the overwhelming public opinion has been to oppose underground disposal.

Geological disposal is unsafe especially in a seismically / tectonically active land like Japan. The reality is that high level nuclear waste will continue to be stored on the surface for the foreseeable future, as it should be. There is no solution for final disposal of high nuclear waste in Japan. In 2010, the Japanese Cabinet Office requested that the Science Council of Japan gives its analysis on the options for the disposal of high level nuclear waste. After reviewing the status of disposal research in Japan, the Council in September 2012 recommended to the then Government that interim storage of high level waste be considered for a period of 300 years. This is isacknowledgment of the reality of the problem for high level waste management, in Japan, and the Government and NUMO should accept this recommendation[8].

1 CNIC Seminar report: The problems with Japan's Plutonium: What are they and how do we deal with them? CNIC, 4 June 2018, ; and Frank von Hippel and Masa Takubo, "An alternative to the continued accumulation of separated plutonium in Japan: Dry cask storage of spent fuel, September 2018, https://www.researchgate.net/publication/327927769_An_alternative_to_the_continued_accumulation_of_separated_plutonium_in_Japan_Dry_cask_storage_of_spent_fuel

2 CNIC Seminar report: The problems with Japan's Plutonium: What are they and how do we deal with them? CNIC, 4 June 2018, ; and Frank von Hippel and Masa Takubo, "An alternative to the continued accumulation of separated plutonium in Japan: Dry cask storage of spent fuel, September 2018, https://www.researchgate.net/publication/327927769_An_alternative_to_the_continued_accumulation_of_separated_plutonium_in_Japan_Dry_cask_storage_of_spent_fuel

3 Actions NUMO is Taking to Promote Deep Geological Disposal of Radioactive Waste. April 12, 2018. Shunsuke Kondo President, Nuclear Waste Management Organization of Japan (NUMO), see https://www.numo.or.jp/topics/1-4Kondo.pdf

4 "Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan", https://www.jaea.go.jp/04/tisou/english/report/H12_report.html

5 Government releases a geoscientific characteristics map showing areas "suitable" for disposal of high-level nuclear waste, CNIC_ OCTOBER 4, 2017

6 Map reference - Actions NUMO is Taking to Promote Deep Geological Disposal of Radioactive Waste, April 12, 2018. Shunsuke Kondo President, Nuclear Waste Management Organization of Japan (NUMO), see https://www.numo.or.jp/topics/1-4Kondo.pdf

7 In Japan the cost of waste disposal was estimated by the Ministry of Economy Trade and Industry (METI) in 2011 as €29 billion.

8 The Science Council of Japan, Disposal of High Level Radioactive Waste, September 2012, see http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-22-k159-1.pdf#page=1 (in Japanese).

5

SWEDEN AND FINLAND

SPENT NUCLEAR REACTOR FUEL MANAGEMENT IN SWEDEN AND FINLAND

Miles Goldstick

INTRODUCTION

This report focuses on the situation in Sweden regarding management of irradiated nuclear fuel, commonly referred to as spent fuel, from Sweden's electricity producing commercial nuclear reactors. Particularly examined are uncertainties and impacts of the method and location proposed by the nuclear industry for a spent fuel repository. A brief look is also taken at the situation regarding the management of spent fuel in Finland.

NUCLEAR WASTE MANAGEMENT IN SWEDEN

In Sweden, creation of nuclear waste began with research into nuclear weapons shortly after the dropping of the Hiroshima and Nagasaki atomic bombs in 1945. In 1947, the Swedish government formed the Atomic Energy Company to pursue military and civilian nuclear research and development. The military work was abandoned in the late 1960s.[1] The early work in the late 1940s included research using plutonium, with resulting contamination and radioactive waste. As in Sweden there are now several facilities in the nuclear fuel chain, both active and out of service, there are also several types of nuclear waste that are managed in various ways.

In Sweden there is one decommissioned uranium mine (at Ranstad), one fuel fabrication plant (in Västerås), one permanently shutdown military research reactor (R1 in Stockholm), one permanently shutdown small commercial reactor (R3 at Ågesta), one military plutonium production reactor that was never fuelled (R4 at Marviken), four commercial nuclear power stations (Barsebäck, Ringhals, Oskarshamn and Forsmark) with a total of 12 nuclear reactors (of which the Barsebäck power station with two reactors is permanently shutdown, and two of the three reactors at Oskarshamn are permanently shutdown; one of the four reactors at Ringhals is scheduled to be shutdown in 2019 and another in 2020), an operating facility for storage of "short-lived" radioactive waste (SFR at Forsmark), and an operating interim storage facility for spent fuel (Clab at Oskarshamn, 32 m underground in bedrock). There is also a testing and treatment operation (Studsvik, near Nyköping). The spent fuel and other waste produced from the research programme is not specifically addressed here. In Sweden there is no conversion of yellowcake, no fuel enrichment and no fuel reprocessing. Sweden did however send spent fuel for reprocessing to Sellafield, England (140 tonnes) and La Hague, France (57 tonnes). Construction of commercial nuclear reactors began in the 1960s. Six reactors began commercial operation in the 1970s and by 1985 six more were in operation.[2]

In 1980, after the results of a non-binding referendum on the future of nuclear power, the government made a decision to phase-out nuclear power by 2010, but allow construction of new reactors to a maximum of 12.[3] The debate on the future of nuclear power continued and the 2010 phase-out date was retained until the mid-1990s. Then, in a new inter-party agreement, the government decided to start the phase-out earlier but abandoned the 2010 deadline. The first reactor (Barsebäck-1) was shut down in 1999 and the second one (Barsebäck-2) in 2005.

The controversy continued.[4] In June 2010, after a vote in the parliament that won by only two votes (174–172), the phase-out legislation was abandoned and it became permissible to build new reactors. In June 2016, another inter-party agreement was reached, this time on energy policy in general.[5] The current goal is for electricity production to be 100% from renewable energy sources by the year 2040. However, reactor operators have stated they will apply for life-time extension for six reactors into the early 2040s.

Since the mid-1970s, the nuclear industry and government have been putting great financial resources towards dealing with long-term management of the full range of nuclear waste, particularly spent fuel. Following is a description of the spent fuel management situation and the current and proposed low and intermediate level nuclear waste facilities. The industry's planned facility for "long-lived" low and intermediate level waste, called "SFL", is in the beginning stages of the planning process and not addressed here (SKB expects to submit a license application for SFL about the year 2030).

SPENT FUEL MANAGEMENT

The law in Sweden specifies that the producer of nuclear waste is responsible for its management and for covering the costs involved (i.e. the polluter pays principle). To manage nuclear waste, the nuclear power companies together formed the Swedish Nuclear Fuel and Waste Management Company (*Svensk Kärnbränslehantering AB*) (SKB). These nuclear power companies and their respective percent of the ownership of SKB are Vattenfall AB (36%), Forsmarks Kraftgrupp AB (30%), OKG Aktiebolag (22%), and Sydkraft Nuclear Power AB (12%).[6] Vattenfall AB is 100% owned by the Swedish state.[7]

The Swedish "Public Access to Information and Secrecy Act" is strong freedom of information legislation. There are established routines for the public to request and receive much of the information handled by all levels of government and government agencies. As SKB is a private company, this area of law does not apply to its work on the nuclear waste issue. The result is a lack of transparency.

	Thermal capacity/net capacity	Electricity production up to and including 2016	Fuel up to and including 2016	Total for planned operation		Electricity production	Spent nuclear fuel
				Planned operating time	Operation up to and including		
Start of commercial operation	MW	TWh	Tonnes of uranium	Years		TWh	Tonnes of uranium
F1 (BWR) 10/12/1980	2 928/984	251	883	60.0	08/12/2040	434	1 348
F2 (BWR) 07/07/1981	3 253/1 120	245	864	60.0	05/07/2041	462	1 418
F3 (BWR) 22/08/1985	3 300/1 167	270	897	60.0	20/08/2045	536	1 509
O1 (BWR) 06/02/1972	1 375/473	81	367	45.4	30/06/2017	82	367
O2 (BWR) 15/12/1974	1 800/638	154	537	41.1	31/12/2015	154	537
O3 (BWR) 15/08/1985	3 900/1 400	256	841	60.0	14/08/2045	568	1 577
R1 (BWR) 01/01/1976	2 540/881	197	720	44.5	14/06/2020	219	773
R2 (PWR) 01/05/1975	2 500/807	210	630	44.2	13/07/2019	224	671
R3 (PWR) 09/09/1981	3 135/1 063	225	607	60.0	07/09/2041	421	1 126
R4 (PWR) 21/11/1983	3 300/1 118	217	672	60.0	20/11/2043	444	1 236
B1 (BWR) 01/07/1975	1 800/600	93	419		30/11/1999	93	419
B2 (BWR) 01/07/1977	1 800/600	108	424		31/05/2005	108	424
BWR total	22 696/7 863	1 657	5 951			2 656	8 372
PWR total	8 935/2 988	651	1 909			1 089	3 032
All total	31 631/10 851	2 308	7 860			3 746	11 404

The fuel's actual weight in the form of complete fuel assemblies is considerably larger. A BWR fuel assembly weighs about 300 kg whereof about 180 kilograms consist of uranium. After burn-up, the uranium weight decreases slightly. For a PWR fuel assembly, the corresponding weights are about 560 kg and about 460 kg respectively.

CURRENT AND PROJECTED QUANTITIES OF SPENT FUEL

From the 12 commercial nuclear reactors listed below (not all of which are operating), according to SKB, up to and including 2016 there was a total of 7,860 tonnes of spent fuel, and the total estimated planned quantity is 11,404 tonnes (both measured as quantity of uranium).[8]

"Operating data plus electricity production and fuel quantities based on planned operation."

Source: SKB. 2017-04. "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." Technical Report TR-17.02. 52 pp. See p. 35. Available at (5 October 2018): https://www.skb.se/publikation/2487964/TR-17-02.pdf https://www.skb.se/publikation/2487964/TR-17-02.pdf. Some of the spent fuel from the research reactors is included in the KBS-3 application but is not included in the estimated quantity in tonnes, though is included in the estimate in the number of canisters.

FINANCING AND THE TRI-ANNUAL RESEARCH AND DEVELOPMENT PROGRAMME

In 2017, SKB estimated total future costs to the point of closure of all the facilities for handling all the nuclear waste originating from nuclear reactors to be SEK 98 billion (about EUR 9.5 billion) of which the costs for spent fuel will be SEK 31.56 billion (about EUR 3 billion).[9] The major portion of the money intended for future management and storage of nuclear waste comes from funds paid according to law by the nuclear industry into the Nuclear Waste Fund,[10] which is managed by the government. At the end of 2017, the size of the fund was SEK 67.236 billion (about EUR 6.45 billion).[11] SKB has estimated the total expenditures from the Nuclear Waste Fund from 1982 and up until the end of 2017 to be about 4.8 billion SEK (about EUR 460 million),[12] which makes an average of about 190 million SEK per year (about EUR 18.22 million per year).

The annual disbursements are subject, according to government ordinances, to a review that began in 1986 of tri-annual research and development reports by the nuclear industry that cover a four-year period into the future.[13] It is of note however that though the government in these to date 12 tri-annual reviews has either implicitly or explicitly approved the KBS-3 method for demonstration and planning purposes, the government has made clear that the method itself has not been approved.[14] It is also of note that the government agency tasked with examining the tri-annual reports has after each examination recommended acceptance to the government, though has pointed out deficiencies. That government agency is the Swedish Radiation Safety Authority (SSM) (since it was founded in 2008 and before then its predecessors), the same agency that had the task of examining the 2011 application by the nuclear industry to build a facility that in each one of these tri-annual reviews continued to be developed. As described below, this application was also examined by the Land and Environment Court.

THE CURRENT, ONGOING COURT AND REGULATORY AGENCY REVIEW

There is an ongoing, formal review of a SKB application to build an underground spent fuel management system using the KBS-3 method (see box).[15] Below is a summary of the distinct phases and milestones in the decision-making process. It will take at least until the end of 2020 to reach the point of a final decision, though it could take several more years. If the government gives its approval, extensive regulation of implementation awaits.

THE KBS-3 METHOD AND SPENT FUEL MANAGEMENT SYSTEM, PROPOSED LOCATION AND MAIN UNCERTAINTIES

There is no facility operating anywhere in the world, using any method, that is intended as a permanent storage for spent fuel produced by commercial electricity producing nuclear reactors. To deal with spent fuel, the nuclear industry worldwide favours a method termed "deep geological repository," of which the KBS-3 method is a variation.[16] The nuclear industry in Finland has adopted the KBS-3 method (see more in the section on Finland).

"Deep" in this context means several hundred meters below the surface. A depth of kilometres deep is referred to as "very deep," which is the proposed depth for the alternative approach called the deep borehole method. The suitability of the KBS-3 method as compared to alternative methods has been debated in Sweden since the KBS-3 method was first introduced. Alternatives proposed for further investigation are dry storage in a highly secure facility onsite at nuclear power stations (e.g. hardened on-site storage - HOSS18[17]) or at a central location (e.g. dry rock deposit - DRD19[18]), and very deep boreholes. Rolling stewardship can be applied with any method but monitoring requirements are small with very deep boreholes and great with dry storage.

KBS: refers to the 1976 "*KärnBränsleSäkerhet*" ("Nuclear Fuel Safety") project formed by the Swedish Nuclear Fuel Supply Co. (*Svensk kärnbränsleförsörjning AB*) (SKBF), the predecessor of Swedish Nuclear Fuel and Waste Management Co. (*Svensk Kärnbränslehantering AB*) (SKB).

KBS-1 (1977): dealt with reprocessed nuclear fuel, and was soon abandoned due to problems surrounding reprocessing.

KBS-2 (1979): the first description of direct deposition of nuclear fuel.

KBS-3 (1983)[19]: the second and more detailed description of a repository several hundred meters underground, and based on the three barriers of copper canisters, bentonite clay, and the bedrock. The copper canisters and bentonite clay are mutually dependent, i.e. one will not function unless the other also functions optimally.

THE KBS-3 METHOD AND SPENT FUEL MANAGEMENT SYSTEM CONSISTS OF:

- Storage under water for about a year on-site at the nuclear power station.

- Interim storage for about 30 years at the underground Clab facility, located at Oskarshamn and currently operating. The Clab facility requires active cooling dependent on electricity. The local community, Oskarshamn municipality, wants the facility decommissioned. Clab may not have the capacity to hold the projected quantity of spent fuel. For that reason, SKB has investigated using temporary dry storage if there is a period when there is not enough room in Clab and deposition is not yet possible in a KBS-3 repository.

- A multi-barrier system to delay release of radionuclides, with three components, granitic bedrock, bentonite buffer, and encapsulation in copper canisters with a cast iron insert. There are concerns about all these barriers, as given below.

- An encapsulation facility proposed to be located immediately adjacent to the Clab facility, together termed "Clink".

- An estimated 5,700 canisters.[20]

- Canister dimensions are: outer diameter 1.05 m, length 4.85 m, copper wall thickness 4.9 cm, average maximum weight about 2.5 tonnes.[21]

• Deposition of the canisters in bedrock 470 m below the surface in circular vertical holes eight meters deep and two meters in diameter, proposed to be located at Forsmark, about one km from the three Forsmark nuclear reactors. The depth may not be adequate to withstand permafrost in the next ice age.[22] Impacts from bacteria at the depth of the canisters is also a concern. Further, the location may not be suitable due to geologic and geophysical conditions, e.g. earthquake risk. In addition, there are the risks associated with close proximity to the Forsmark nuclear power station. The coastal placement also adds the risk of contamination of the Baltic Sea, which according to HELCOM is one of the most radioactive seas on Earth.[23]

• Surrounding the canisters with bentonite clay. The clay buffer could be compromised by several processes, particularly due to exposure to water, heat and air. For example, water is needed for the clay to swell and protect the copper canister. The bedrock at Forsmark is however relatively dry and swelling could take over a thousand years. Heat from the canisters over this long period may mean the clay will be dry due to the heat and never swell as required.

• Filling the underground tunnels up to the surface, closure, and abandonment by the nuclear industry, without any method of monitoring in place. There is a long-term risk of unintentional and intentional intrusion. There is also the issue of whether or not a monitoring system should be designed, and how to preserve knowledge in the long-term about the site location and hazards of the materials in the repository.

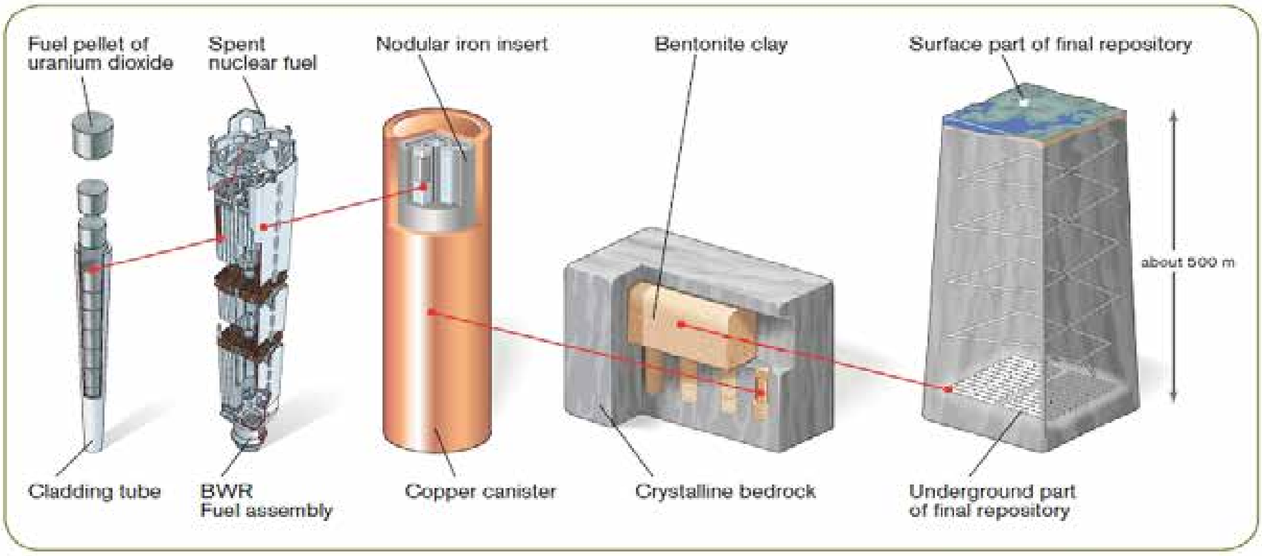


Figure S-2. The KBS-3 method. The method involves encapsulating the spent fuel in copper canisters which are then emplaced, surrounded by a buffer of bentonite clay, in deposition holes in a tunnel system at a depth of about 500 metres in the bedrock.

“**The KBS-3 method.** The method involves encapsulating the spent fuel in copper canisters which are then emplaced, surrounded by a buffer of bentonite clay, in deposition holes in a tunnel system at a depth of about 500 metres in the bedrock.”

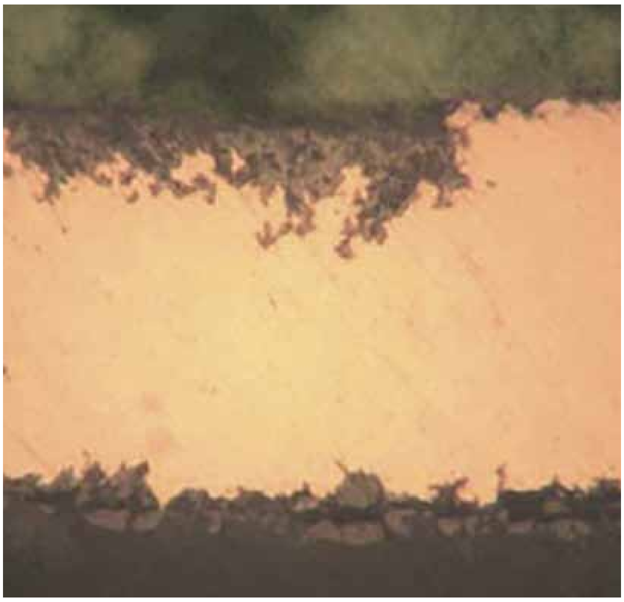
Source: SKB. 2011-03. “Environmental Impact Statement, Interim storage, encapsulation and final disposal of spent nuclear fuel.” 337 pp. See Figure s-2, p. 12.
Available (5 October 2018) at: http://www.skb.com/future-projects/the-spent-fuel-repository/our-applications/ (PDF, 37.3 MB).
Direct link: http://www.skb.com/wp-content/uploads/2016/03/21014-MKB-ENG-webb-150dpi.pdf.

COPPER CORROSION

The safety of the KBS-3 method is based on a number of principle assumptions, of which one is that the canister material, copper, will corrode so slowly that the radionuclides will not be released over the period the waste is dangerous to life forms. Copper was chosen in the 1970s as a material because of its well-known corrosion resistance.[24] In some environments, copper is immune to corrosion, as proven by geological formations containing copper. It is however not possible to replicate such environments due to the presence of water and air in any constructed system. Of concern is thus the rate of copper corrosion, not if corrosion will occur. The Swedish Radiation Safety Authority has carried out a detailed assessment and continues to examine concerns.[25] Several factors influence the rate of copper corrosion. Main factors are the ability of the bentonite buffer to isolate the copper from water and air and the resulting chemical processes, and how these processes are influenced by heat, radioactivity, and the presence or absence of oxygen.[26] The Swedish Land and Environmental Court identified five main concerns (see below).

Due to the complex factors that cause corrosion, it is uncertain if copper and iron are suitable materials. Research independent of the nuclear industry has found that leakage due to copper corrosion may begin after 100 years, and leakage from most canisters would occur after about 1,000 years.[27] Further, tests simulating the intended system with spent fuel in a canister have not been carried out.[28]

Appearance of copper after 15 years of exposure in distilled water at room temperature. Hydrogen from corrosion can escape from the left container but not from the container to the right. The water volume was equal in the flasks in beginning of the exposure.



Light optical cross-section of a green area seen in the left flask above of the initially 100µm metallic copper foil after 15 years exposure in distilled water. Localised corrosion attack is clearly visible.

Source: Hultquist, G. B., Szakálos, P., Graham, M. J., Sproule, G. I., & Wikmark, G. 2008. Detection of hydrogen in corrosion of copper in pure water. In Int. Corros. Congr.: Corros. Control Serv. Soc. (pp. 2378–2386). Available at (10 July 2018): https://www.researchgate.net/publication/238102363_Detection_of_hydrogen_in_corrosion_of_copper_in_pure_water (PDF, 2.5 MB).

THE NUCLEAR FAMILY

The current legal review can be considered to have started in 2002 when SKB started the consultation process required for its license application. Many people involved in the legal review are veterans who have followed the spent fuel management issue since the mid-1970s when the nuclear industry first presented the KBS concept. Beginning in 2002, the interaction between the full range of stakeholders intensified. Typically, there were more than a dozen meetings a year with all of the stakeholders present, whereas before, the public and environmental NGOs were often excluded. There has thus been much opportunity for all stakeholders to interact. This led in the early 2000s to describing the regular meeting attendees as the "nuclear family".

Meeting organisers often made a special effort to attract all stakeholders. The Nuclear Waste Council, a committee appointed by the government, usually at least once a year invited most stakeholder organisations, excluding SKB, to send a few representatives to a roundtable discussion about current priorities.

THE DECISION MAKING PROCESS AND MILESTONE DATES

1— PUBLIC CONSULTATION

From 2002 to 2014. Beginning in 2005, funding became available from the Nuclear Waste Fund for environmental NGOs to participate in the public consultation process. Municipalities involved in site investigation studies began to receive funding from the Nuclear Waste Fund in about 2001. In 2007, an evaluation of the support to the NGOs was carried out by the Swedish Agency for Public Management (*Statskontoret*), the government agency for analysis and evaluation of state and state-funded activities. The result was a recommendation to continue the funding.[29] Funding has continued to date, though in 2017 began to come from the government's general budget, rather than the Nuclear Waste Fund.

2—FORMAL SUBMISSION OF APPLICATIONS

16 March 2011. The law requires submission of applications according to two areas of law, as well as compliance with laws that are the responsibility of the respective county and municipality. One of these areas of law is the Environmental Code, which is handled by the Land and Environment Court (*Mark- och miljödomstolen*) (MMD), that addresses environmental impacts in general, including impacts on human health. The other area of law is the Nuclear Activities Act, which is handled by the Swedish Radiation Safety Authority (*Strålsäkerhetsmyndigheten*) (SSM) and focuses on radiation safety issues. The applications together comprise about 9,000 pages (excluding later submitted supplementary information) of which there is an approximate 2,000 page overlap.

3— ASSESSMENT OF THE APPLICATIONS WITH REGARD TO COMPLETENESS

During this phase, both SSM and MMD carried out rounds of public consultations where the public was invited to submit comments on the completeness of the initial application documents, and then on SKB's replies, which included supplementary information both requested by SSM and MMD, as well as provided on SKB's own initiative.

4 — RELEASE OF THE APPLICATIONS FOR PUBLIC REVIEW

29 January 2016 by both SSM and MMD. The ensuing review included further rounds of public comment.

5—FORMAL, LEGAL, PUBLIC, ORAL HEARINGS HELD BY MMD

Five weeks of hearings were held in September and October 2017, including three weeks in Stockholm and one week in each of the municipalities of Östhammar and Oskarshamn, and on-site inspections of the two locations. During these hearings, independent scientists who made submissions took the position that the application should not be approved because of uncertainties in the area of their particular expertise. All the environmental NGOs and members of the general public who participated also took the position that the application should not be approved, for a wide range of reasons including the moral and ethical dimension. Many of the independent scientists and representatives of the environmental NGOs were veterans who had followed the nuclear waste issue since the 1970s. The municipality of Oskarshamn expressed support for the proposal, and the municipality of Östhammar declined to take a position.

6—FINAL STATEMENTS TO THE GOVERNMENT BY SSM AND MMD

23 January 2018. These statements cannot be appealed in the court system. Reuters reported the same day that Environment and Energy Minister Karolina Skog stated no decision would be made during 2018.[30] That was to be expected due to the date for Swedish parliamentary elections set for 9 September 2018. Östhammar municipality had planned a non-binding referendum 4 March 2018. Only hours after the announcement on 23 January 2018 of the "no" by MMD , Östhammar municipality cancelled their referendum, stating they would re-examine the need for a referendum in the future. SSM had been examining the nuclear industry's waste plans since the agency was founded in 2008, and had inherited responsibility from the agency's predecessors. For MMD the review was a first worldwide for a court of law.

7— INITIAL GOVERNMENT REVIEW:

began 23 January 2018 and is currently underway. The government appointed a working group that has requested SKB provide comments on specific information by 30 April 2019. Taking place at the same time as this government review is a special government examination of the Nuclear Activities Act, which is planned to be completed by April 2019 at the latest.

8— REQUEST BY THE GOVERNMENT FOR THE RESPECTIVE MUNICIPALITY TO MAKE A DECISION REGARDING PERMISSIBILITY

If the government does not at the outset reject SKB's application, before making its decision, which is termed a decision on permissibility, the government must ask the local municipalities of Östhammar and Oskarshamn if they will permit the respective local activity. If a municipality says no, but the government wants to approve permissibility, the government can regardless give approval under certain conditions, i.e. force the municipality to accept the facility. Though the government has not yet communicated with the two municipalities on the subject, on 11 June 2018 the municipality of Oskarshamn gave their approval to the government for continued operation of the Clab interim storage facility and for construction of the encapsulation facility, referred to as Clink. The municipality of Östhammar has stated that they will wait for contact from the government, and may carry out a non-binding municipal referendum before making a decision.

9—FINAL GOVERNMENT REVIEW AND DECISION.

In this phase the government has authority to decide whether or not a full parliamentary debate will be held. Previous Ministers and some individual Members of Parliament have stated that they favour a full parliamentary debate. If the government gives its approval, it is possible to appeal the decision to the Supreme Administrative Court. Environmental lawyers have pointed out that without adequate facts, government approval would not comply with the Environmental Code due e.g. to uncertainty regarding the risks of corrosion of the copper canisters.[31]

10 — IF GOVERNMENT APPROVAL IS GRANTED, REGULATION OF IMPLEMENTATION

If the government gives its approval, the industry application goes back to both SSM and MMD who must set conditions for implementation according to their respective laws. The nuclear industry is obligated to comply with these conditions. In theory, a condition can be so stringent that the industry is unable to comply. The conditions set by the MMD can be appealed to a higher court. The industry can apply to be able to carry out its implementation unhindered during an appeal process. Once implementation begins, the County Administrative Board (*Länsstyrelsen*) and the Environmental Protection Agency (*Naturvårdsverket*) have responsibility for monitoring compliance with the Environmental Code. The Radiation Safety Authority monitors compliance with the Nuclear Activities Act.

"DECISION-MAKING IN THE FACE OF UNCERTAINTY"

"Decision-making in the Face of Uncertainty" is the title of the 2018 annual "Nuclear Waste State-of-the-Art Report" published by the Swedish Council for Nuclear Waste. The council is a committee of specialists appointed by the government to "clarify matters relating to nuclear waste and decommissioning and dismantling of nuclear facilities and to advise the Government in these matters".[32] The subject matter, for which about 118 pages are devoted, and title of the report was well chosen as at the time of this writing, more than 40 years after the KBS project began, there is a general consensus among all stakeholders, with few exceptions, that there are many uncertainties. The stakeholders with this common ground include both proponents and opponents of the industry proposal currently being examined: the nuclear industry, all levels of government, independent researchers, and environmental NGOs. There is however a wide range of views among this diverse group of organisations and individuals about the severity of the uncertainties and how to deal with them, with seemingly all possible combinations present. This is particularly evident when comparing the results of the reviews by the Land and Environment Court (MMD) and the Swedish Radiation Safety Authority (SSM). The main results of their reviews are given below, followed by a short comparison of the two.

RESULT OF THE REVIEW BY SWEDISH RADIATION SAFETY AUTHORITY (SSM)

SSM wrote in their 23 January 2018 statement to the government that they approve SKB's application provided certain conditions are met. Following are three quotes from the statement (emphasis added).

PRECONDITIONS FOR SSM'S RECOMMENDATION

SSM recommends approval of the licence applications **subject to the precondition that SKB ensures that the preparatory preliminary safety analysis reports (F-PSARs) as well as management systems for the facilities are further developed** in accordance with the established procedure for a step-wise permitting process under the Act on Nuclear Activities,... [33]

SKB may commence construction of the facility only after SSM has examined and approved a Pre-construction Safety Analysis Report (PSAR).[34]

SKB's preparatory preliminary safety reports for the encapsulation plant and the final repository, prior to the government's decision on a permit under the Nuclear Activities Act, aim primarily to justify the company's selection of location and method in the permit application. For the examination of SKB's documentation for the permit review regarding these issues, SSM takes into account that **certain supplementary information is expected** for details during the continued stepwise review process after a government decision on permission and before a decision by SSM to allow the facilities to begin operation.[35]

Specifically with regard to the copper corrosion issue SSM wrote that the issue might be resolved in the future. Three quotes from the statement on this topic follow (emphasis added).

According to SSM **there is potential to achieve** an acceptable corrosion barrier with a 50 mm thick copper casing.[36]

A development phase is also required to demonstrate appropriate techniques for manufacturing, sealing and testing such canisters to make it likely that the required requirements can be complied with.[37]

SSM has not formulated specific requirements related to the speed of corrosion of the encapsulation.[38]

THE MMD REVIEW - THE ONLY REVIEW WORLDWIDE BY A COURT OF LAW

The review by a court of law in Sweden of the application by the Swedish nuclear industry to build a system for managing spent fuel is the only review by a court of law ever to have taken place anywhere in the world dealing specifically with an application for a spent fuel management system.[39] The review was based on the area of law termed the Environmental Code (*Miljöbalken*), which came into force in 1999 in order to better formulate regulations spread over a multitude of other laws.36F[40] Compliance with the Environmental Code is handled by a special branch of the court system called the Land and Environment Court (*Mark- och miljödomstolen*) (MMD).37F[41] An MMD review is a formal court process that results in either a judgment or in some specific situations in a statement to the government regarding permissibility. For such exceptions, if the government decides to permit the activity, the case is returned to MMD to examine details of the permit and conditions that apply. According to Chapter 17, Section 1 (1) of the Environmental Code an application to build a spent fuel management system is such an exception. Thus, responsibility for the final decision rests with the government. The statement by MMD, and by the Radiation Safety Authority (SSM) according to the Nuclear Activities Act, are considered recommendations to the government and cannot be appealed in a court process.

The Land and Environment Court is usually made up of a four-member panel consisting of one judge, one technical counsellor, and two special members with technical competence. In exceptional situations, so as to broaden the expertise available to the court, two more members may be added. This occurred with the application to build a spent fuel management system, which was heard by a six-member panel, the maximum number that may be appointed. There were two judges, two court technical councillors, and two special members.

RESULT OF THE REVIEW BY THE COURT: NO APPROVAL UNLESS CERTAIN CONDITIONS ARE MET

MMD wrote in their press release regarding their 23 January 2018 statement to the government:

The court cannot, based on the current safety assessment, find that the final repository is safe in the long-term.[42]

Though the overall result of the Land and Environment Court (MMD) review was that the industry application should not be permitted, some aspects of the application were considered permissible, e.g. the encapsulation plant, where the copper canisters are intended to be built and loaded. The formulation used for the overall result was not that the activity should be prohibited due to certain deficiencies, but rather the activity can be permitted if specific uncertainties are resolved. The court wrote the following on page one of its 23 January 2018 statement, which is also included as page one in the separately published summary.

The disposal activity is permissible if:

The Swedish Nuclear Fuel and Waste Management Co. provides documentation that the final repository will meet the requirements of the Environmental Code in the long term, despite remaining uncertainties regarding how the protective capability of the canister is affected by:

a. corrosion due to reactions in oxygen-free water
b. pit corrosion due to reaction with sulphide, including the contribution of the sauna effect to pit corrosion
c. stress corrosion due to reaction with sulphide, including the contribution of the sauna effect to stress corrosion
d. hydrogen embrittlement
e. radioactive radiation impact on pit corrosion, stress corrosion and hydrogen embrittlement.

The long-term responsibility for the final repository according to the Environmental Code has been clarified.[43]

Regarding various uncertainties, following are more quotes from the court's statement.

LONG TERM RESPONSIBILITY:

According to the SKB application their responsibility ends after a few decades when the facility is sealed. The court however clearly opposed the industry approach of abandonment. The Land and Environment Court is of the view that the final storage of nuclear waste is an activity that will continue even after the final repository is sealed. According to the Environmental Code, **the licensee has a responsibility for the activity until further notice, i.e., there is no time limit**. ... Östhammar municipality is opposed to taking ultimate responsibility for the final repository. ... **It is of urgent importance to clarify who has long-term responsibility** under the Environmental Code.[44]

RISK OF COPPER CORROSION:

The investigation shows that there are uncertainties, or risks, regarding how much certain forms of corrosion and other processes can impair the ability of the canister to contain the nuclear waste in the long term. **Overall, these uncertainties about the canister are significant and have not been fully taken into account** in the conclusions of SKB's safety analysis.[45]

RADIATION SAFETY

SKB and SSM have expressed the view that conditions relating to radiation safety should not be prescribed in a permit under the Environmental Code. **The Court finds that the evidence presented to date does not provide a sufficient basis on which to assess the issue.**[46]

RISK IN GENERAL

...a new calculated result of the entire safety assessment is required...[47]

— UNCERTAINTIES IN GENERAL CONCERNING THE REPOSITORY, RADIATION SAFETY, AND THE GEOLOGIC CONDITIONS

The Land and Environment Court finds that a number of uncertainties regarding the protective capability of the repository remain outstanding. The investigation of radiation safety issues to date shows that the effects of the activity cannot be predicted with enough certainty to permit the formulation of any final conditions. There may therefore be a need to provide for a probationary period for evaluation under the Environmental Code. However, further investigation and deliberation are necessary. **The Court however emphasizes that the study of the bedrock formation at Forsmark, for example, leaves ambiguities that may justify a probationary period** for evaluation for the determination of conditions regarding respect distances or other precautionary measures.[48]

— UNINTENTIONAL AND INTENTIONAL INTRUSION

• The issue of long-term knowledge retention should be resolved at the latest when the repository is sealed in about 70 years.[49]

• Comparison of the Statements by SSM and MMD to the Government

• SSM gave a yes providing certain conditions are met, and MMD gave a no unless certain conditions are met. The legal tradition followed by MMD does not allow giving approval if events in the future eventually lead to compliance. On this topic MMD stated:

• When assessing the long-term safety of the final repository, no consideration can be given to research and development to be undertaken after a decision on permissibility.[50]

• Though SSM and MMD used different formulations, for SKB the result in practice in some key areas is the same. Both SSM and MMD see the need for an improved overall safety analysis and resolution of the copper corrosion issue as severe. For both SSM and MMD the uncertainties surrounding copper corrosion are currently so great that the project should not be implemented unless the uncertainties are resolved. Further, of primary importance is that both SSM and MMD recommended to the government that SKB at present not be allowed to begin construction of any part of the system applied for.

— LOW AND MEDIUM LEVEL NUCLEAR WASTE

There is currently an operating facility for storage of low and medium level nuclear waste, owned and operated by the Swedish nuclear industry. The facility is called SFR[51] and is located at Forsmark in the municipality of Östhammar, about 145 km north of Stockholm. SFR began operation in 1988. The facility is in bedrock from 50 to 140 meters below the Baltic Sea and consists of four caverns 160 meters in length and a chamber with a 50 m deep silo. The facility is connected to the surface with two parallel km long tunnels. SFR has a capacity of 63,000 cubic meters of waste, of which about 60% has been used to date. The facility is continually filling with water, which is being pumped out. Closure of the facility entails shutting off the pumps, thus allowing the facility to fill with water. A major uncertainty is the rate of contamination by radioactivity of the Baltic Sea that will result.

There is currently a legal review underway for an additional low and medium level waste facility proposed to be placed immediately adjacent to the currently operating one. The proposed new facility is twice as big as the current one, is proposed to also be underneath the Baltic Sea but at a depth of 120–140 m below the surface. This new facility is subject to the same decision making process described above for management of spent fuel. SKB has estimated that if all the approvals required are received, construction could begin sometime in 2020 and take about six years.[52]

FINLAND – BRIEF OVERVIEW OF THE CURRENT SITUATION

There are two nuclear power stations in Finland, Olkiluoto and Loviisa. At Loviisa there are two reactors in operation. At Olkiluoto there are two reactors in operation and one under construction.[53] A fourth has received a construction permit from the government but work has not begun. The one under construction has faced huge economic problems to the extent that it remains to be seen if it will ever be completed.[54] According to Posiva, at the end of 2017 from both Olkiluoto and Loviisa there was a total of 2,200 tonnes of spent fuel.[55]

In 2011, Posiva submitted its application to the Radiation and Nuclear Safety Authority (STUK) to build a KBS-3 facility, and received permission from both STUK and the government in 2015.[56] There was no review by a court of law. The facility, called "Onkalo", has a capacity to hold about 6.500 tonnes of spent fuel, though can be expanded. Shafts and tunnels have been excavated to the planned depth of about 470 meters. The phase currently underway is test deposition. An encapsulation facility has not yet been constructed.[57] The facility was originally planned to be completed in the year 2020[58], and is now delayed until 2023.[59]

The reason for the speed at which a facility is being built in Finland compared to Sweden is that in the year 2000 the government made a decision in principle to use the KBS-3 method and chose the location Olkiluoto, situated adjacent to the Olkiluoto nuclear power station.

The technical issues listed above in the description of the KBS-3 facility in Sweden apply as well to the facility already build in Finland. Also, Finland is relying on the assessment of the copper corrosion issue in Sweden, rather than carrying out its own research. The geological conditions are in general similar. The depth of the facility is the same, and thus the research in Finland noted above, that the depth may not be adequate to withstand permafrost in the next ice age, also applies to Sweden.[60]

Regarding costs, in July 2015 the Finnish Ministry of Employment and the Economy, Energy Department estimated total future costs to the point of closure of all the facilities for handling all the nuclear waste originating from nuclear reactors to be EUR 6.5 billion, of which the costs for spent fuel will be EUR 3.5 billion.[61]

KBS-3: the third version of the *Kärnbränslesäkerhet* (Nuclear Fuel Safety) project formed by the Swedish nuclear industry.

• *MMD: Mark-och miljödomstolen* (Land and Environment Court)

• SKB: *Svensk Kärnbränslehantering AB* (Swedish Nuclear Fuel and Waste Management Co.)

• SSM: *Strålsäkerhetsmyndigheten* (Swedish Radiation Safety Authority), the regulatory agency dealing with radiation issues

For More Information from Environmental NGOs in Sweden
• The Swedish NGO Office for Nuclear Waste Review (MKG): www.mkg.se/en

• The Swedish Environmental Movement's Nuclear Waste Secretariat (Milkas): www.milkas.se and www.nonuclear.se/en/kbs3

1 Jonter, T. 2002. “Nuclear Weapon Research in Sweden. The Co-operation Between Civilian and Military Research, 1947-1972.” SKI Report 02:18. 82 pp. Available in PDF (533 KB) at (10 July 2018):
https://www.stralsakerhetsmyndigheten.se/en/publications/reports/non-proliferation/2002/200218/

2 IAEA. Undated. “Power Reactor Information System (PRIS), Sweden.” Available at (5 October 2018):
https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=SE.

3 Lindström Marianne, Åhäll Karl-Inge, Holmstrand Olov, Helander Björn, Goldstick Miles.1998-06. “Nuclear Waste in Sweden - The Problem Is Not Solved!” Available at (5 October 2018): http://www.nonuclear.se/nuclear-waste-in-sweden1988. Direct link to the section on the 1980 referendum:
http://www.nonuclear.se/nuclear-waste-in-sweden1988#nwchap4.

4 Karlsson, Lasse. 2016-07-05. “Historien om avvecklingen som inte blivit av. Aktualiserad juni 2016. Framställt för Folkkampanjen mot Kärnkraft-Kärnvapen.” (“The Story About the Phase-out that Didn’t Happen. Updated June 2016. Prepared for the Swedish Anti-nuclear Movement.”) (In Swedish only.) Available at (5 October 2018):
http://www.nonuclear.se/historien-om-avvecklingen-lasse-karlsson.

5 Government Offices of Sweden. 16 June 2016 .“Framework agreement between the Swedish Social Democratic Party, the Moderate Party, the Swedish Green Party, the Centre Party and the Christian Democrats.” Available at (5 October 2018):
https://www.government.se/49d8c1/contentassets/8239ed8e9517442580aac9bcb00197cc/ek-ok-eng.pdf.

6 SKB. 2017-09-21. “Organisation.” SKB website (10 July 2018):
http://www.skb.com/about-skb/organisation/

7 Vattenfall. 2015-10-22. “Ownership.” Vattenfall website (10 July 2018:
https://corporate.vattenfall.com/investors/key-facts/ownership/.

8 SKB. 2017-04. “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.” Technical Report TR-17.02. 52 pp. See p. 35. Available at (5 October 2018):
https://www.skb.se/publikation/2487964/TR-17-02.pdf.
Some of the spent fuel from the research reactors is included in the KBS-3 application but is not included in the estimated quantity in tonnes, though is included in the estimate in the number of canisters.

9 Ibid. See pp. 37-38.

10 The Nuclear Waste Fund. 2018. “Facts about the Nuclear Waste Fund 2017”. 20 pp. Available at (5 October 2018):
http://www.karnavfallsfonden.se/informationinenglish/annualreport.4.4945b3d81223a8cbbf8800024168.html.
Direct link (5 October 2018):
http://www.karnavfallsfonden.se/download/18.46d462c3159fb761aca1f4f/1523619691724/Fakta+om+K%C3%A4rnavfallsfonden+2017+engelska.pdf (276 KB).

11 Ibid. See p. 2.

12 Op. cit., note 8. See p. 39.

13 SKB. 2016-09. “Programme for research, development and demonstration of methods for the management and disposal of nuclear waste.” Technical Report TR-16-15. 314 pp. Available at (5 October 2018).
https://www.skb.se/publikation/2485289/.
The financial data is given in a separate document, of which “Plan 2016” referenced above is the companion volume for 2016.

14 See e.g. the government’s decision on the 1995 and 1998 reports, for which the references follow. [1995] Miljödepartementet. 1996-12-19. “Regeringens beslut. Program för forskning m.m. angående kärnkraftavfallets behandling och slutförvaring.” In Swedish only. 6 pp. See p. 3. [1998] Miljödepartementet. 2001-11-01. “Regeringens beslut. Komplettering av program för forskning, utveckling och demonstration för kärnavfallets behandling och slutförvaring, Fud-program 98.” In Swedish only. 8 pp. See p. 1.

15 Much of the application is available in English on the SKB website, e.g. (5 October 2018):
http://www.skb.com/future-projects/the-spent-fuel-repository/our-applications/.

16 See e.g.: Chatzis, Irena (IAEA Department of Nuclear Energy). 5 January 2018. “Solving the Back End: Finland’s Key to the Final Disposal of Spent Nuclear Fuel.” Available at (5 October 12018):
https://www.iaea.org/newscenter/news/solving-the-back-end-finlands-key-to-the-final-disposal-of-spent-nuclear-fuel#infobox.

17 Kamp, Kevin. 2010-11-16. “Statement of Kevin Kamps, Beyond Nuclear to Blue Ribbon Commission on America’s Nuclear Future, November 16, 2010, Washington, D.C.” Available at (5 October 2018): http://www.nonuclear.se/KevinKampBRC20101116.

18 Mörner, Nils-Axel. 2013. "Dry Rock Deposit - an alternative of handling the high level nuclear waste - the DRD method - a short presentation." 30 pp. Available at (5 October 2018):
http://www.nonuclear.se/drd_method2013morner.

19 SKB. 2016-11-02. "Our method of final disposal." Available at (5 October 2018):
http://www.skb.com/future-projects/the-spent-fuel-repository/our-methodology/.
The "3" in "KBS-3" is sometimes interpreted as referring to the three barriers though that was not the meaning initially.

20 Op. cit., note 8. See p. 36.

21 SKB. 2010-12. "Design, production and initial state of the canister." Technical Report TR-10-14. See p. 28 re. weight, and pp. 33-34 for dimensions. Available from (10 July 2018):
http://skb.se/upload/publications/pdf/TR-10-14.pdf (3.8 MB).

22 SKB addresses the permafrost depth issue on e.g. page 200 in their March 2011 application in the document: "Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. Volume I. Technical Report TR-11-01." A 2015 study by specialists at the University of Turku, Finland found that in the next ice age permafrost could reach to the depth of the planned repository in Finland and Sweden. Reference for the report: Räsänen, Matti E.; Huitti, Janne V.; Bhattarai, Saroj; Harvey Jerry III; Huttunen, Sanna. 2015.
«The SE sector of the Middle Weichselian Eurasian Ice Sheet was much smaller than assumed.» Quaternary Science Reviews 122 (2015) 131e141.
All authors from University of Turku, Finland. Available at (5 October 2018):
https://www.sciencedirect.com/science/article/pii/S0277379115002243.

23 Swedish Environmental Movement's Nuclear Waste Secretariat (Milkas). 2006-12. "The Baltic Sea is Radioactive." 4 pp.
Available at (5 October 2018): http://www.nonuclear.se/baltic-radioactive200612.html.

24 Copper Development Association Inc.. December 1998. "Copper's Role in the Safe Disposal of Radioactive Waste: Copper's Relevant Properties - Part I." Available at (5 October 2018): https://www.copper.org/publications/newsletters/innovations/1998/12/nuclear.html; and Source: Hultquist, G. B., Szakálos, P., Graham, M. J., Sproule, G. I., & Wikmark, G. 2008. Detection of hydrogen in corrosion of copper in pure water. In Int. Corros. Congr.: Corros. Control Serv. Soc. (pp. 2378–2386). Available at (5 October 2018):
https://www.researchgate.net/publication/238102363_Detection_of_hydrogen_in_corrosion_of_copper_in_pure_water (PDF, 2.5 MB).

25 Macdonald Digby D.; Sharifi -Asl, Samin; Engelhard, George R.; Urquidi-Macdonald, Mirna. "Issues in the corrosion of copper in a Swedish high level nuclear waste repository." 2012. Swedish Radiation Safety Authority (SSM) Report number 2012:11. 160 pp.
Available at (5 October 2018): https://www.stralsakerhetsmyndigheten.se/en/publications/reports/waste-shipments-physical-protection/2012/201211/.

26 Regarding the presence or absence of oxygen see: He, Xihua & M. Ahn, Tae & Gwo, Jin-Ping. 2017. Corrosion of Copper as a Nuclear Waste Container Material in Simulated Anoxic Granitic Groundwater. CORROSION. 74. 10.5006/2471.

27 Szakálos Peter, Leygraf Christofer, Rosengren Anders, Seetharaman Seshadri, Grinder Olle, Linder Jan. 2018-04-26. "Analys av kärnbränsleförvarsfrågan efter mark-och miljödomstolens yttrande till regeringen." ("Analysis of the nuclear fuel management issue after the Land and Environment Court's statement to the government.") In Swedish only. 4 pp. Available at (5 October 2018):
http://www.nonuclear.se/szakalos-et-al20180426analys-av-karnbransleforvarsfragan. This document was submitted to the government for its ongoing review, and the government has requested comments from SKB by 30 April 2019. The authors include a group of specialists at The Royal Institute of Technology (KTH) in Stockholm, who are at the forefront of copper corrosion research worldwide, and a former employee of SSM. Research in Sweden on copper corrosion by independent specialists was spearheaded by KTH Associate Professor Gunnar Hultquist, who died in February 2016. He initiated an experiment in 1986 showing that copper corrodes in oxygen-free water. His results were eventually confirmed internationally by independent methods.

28 Ibid.

29 Statskontoret. 2008-04-17. Samråd, stöd och slutförvar – en utvärdering av stöd till ideella organisationer ur Kärnavfallsfonden. 104 pp. In Swedish only. Available at (5 October 2018):
http://www.nonuclear.se/statskontoret20080417.html.

30 Reuters. 2018-01-23. "Swedish regulators disagree on safety of nuclear waste plan." Available at (5 October 2018):
https://uk.reuters.com/article/us-sweden-nuclear-regulator/swedish-regulators-disagree-on-safety-of-nuclear-waste-plan-idUKKBN1FC21P

31 SVT Nyheter (Swedish Television News). 2018-01-25. "*Miljöjurister om slutförvaret: Osäkerhet bör leda till ett nej*." ("Environmental lawyers comment on the final repository: uncertainty should lead to a no.") In Swedish only. Available at (5 October 2018):
https://www.svt.se/nyheter/lokalt/uppsala/miljojuristen-regeringen-borde-saga-nej.

32 This quote is from the Council's website, Available at (5 October 2018): http://www.karnavfallsradet.se/en. The annual reports are available in Swedish and English at the Council's website. For the 2018 report see: http://www.karnavfallsradet.se/en/nuclear-waste-state-of-the-art-report-2018-decision-making-in-the-face-of-uncertainty. Direct link (10 July 2018) (1.1 MB):
http://www.karnavfallsradet.se/sites/default/files/documents/sou_2018_8_eng_webb.pdf.

33 SSM. 2018-01-23. "Pronouncement on licence applications for permission to develop facilities for final management of spent nuclear fuel - Statement of the Swedish Radiation Safety Authority." 5 pp. See p. 2. Ref. no: SSM2011-1135 and SSM2015-279. Document no: SSM2011-1135-23. Available at (5 October 2018):
https://www.stralsakerhetsmyndigheten.se/en/areas/radioactive-waste/spent-nuclear-fuel-repository/final-repository-for-spent-nuclear-fuel/our-review-process/pronouncement-on-repository-applications/. Direct link to PDF (364 KB) (5 October 2018): https://www.stralsakerhetsmyndigheten.se/contentassets/078506f952ae4357847628edcc1785a4/pronouncement-on-licence-applications-for-permission-to-develop-facilities-for-final-management-of-spent-nuclear-fuel-statement-of-the-swedish-radiation-safety-authority.
Swedish original: SSM. 2018-01-23. "Yttrande över ansökningar om tillstånd till anläggningar för slutligt omhändertagande av använt kärnbränsle." 4 pp. See p. 2. Diarienr: SSM2011-1135 and SSM2015-279. Dokumentnr: SSM2011-1135-23. Available at (5 October 2018):
https://www.stralsakerhetsmyndigheten.se/omraden/radioaktivt-avfall/slutforvar/slutforvar-for-anvant-karnbransle/stralsakerhetsmyndighetens-granskning-av-ansokan/slutforvarsyttrande-till-regeringen/. Direct link to PDF (5 October 2018) (345 KB): https://www.stralsakerhetsmyndigheten.se/contentassets/b99c23f76a044b57b76174051b587407/ssm2011-1135-23-yttrande-over-ansokningar-om-tillstand-till-anlaggningar-for-slutligt-omhandertagande-av-anvant-karnbransle.pdf.

34 Ibid. See p. 3.

35 SSM. 2018-01-23. "2018:02. Sammanfattning. Beredning inför regeringens prövning Slutförvaring av använt kärnbränsle." In Swedish only. Unofficial translation. 102 pp. See p. 10. Report no. 2018:02 ISSN 2000-0456. Available at (5 October 2018):
https://www.stralsakerhetsmyndigheten.se/omraden/radioaktivt-avfall/slutforvar/slutforvar-for-anvant-karnbransle/stralsakerhetsmyndighetens-granskning-av-ansokan/slutforvarsyttrande-till-regeringen/. Direct link to PDF (10 July 2018) (2.3 MB):
https://www.stralsakerhetsmyndigheten.se/contentassets/96342ee1d37e4111b032be88ccb158bf/201802-sammanfattning.

36 Ibid. See p. 66.

37 SSM. 2018-01-23. "2018:03. Remissammanställning. Beredning inför regeringens prövning Slutförvaring av använt kärnbränsle." In Swedish only. Unofficial translation. 142 pp. See p. 48. Report no. 2018:03 ISSN 2000-0456. Available at (5 October 2018):
https://www.stralsakerhetsmyndigheten.se/omraden/radioaktivt-avfall/slutforvar/slutforvar-for-anvant-karnbransle/stralsakerhetsmyndighetens-granskning-av-ansokan/slutforvarsyttrande-till-regeringen/.
Direct link to PDF (10 July 2018) (2.6 MB):
https://www.stralsakerhetsmyndigheten.se/contentassets/a3ade3d30e7944038eeed5dc33ef8edf/201803-remissammanstallning.

38 Ibid. See p. 98.

39 There have however been court proceedings that have included spent fuel management in a general sense as part of the case. Two Greenpeace initiated examples are the rejection in 1995 by the Supreme Court regarding construction of a reprocessing plant in Zheleznogorsk in the Krasnoyarsk Territory of Russia, and the High Court ruling in the UK in 2007 that a "misleading" and "seriously flawed" consultation process had been carried out by the government on the construction of new nuclear power plants.
An IAEA report from 1993 "Nuclear Energy Inquiries - National and International" documents more than 30 inquires that vary widely in nature (http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/25/026/25026317.pdf). In Canada, in 1997 a 10-year federal environmental assessment review of AECL's planned concept for a geologic repository was concluded. No site was chosen and the conclusion was that there were many unanswered questions about the system and thus it was not ready to be implemented (see e.g.: www.ccnr.org/fearo_hlw.html and www.ccnr.org/hlw_fearo_summary.html). Also in Canada there is a 1980 report of nuclear waste management that followed 15 weeks of hearings by the Parliamentary Select Committee on Ontario Hydro Affairs. The California Energy Conservation and Development Commission under the guidance of Emilio Varanini III conducted a series of hearings in the 1970s on the question of whether or not there exists a safe method for disposing of spent fuel and concluded that such a method did not currently exist, and also stated that such a method may never exist. Emilio Varanini III, in an interview, famously said that the belief in safe disposal was based not so much on scientific evidence but rather on "engineering euphoria". The California Report had legislative consequences, as the California Legislature had previously enacted a law banning any further nuclear reactors in California unless a safe disposal method could be shown to exist. The Legislature accordingly asked the Commission to determine whether or not such was the case. The Legislature accepted the advice of the Commission and so no new reactors were allowed in California.

40 Government Offices of Sweden. 1999. "The Swedish Environmental Code, Ds 2000:61." 164 pp. Available at (5 October 2018):
https://www.government.se/legal-documents/2000/08/ds-200061/. Direct link (10 July 2018):
https://www.government.se/49b73c/contentassets/be5e4d4ebdb4499f8d6365720ae68724/the-swedish-environmental-code-ds-200061 (PDF, 559 KB). This English version does not include revisions that came into force on 1 August 2018, which changed the clause regarding nuclear activities from Chapter 17, Section 1 (6) to Chapter 17, Section 1 (1).

41 See the website of the Swedish Courts, e.g. (10 July 2018):
http://www.domstol.se/Funktioner/English/The-Swedish-courts/District-court/Land-and-Environment-Courts/

42 Mark- och miljödomstolen, Nacka tingsrätt. 2018-01-23. ”Mark- och miljödomstolen lämnar sitt yttrande till regeringen i målet om ett slutförvar för kärnavfall”. (Unofficial translation: ”The Land and Environment Court submit their statement to the government in the case regarding a final repository for nuclear waste”.) In Swedish only. Available at (5 October 2018):
http://www.nackatingsratt.domstol.se/Om-tingsratten/Uppmarksammade-mal/Ansokan-om-slutforvar-for-anvant-karnbransle-mm/.

43 Nacka District Court, Land and Environmental Court. 2018-01-23. “Summary Statement of the Land and Environmental Court, Case no. M 133-11, Matter: Permit according to the Environmental Code for an integrated system for final disposal of spent nuclear fuel and nuclear waste; at this time a matter of a statement to the government.” Unofficial translation. Available at (5 October 2018):
http://www.nonuclear.se/mmd20180123summary-statement-case-m1333-11spent-fuel.

44 Ibid. See page 4 *

45 Op. cit., note 44, see page 4.

46 Op. cit., note 44, see page 11.

47 Op. cit., note 44, see page 10.

48 Op. cit., note 44, see pp. 11-12.

49 Mark- och miljödomstolen, Nacka tingsrätt. 2018-01-23. ”Yttrande, Mål nr M 1333-11, Saken: Tillstånd enligt miljöbalken till anläggningar i ett sammanhängande system för slutförvaring av använt kärnbränsle och kärnavfall; nu fråga om yttrande till regeringen”. 566 sid. Se sid. 80. In Swedish only. Available at (5 October 2018):
http://www.nackatingsratt.domstol.se/Om-tingsratten/Uppmarksammade-mal/Ansokan-om-slutforvar-for-anvant-karnbransle-mm/.

50 Op. cit., note 44, see page 6.

51 SKB. Undated. “SFR - Final Repository for Short-lived Radioactive Waste.” Six pp. Available at (5 October 2018):
http://www.skb.com/our-operations/sfr/. Direct link to download (5 October 2018): http://skb.se/upload/publications/pdf/SFR_folder_engelsk.pdf.

52 SKB. 2017-12-11. “Planned extention of the SFR.” SKB website. Available at (5 October 2018):
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6

UNITED KINGDOM

UK RADIOACTIVE WASTE 'DISPOSAL' POLICY

Pete Roche

The launch of two new consultation documents[1] in January 2018 marked the start of the UK Government's sixth attempt in the past 42 years to find a community willing to host a radioactive waste dump. Having failed to find a site for a nuclear waste dump during the 1970s, 80s and 90s the Government decided to try a new approach based on what it called "voluntarism and partnership". Past experience had taught the Government and nuclear industry that it wouldn't get away with imposing a nuclear waste facility without the community's consent but both continue to insist that geological disposal is the only way forward.[2]

In 2003 the UK Government set up a new independent committee – the Committee on Radioactive Waste Management (CoRWM) to review options for managing radioactive waste and make recommendations. Three years later the Committee made a series of recommendations. Although it recommended that geological disposal was the best available option for existing and committed waste arisings, there were lots of caveats and other important recommendations which the Government ignored. For instance it said "…*the uncertainties surrounding the implementation of geological disposal …lead CoRWM to recommend a continued commitment to the safe and secure management of wastes*."[3]

Former CoRWM member Professor Andy Blowers explains: "*Deep disposal may be the eventual long-term solution but demonstrating a safety case, finding suitable geology and a willing community are tough challenges and likely to take a long time. The search for a disposal site diverts attention from the real solution for the foreseeable future, which is to ensure the safe and secure management of the unavoidable legacy wastes that have to be managed*."[4]

On 30th January 2013, Cumbria County Council, in North-west England – home to the Sellafield nuclear reprocessing facility and the Lake District National Park - rejected the Government's plans to undertake preliminary work on an underground radioactive waste dump. The county and its western district councils Allerdale and Copeland were the only municipalities in the UK still involved in feasibility studies for a £12bn disposal facility. So the rejection left the UK once again, without a plan for dealing with its nuclear waste legacy, let alone waste from proposed new reactors.[5]

This fifth search for an underground site for a nuclear waste dump had started in 2008. Communities across the country were invited to talk to them about potentially hosting a site that would ultimately become a 'Geological Disposal Facility'. Allerdale Borough Council, Copeland Borough Council and Cumbria County Council were the only authorities to volunteer and agree to discuss the possibility of a search for a site in West Cumbria. The West Cumbria Managing Radioactive Waste Safely Partnership was set up by the three Councils "*to ensure that a wide range of community interests were involved in the discussions.*"[6]

The Partnership met roughly every six weeks for more than three years to look at the issues that would be involved in West Cumbria taking part in the search for somewhere to build a repository for higher activity radioactive waste. The Partnership's final report was published on 16th August 2012.[7] Although nowhere in Cumbria had been ruled out, apart from the areas ruled out by the British Geological Survey (BGS), two highly sensitive areas that could have been investigated further were identified by one geologist. These were Eskdale in the South West Lakes and Silloth in the North Lakes areas.[8]

At various public meetings in Cumbria, Professor Stuart Haszeldine of Edinburgh University[9], and Emeritus Prof David Smythe of Glasgow University, explained that more than enough information already existed to make a decision to exclude possible sites in Allerdale and Copeland. David Smythe said he had demonstrated that both the rock groups found around Eskdale and Silloth were unsuitable.[10]

Interestingly, Tim Knowles, who chaired the West Cumbria Managing radioactive Waste Safely Partnership, no longer supports the idea of geological disposal of nuclear waste in Cumbria. He appears to be of the view that Cumbria does not have suitable geology, and that there are much better sites elsewhere in the country. Tim suggested that near surface secure interim storage may be a better solution and that this could be under the Sellafield site. The key difference between this and a GDF, is that these facilities are retrievable stores, typically around 30 metres below the surface, with a lifespan of 100-200 years, rather than deep permanent disposal sites, so geology is much less important.[11]

SELLAFIELD – THE UNAVOIDABLE LEGACY

Sellafield – the site of the UK two operating reprocessing plants – is also located in Cumbria. In 2012, a National Audit Office (NAO) report criticised Sellafield for posing a "*significant risk to people and the environment*" because of the deteriorating conditions of radioactive waste storage facilities and called for immediate improvements in the management of major projects on site.[12] The lack of progress exposed in the NAO report prompted Rt. Hon. Margaret Hodge MP, chair of the House of Commons Public Accounts Committee (PAC) to declare that Sellafield posed an "*intolerable risk*".[13] Then in February 2013 PAC published its own report which described Sellafield as: "*…an extraordinary accumulation of hazardous waste, much of it stored in outdated nuclear facilities*".[14]

More recently, the National Audit Office (NAO) has detailed the unstable condition of highly dangerous plutonium canisters at the Sellafield nuclear plant, which it said were "*decaying faster than anticipated*".[15]
Hardly surprising then, that many argue that the priority should be to "*ensure the safe and secure management of the unavoidable legacy wastes that have to be managed*."

Cumbria County Council, for instance has called for more clarity on how the high level waste - the majority of which is currently stored at Sellafield will be kept safe if a suitable location is not identified "*There is also no detail provided about what will happen if no volunteer community is found within the 20 year period required to prepare for a GDF. Having a plan B for the safe storage of this waste during the 15 to 20 year period the government estimate this process, to identify and select a site, will take is vital. The waste is still in situ and needs safe surface or near surface storage facilities in the intervening time, which cannot be of a sub-standard quality*."[16]

40-YEAR SEARCH ENDED IN FAILURE

So after more than 60 years of a civil nuclear power programme, the UK is still seeking a long-term solution for dealing with its higher activity radioactive waste. The search for a site to build an underground dump began almost forty years ago in 1976 when eight potential sites were selected. This fuelled massive public opposition to nuclear waste disposal, which forced the Government to back down and abandon the programme in December 1981.

After several further attempts to find a dump site, the fourth attempt– promoted by the waste agency at the time, Nirex – was to build a "Rock-Characterisation Facility" at Sellafield. A public inquiry, lasting five months, was held at the end of 1995, ending on 1st February1996. On 17th March 1997, just prior to a General Election, the then Secretary of State for the Environment, John Gummer, rejected Nirex's planning application. So, when the Blair Government published its first Energy White Paper in February 2003 this quite sensibly said the Government would not be bringing forward proposals to build new nuclear power stations because "*there were important issues of nuclear waste to be resolved*".[17]

A NEW REACTOR PROGRAMME

When Gordon Brown's Government published another Energy White Paper in January 2008[18] it argued that sufficient progress had now been made on nuclear waste to justify a change in policy with regard to new nuclear build, ignoring yet another important recommendation of CoRWM. CoRWM 2006 recommendations included the observation that "… *the political and ethical issues raised by the creation of more wastes are quite different from those relating to committed – and therefore unavoidable –wastes*". Later the Committee elaborated saying: "… *a solution that is ethically acceptable for dealing with existing spent fuel is not necessarily a solution that would be ethically acceptable for dealing with new or changed materials*."[19]
In other words, Prof Blowers says: "*It is perverse to compound the problem by a new-build programme that will result in vastly increased radioactivity from spent fuel and other highly radioactive wastes which will have to be stored indefinitely at vulnerable sites scattered around our coasts*."[20]

NEW BUILD WASTE

Unlike the spent fuel from the UK's existing reactors which is transported, usually by train, to Sellafield in Cumbria for reprocessing, the Government does not expect spent fuel from new reactors such as Hin/kley Point C to be treated in that way. In fact the Thermal Oxide Reprocessing Plant (THORP) at Sellafield which reprocesses the spent fuel from the ageing Advanced Gas-cooled Reactors (AGRS) is due to close in 2018, and there are no plans to replace it.

The UK Government's Radioactive Waste Management Ltd. says the proposed new reactors for England and Wales will use high burn-up fuel (65 GW/tU) which will require a cooling period of up to 140 years before it could be emplaced in an underground repository – which could mean spent fuel stored on new reactor sites for up to 200 years (i.e. 140 years after the reactor closes). However by the judicious mixing of long-cooled and short-cooled Spent Fuel it's possible the duration of storage after the end of power station operation could be reduced to the order of 60 years before disposal (i.e. storage for 120 years).[21]

In any case a Geological Disposal Facility (GDF) is not expected to be ready to receive waste until at least 2040. Waste from new reactors like Hinkley Point C is not expected to be emplaced in the GDF until after all our existing waste has been emplaced which is expected to take around 90 years – until around 2130. So spent fuel from the UK's proposed new reactors could remain on site for at least the next 120 years.

The nuclear industry and government repeatedly claim that the volume of nuclear waste produced by new reactors will be small, approximately 10% of the volume of existing wastes; implying this additional amount will not make a significant difference to finding an underground dump for the wastes the UK's nuclear industry has already created.[22] The use of volume as a measure of the impact of radioactive waste is, however, highly misleading. Volume is not the best measure to use to assess the likely impact of wastes and spent fuel from a new reactor programme, in terms of its management and disposal.

The 'high burn-up fuel' which Hinkley Point C is expected to use will be much more radioactive than the spent fuel produced by existing reactors. So rather than using volume as a yardstick, the amount of radioactivity in the waste, which affects how much space will be required in a deep geological repository, are more appropriate ways of measuring the impact of nuclear waste from new reactors.

According to Radioactive Waste Management Ltd, the radioactivity from existing waste (i.e. not including new reactors) is expected to be 4,770,000 Terabecquerels (TBq) in the year 2200. The radioactivity of the spent fuel alone (not including other types of waste) generated by a 16GW programme of new reactors is expected to be around 19,000,000TBq. Hinkley Point C would be a 3.2GW station, so the amount of radioactivity in the spent fuel from Hinkley Point C alone in the year 2200 would be 3,800,000TBq – or about 80% of the radioactivity in existing waste.[23]

Finally, another way of examining the impact of nuclear waste produced by the UK's proposed new reactor programme is to look at the underground area likely to be taken up by existing waste and the area likely to be taken up by existing waste plus waste from a 16GW new build programme. The area required will depend on the rock type used.[24]

Rock Type	Inventory of waste created by existing reactors	Inventory from existing reactor plus new 16GW programme
High Strength Rock	5.6 km^2	12.3 km^2
Lower strength Rock	10.3 km^2	25.0 km^2
Evaporite	8.8 km^2	24.1km^2

It can be see that the area required underground for waste 'disposal' is almost tripled in some case by the new build reactor programme.

GEOLOGICAL DISPOSAL FACILITY SAFETY CASE

In 2010, the Nuclear Waste Advisory Associates (NWAA) published an 'Issues Register' which listed 100 outstanding issues that need to be resolved before we could even begin to produce an adequate safety case for a Geological Disposal Facility.[25] Along with similar studies, such as the Greenpeace International Report, Rock Solid[26], these call into question whether it will ever be possible to demonstrate with any scientific credibility that the resultant radiation dose to people from a nuclear waste repository would be at an acceptably low level into the far distant future.

COSTS

Current cost models of the planned GDF for radioactive waste were UK12 billion sterling as of 2008 but exclude spent fuel from new nuclear reactors. But as with nations worldwide, there are enormous uncertainties. Although it had originally planned to charge a fixed price for new generated spent fuel, this was changed in 2011 to a variable, but capped, Waste Transfer Price (WTP).
The Waste Transfer Price will increase over time, as the final outturn costs of actually siting, building and operating the deep GDF are better understood. The uncertainties and likely underestimates in costs where highlighted by consultant Ian Jackson in 2011.[27] Where the UK978,000 sterling for each ton uranium (in spent fuel), may be too low to cover the government's costs when it assumes that nuclear disposal costs will rise at only 3.3% per annum above inflation. But past experience shows that nuclear costs typically escalate at between 4.2–4.5% above inflation. A cost underestimation would mean that the UK Nuclear Decommissioning Authority (NDA) will not fully recover all of its disposal costs for new build reactor spent fuel, and so the NDA will require an indirect government subsidy to make up the shortfall.

CONCLUSIONS

Cumbria County Council – the UK municipality with most experience of attempts to find a site for a geological disposal facility – has described the Government's most recent sixth attempt as fundamentally flawed. In particular it bemoans the failure to address the need for secure interim storage, despite the most dangerous elements within waste being too hot to bury for well over a century.[28]
So there will be serious doubts about whether any progress will be made. Various studies have called into question whether it will ever be possible to demonstrate with any scientific credibility that the resultant radiation dose to people from a nuclear waste repository would be at an acceptably low level into the far distant future.
Meanwhile, the UK has embarked on a new nuclear construction programme which will compound the problem and result in vastly increased radioactivity from spent fuel and other highly radioactive wastes which will have to be stored indefinitely at vulnerable sites scattered around our coasts.

ANNEXE – FIVE PREVIOUS ATTEMPTS TO FIND A SITE.

First Attempt:
1976: United Kingdom Atomic Energy Authority (UKAEA) search for a deep disposal site begins.
1981: Public inquiries fuel massive public opposition to the programme, but test drilling was only ever carried out at one site – Altnabreac in Caithness. The UK Government backs down and abandons the programme of test drilling in December 1981.

Second Attempt:
1982: Nirex is formed and announces a new policy: a deep anhydrite mine under Billingham in Cleveland was proposed as a site for ILW, and Elstow in Bedfordshire was proposed as a site for the shallow burial of LLW.
1986: Billingham abandoned.

Third Attempt:
1987: Three additional sites are nominated to join Elstow.
May 1987: UK Government abandons the programme.

Fourth Attempt:
Nov 1987: Nirex launches "The Way Forward".
1989: The focus for Nirex is on Sellafield & Dounreay.
March 1997: UK Government reject Nirex's Sellafield planning application.

Fifth Attempt:
July 2002: UK Government announces that it was going to establish a new independent committee (CORWM) to review options for managing radioactive waste and to make recommendations. It recommends a deep waste repository with significant caveats.
Aug 2012: Managing Radioactive Waste Safely Partnership report published.
Jan 2013: Cumbria County Council decides to withdraw from the process.

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7

UNITED STATES

HIGH LEVEL NUCLEAR WASTE IN THE UNITED STATES

Robert Alvarez

In the 60 years since the start of civil nuclear power production, nuclear power reactors in the United States have generated roughly 30 percent of the total global inventory of spent nuclear fuel (SNF) – by far the largest.[1,2] There are approximately 80,150 metric tons stored at 125 reactor sites, of which 99 remain operational.[3]

The extraordinary hazards of high-level radioactive wastes generated by reactors was described by Johns Hopkins University professor Abel Wolman in January 1959 at the first U.S. congressional inquiry into the subject. "Their toxicity in general terms, both radioactive and chemical, is greater by far than any industrial material with which we have hitherto dealt in this or in any other country" he said. "We dispose of the wastes of almost every industry in the United States by actual conversion into harmless material," Wolman stressed, "This is the first series of wastes of any industry where that kind of disposal is nonexistent."

Wolman's observation still holds true as nations with nuclear power stations attempt to contain some of the world's largest concentrations of artificial radioactive elements on a time scale that transcends the geologic era defining the presence of human civilization. As of 2012, spent nuclear fuel in the United States was estimated to contain a total of 851,000 PBq (23 billion curies) of radioactivity.[4] Each year about 2,200 metric tons of SNF are generated and is expected to reach a total of about 146,500 mt by 2048 containing more than 1,221,000 PBq (>33 billion curies).

Spent nuclear fuel at U.S. nuclear power sites is made up of more than 244,000 long rectangular assemblies containing tens of millions of fuel rods.[5] The rods, in turn, contain trillions of irradiated uranium pellets, the size of a fingertip. After bombardment with neutrons in the reactor core, about 5 to 6 percent of the pellets are converted to a myriad of radioactive elements with half-lives ranging from seconds to millions of years. Standing within a meter of spent nuclear fuel discharged after one year guarantees a lethal radiation dose in about 20 seconds.[6]

However, after many years of focus on reactor melt-downs, it is becoming apparent that the large accumulation of spent nuclear fuel in U.S. reactor pools poses a far more potentially consequential hazard. This is because the pools are holding several irradiated cores or 3-4 times more spent nuclear fuel than the original designs intended. The pools lack defense-in-depth such as secondary containment and their own back-up power.

Heat from the radioactive decay in spent nuclear fuel is a principal safety concern. A few hours after a full reactor core is offloaded, it can initially give off enough heat from radioactive decay to match the energy capacity of a steel mill furnace. This is hot enough to melt and ignite the fuel's reactive zirconium cladding and destabilize a geological disposal site it is placed in. By 100 years, decay heat and radioactivity drop substantially but remains dangerous.

The Fukushima accident in March 2011 made it clear that the high heat hazard of spent fuel pools was not an abstract issue. Following the earthquake and tsunami, an explosion destroyed the reactor building of unit 4, exposing the pool containing an entire core-worth of freshly discharged spent nuclear fuel to the open air. By sheer luck, an accidental leak from a water line not actually intended to serve the cooling pool prevented water levels from dropping in the pool and thereby preventing a severe fire of the overheated zirconium cladding.[7]

THE HAZARDS OF SPENT NUCLEAR FUEL STORAGE IN POOLS

For nearly 30 years, NRC waste-storage requirements have been contingent on the timely opening of a permanent waste repository. This has allowed plant operators to legally store spent fuel in onsite cooling ponds much longer, and at higher densities (on average four times higher), than was originally intended.

Decades of nuclear safety research has shown that severe accidents from decay heat can occur if a spent fuel cooling pool loses a significant amount of water. If the fuel assemblies in a pool are exposed to air and steam, their zirconium cladding will react exothermically, after several hours or days catching fire similar to an enormous fireworks sparkler. (Because of its high reactivity to heat, zirconium was at one time used as a filament in camera flash bulbs.)

According to the U.S. Nuclear Regulatory Commission (NRC) 69 radionuclides in spent nuclear fuel pose potentially significant accident consequences
(See list 1).[8]

List 1: the 69 nuclides important to accident consequence studies

241Am, 137mBa, 139Ba, 140Ba, 141Ce, 143Ce, 144Ce, 242Cm, 244Cm, 58Co‡, 60Co‡, 134Cs, 136Cs, 137Cs, 131I, 132I, 133I, 134I, 135I, 85Kr, 85mKr, 87Kr, 88Kr, 140La, 141La, 142La, 99Mo, 95Nb, 97Nb, 97mNb, 147Nd, 239Np, 143Pr, 144Pr, 144mPr, 238Pu, 239Pu, 240Pu, 241Pu, 86Rb, 88Rb, 103mRh, 105Rh, 106Rh, 103Ru, 105Ru, 106Ru, 89Sr, 90Sr, 91Sr, 92Sr, 99mTc, 127Te, 127mTe, 129Te, 129mTe, 131Te, 131mTe, 132Te, 133Xe, 135Xe, 135mXe, 90Y, 91Y, 91mY, 92Y, 93Y, 95Zr, 97Zr

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If the fuel were exposed to air and steam, the zirconium cladding would react exothermically, catching fire at about 800-1000 degrees Celsius. Particularly worrisome is the large amount of cesium-137 in spent fuel pools, which contain anywhere from 44 to 84 million curies of this dangerous isotope in U.S. spent fuel ponds. With a half-life of 30 years, cesium-137 gives off highly penetrating radiation and is absorbed in the food chain as if it were potassium.

The damage from a large release of fission products, particularly cesium-137, was demonstrated as a result of the accidents at Chernobyl and Fukushima. The Chernobyl accident forced the permanent resettlement of 100,000 people because of contamination by cesium-137. The total area of this radiation-control zone is huge: more than 1,000 square kilometers, equal to roughly two-thirds the area of the State of New Jersey. During the following decade, the population of this area declined by almost half because of migration to areas of lower contamination.

Following the terrorist attacks of September 11, 2001, my colleagues and I published a paper warning that acts of malice or accidents could cause drainage of spent nuclear fuel pools in the United States, causing spent fuel cladding to catch fire and release catastrophic amounts of long-lived radioactivity—far more than a reactor melt down.[9]

This was followed up by my colleagues, who reported in 2016, if such a fire occurred at the Limerick boiling water reactor near Philadelphia, radioactive fallout could force approximately eight million people to relocate and result in $2 trillion in damages.[10] Other than a major war, there are few, if any, technological mishaps that can hold a candle to the consequences of a major power reactor spent fuel pool fire.

The NRC's 2007 own dispersion model used by emergency responders estimated that within six hours of pool drainage, following a major earthquake at the San Onofre Nuclear Generating Station, spent fuel cladding will catch fire, releasing approximately 86 million curies of radioactive material into the atmosphere. Of that, about 30 percent of the radio-cesium in the spent fuel (roughly 40 million curies) would be released—more than 150 percent of the amount released by all atmospheric nuclear weapons tests. An area within a 10-mile radius—encompassing 314 square-miles of land and offshore waters—could be lethally contaminated.[11]
Naoto Kan, Japan's prime minister when the Fukushima accident occurred, made this point very clear. After being informed about the consequences if the spent fuel in Fukushima Unit 4 pool had caught fire, he later said,

> ***"[W]e would have to evacuate 50 million people. It would have been like losing a major war... I feared decades of upheaval would follow and would mean the end of the State of Japan.[12]"***

Currently, about 70 percent of some 244,000 spent nuclear fuel assemblies in the United States sit in US power reactor cooling pools, with the remaining 30 percent contained in dry storage casks. About a third of the spent fuel in wet storage sits at decades-old boiling water reactors, in pools built several stories above the ground; the remainder is at pressurized water reactors, where the cooling pools are embedded in the ground.

To significantly reduce the probability of such an event, we called for an end of the high-density pool storage of used nuclear fuel and the placement of most spent nuclear fuel in dry, hardened storage containers. This change in fuel storage arrangements could be completed within 10 years, we estimated, at a cost of $3.5 to $7 billion.[13]

In May 2016, for the second time, a National Academy of Science panel refuted the NRC's expressions of confidence in the safety of spent fuel pools. Finding flaws in the agency's technical assumptions, the panel stated that the loss of spent fuel pool cooling at the Fukushima site "should serve as a wake-up call to nuclear plant operators and regulators about the critical importance of having robust and redundant means to measure, maintain, and, when necessary, restore pool cooling." The members also urged the NRC to "ensure that power plant operators take prompt and effective measures to reduce the consequences of loss-of-pool-coolant events in spent fuel pools that could result in propagating zirconium cladding fires."

HIGH BURNUP SPENT NUCLEAR FUEL

Since the 1990's, U.S. reactor operators, were permitted by the U.S. Nuclear Regulatory Commission (NRC) to effectively double the amount of time nuclear fuel can be irradiated in a reactor, by approving an increase in the percentage of uranium-235, the key fissionable material that generates energy. Known as increased "burnup" this practice is described in terms of the amount of electricity in megawatts (MW) produced per day from a metric ton of uranium. US commercial nuclear power plants use uranium fuel that has had the percentage of its key fissionable isotope—uranium 235—increased, or enriched, from what is found in most natural uranium ore deposits. In the early decades of commercial operation, the level of enrichment allowed US nuclear power plants to operate for approximately 12 months between refueling. In recent years, however, US utilities have begun using what is called high-burnup fuel, defined as >45 GWd/t.
High burnup spent nuclear fuel is proving to be an impediment to the safe storage and disposal of spent nuclear fuel. For more than a decade, evidence of the negative impacts on fuel cladding and pellets from high burnup has increased, while resolution of these problems remains elusive.

Research shows the fuel cladding thickness of used fuel is reduced and a hydrogen-based rust forms on the zirconium metal used for the cladding, and this thinning can cause the cladding to become brittle and fail. High burnup fuel temperatures make spent nuclear fuel more vulnerable from handling and transport.

"The technical basis for the spent fuel currently being discharged (high utilization, burnup fuels) is not well established," notes an expert with the National Academy of Engineering in 2012.[14] In May 2016, the Nuclear Waste Technical Review Board, an expert panel that provides scientific oversight for the Energy Department on spent fuel disposal. That panel said there is little to no data to support dry storage and transport for spent fuel with burnups greater than 35 gigawatt days per metric ton of uranium.[15] Over the past 20 years, more than 70 percent of the total inventory of the spent nuclear fuel generated are high burnup.[16] As of 2013, only 8 percent of high burnup spent fuel is stored in dry casks.[17]

A LACK OF PLANNING FOR STORAGE AND DISPOSAL

Recently, a Bloomberg energy finance report suggested that more reactor closures may be on the horizon: "More than half of America's nuclear reactors are bleeding cash, racking up losses totaling about $2.9 billion a year." The accelerated closure of more US reactors could seriously affect a system that lacks necessary planning and logistics for the management of a rapidly growing inventory of wastes. Nearly 20 percent of the nation's spent nuclear fuel is located at closed or soon-to-be closed reactors.[18]

Transporting spent nuclear fuel is further complicated because the storage at reactor sites involves a complicated mix of containers; each spent nuclear fuel canister system has its own unique challenges.

The NRC has licensed 51 different designs for dry cask storage, 13 which are for storage only and not for transport. As many as 11,800 onsite dry storage canisters may have to be reopened or repackaged before transport to either a centralized interim storage facility or to a permanent repository.[19]

The current generation of dry casks was intended for short-term on-site storage— not for direct disposal in a geological repository. None of the dry casks storing spent nuclear fuel is licensed for long-term disposal. The large storage canisters in use at power plants can place a major burden on a geological repository in terms of handling and emplacement of cumbersome packages with high heat loads and high radioactivity.

Indeed, repackaging for disposal may require tens of thousands of smaller canisters, and at an estimated average cost of $50,000 to $87,000 per used fuel assembly, repacking won't be cheap. The estimated cost of managing low-level radioactive waste from removing spent fuel to new canisters is estimated at $9,500 per assembly and could be more than the current cost to load an assembly in any canister.[20]

By the time a centralized interim storage site may be available, there could be a "wave" of reactor shutdowns that could clog transport and impact the schedule for a centralized storage operation. Among the uncertainties identified by DOE include:

• Transportation infrastructures at or near reactor sites are variable and changing;

• Each spent nuclear fuel canister system has unique challenges. For instance, **some dry casks that are licensed for storage only and not for transport.**

• Constraint on decay heat from spent nuclear fuel can impact the timing of shipping.

• The pickup and transportation order of spent fuel has yet to be determined. It has been assumed that the oldest would have priority, leaving sites with fresher and thermally hotter fuel that may be "trapped" at sites for to cool down.[21]

THE ELUSIVE SEARCH FOR GEOLOGICAL DISPOSAL

In 2008, the DOE issued a revised life-cycle cost estimate totalling $113 billion (2016 dollars) for the disposal of 70,000 metric tons of commercial power reactor spent fuel at the Yucca Mountain site.[22] Under current law, spent nuclear fuel more than that amount would have to be disposed in a second disposal site. Under the Nuclear Waste Policy Act, the cost for disposal is to pay by a fee levied on consumer of nuclear powered electricity of one mill ($0.001) per kilowatt-hour. This fee does not cover an estimated cost in the $billions, for predisposal surface storage, transport and repackaging. Efforts to restart the Yucca Mountain licensing process remain stalled.

After cancellation of the Yucca Mountain project in 2010, the U.S. Department of Energy projected that 122,100 Mt of spent nuclear fuel would require 16 years to transport and 50 years for total emplacement in the repository. The repository would be permanently closed after 150 years.[23] Reprocessing of spent nuclear fuel, prior to disposal is not considered viable. The Electric Power Research Institute, a U.S. energy industry organization concludes: "near-term US adoption of spent fuel processing would incur a substantial cost penalty...processing would have to be accompanied by deployment of fast reactor plants. But demonstration fast reactor plants to-date has mostly proved expensive and unreliable, which aggravates processing's economic handicap."[24]

The Yucca Mt. repository was chosen, first and foremost, by the U.S. Congress in 1987, to avoid the growing political controversy over siting a disposal site in the eastern United States. The Yucca Mountain site does not meet the basic geological requirements for long term storage established by the International Atomic Energy Agency. Among them are a "stable geochemical or hydro chemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals; and long term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity and heat flow"[25] With the distinct possibility of a volcano erupting within the 10,000 year time frame set for isolating the wastes,[26] and the penetration of moisture, Yucca Mountain has neither.

According to the DOE the site requires forced ventilation for at least 100 years to remove decay heat that could impact waste containers and the geology of the site.[27] Maintenance of power and rail and other transport systems to support the repository will be required for about 150 years. After years of claiming that the Yucca Mountain site was dry, DOE conceded that moisture can penetrate and compromise the waste packages.[28] And so, after ~100 years, in a dangerous high temperature environment, of more than 11,000 large titanium drip shields are planned to be emplaced to prevent moisture from corroding the waste packaging.[29] The drip shields would require nearly two thirds of the world's current annual consumption of titanium.[30]

WHAT NEEDS TO BE DONE

The basic approach undertaken in this country is to continue its 60-year quest for geological disposal site and hope for the best. Meanwhile the U.S. lacks a coherent policy for long-term surface storage, which increasingly is very likely. In recognition of major uncertainties, the U.S. Department of Energy has stated that "extended storage, for periods of up to 300 years, is being considered within the U.S."[31] A nuclear industry expert suggests that unless the federal government finds a way to restart efforts to site a repository quickly, the DOE program may never have to take spent fuel from an operating site."[32]

A national policy for the storage and disposal of spent nuclear fuel needs to be fundamentally revamped to address vulnerabilities of spent fuel storage in pools. First and foremost, to protect public safety, high density pool storage of spent nuclear fuel should end.

The U.S. Government Accountability Office, the investigative arm of the U.S. Congress reported in April 2017 that "spent nuclear fuel can pose serious risks to humans and the environment .and is a source of billions of dollars of financial liabilities for the U.S. government. According to the National Research Council and others, if not handled and stored properly, this material can spread contamination and cause long-term health concerns in humans or even death." [33]

Instead of waiting for problems to arise, the NRC and the Energy Department need to develop a transparent and comprehensive road map identifying the key elements of—and especially the unknowns associated with—interim storage, transportation, repackaging, and final disposal of all nuclear fuel, including the high-burnup variety. Otherwise, the United States will remain dependent on leaps of faith in regard to nuclear waste storage—leaps that are setting the stage for large, unfunded radioactive waste "balloon mortgage" payments born by the public in the future.

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