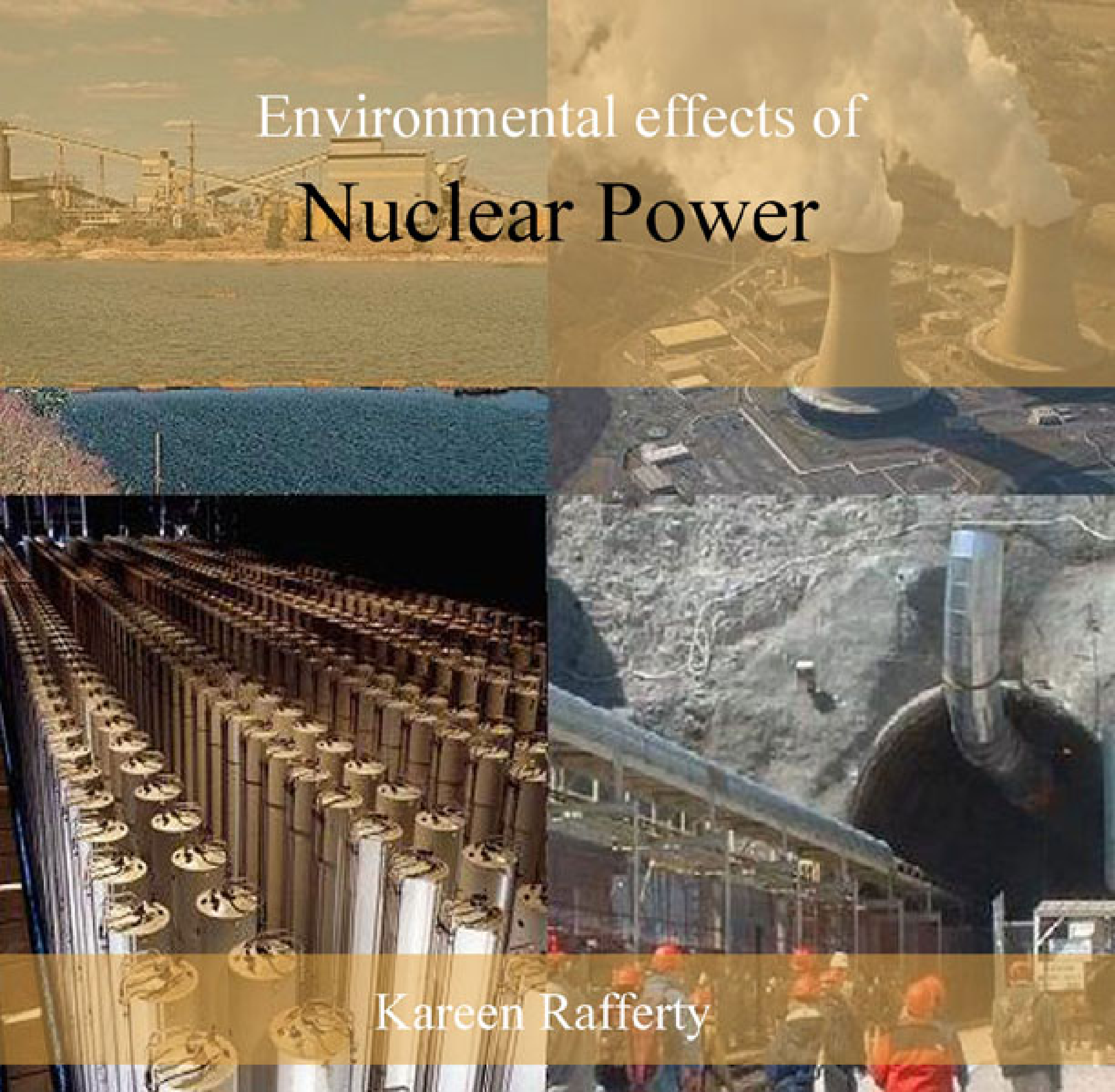
Environmental effects of Nuclear Power

Kareen Rafferty



First Edition, 2011

ISBN 978-93-81157-55-8

© All rights reserved.

Published by:
The English Press
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1- Environmental Effects of Nuclear Power

Chapter 2 - Waste Streams

Chapter 3 - Radioactive Waste

Chapter 4 - Nuclear Fallout

Chapter 5 - Nuclear Winter

Chapter 6 - Chernobyl Disaster Effects

Chapter 7 - High-Level Radioactive Waste Management

Chapter- 1

Environmental Effects of Nuclear Power

Nuclear power activities involving the environment; mining, enrichment, generation and geological disposal.

Nuclear power has an effect on the environment through the nuclear fuel cycle, through operation, and from the lingering effects of the Chernobyl disaster.

Waste streams

Nuclear power have at least four waste streams that contaminate and degrade land:

- (1) they create spent nuclear fuel at the reactor site (including plutonium waste)
- (2) they produce tailings at uranium mines and mills
- (3) during operation they routinely release small amounts of radioactive isotopes
- (4) during accidents they can release large quantities of pollution

Radioactive waste

High level waste

Around 20-30 tons of high-level waste are produced per month per nuclear reactor. Currently most spent nuclear fuel outside the U.S. is reprocessed for the useful components, leaving only a much smaller volume of short half-life waste to be stored. In the U.S. reprocessing is currently prohibited by executive order, and the spent nuclear fuel is therefore stored in dry cask storage facilities (this has the disadvantage of keeping the long-lived isotopes with the other waste, thus greatly extending the half-life of the waste).

Several methods have been suggested for final disposal of high-level waste, including deep burial in stable geological structures, transmutation, and removal to space. So far, none of these methods have been implemented. Recognising that long-term management options may require significant time to be achieved, interim storage is currently used.

Since the spent nuclear fuel has nowhere to go, some experimental nuclear reactors, such as the Integral Fast Reactor, have been proposed that use a different nuclear fuel cycle that avoids producing waste containing long-lived radioactive isotopes or actually "burns" those isotopes from other plants, via transmutation into elements with lower radioactivity.

According to anti-nuclear organizations and current public opinion in the US, rendering nuclear waste harmless is not being done satisfactorily and it remains a hazard for anywhere between a few years to many thousands of years, depending on the particular isotopes. The same organizations lobby against processing the waste to reduce its radioactivity and longevity, claming that the method has proliferation concerns and is uneconomic.

The length of time waste has to be stored is controversial because there is a question of whether one should use the original ore or surrounding rock as a reference for safe levels. Anti-nuclear organizations tend to favor using normal soil as a reference, in contrast to pro-nuclear organizations who tend to argue that geologically disposed waste can be considered safe once it is no more radioactive than the uranium ore it was produced from.

Other waste

Moderate amounts of low-level waste are produced through chemical and volume control system (CVCS). This includes gas, liquid, and solid waste produced through the process of purifying the water through evaporation. Liquid waste is reprocessed continuously, and gas waste is filtered, compressed, stored to allow decay, diluted, and then discharged. The rate at which this is allowed is regulated and studies must prove that such discharge does not violate dose limits to a member of the public.

Solid waste can be disposed of simply by placing it where it will not be disturbed for a few years. There are three low-level waste disposal sites in the United States in South Carolina, Utah, and Washington. Solid waste from the CVCS is combined with solid radwaste that comes from handling materials before it is buried off-site.

Power plant emissions

Radioactive gases and effluents

The Grafenrheinfeld Nuclear Power Plant. The tall chimney releases effluent gases.

Most commercial nuclear power plants release gaseous and liquid radiological effluents into the environment as a byproduct of the Chemical Volume Control System, which are monitored in the US by the EPA and the NRC. Civilians living within 50 miles (80 km) of a nuclear power plant typically receive about 0.01 milli-rem per year. For comparison, the average person living at or above sea level receives at least 26 milli-rem from cosmic radiation.

The total amount of radioactivity released through this method depends on the power plant, the regulatory requirements, and the plant's performance. Atmospheric dispersion models combined with pathway models are employed to accurately approximate the dose to a member of the public from the effluents emitted. Effluent monitoring is conducted continuously at the plant.

Limits for the Canadian plants are shown below:

Regulatory limits on Radioactive Effluents from Canadian Nuclear Power Plants

Effluent	**Tritium**	**Iodine-131**	**Noble Gases**	**Particulates**	**Carbon-14**
Units	**(TBqb × 10^4)**	**(TBq)**	**(TBq-MeVc × 10^4)**	**(TBq)**	**(TBq × 10^3)**
Point Lepreau Nuclear Generating Station	43.0	9.9	7.3	5.2	3.3
Bruce Nuclear Generating Station A	38.0	1.2	25.0	2.7	2.8
Bruce B	47.0	1.3	61.0	4.8	3.0
Darlington	21.0	0.6	21.0	4.4	1.4
Pickering Nuclear Generating Station A	34.0	2.4	8.3	5.0	8.8
Pickering B	34.0	2.4	8.3	5.0	8.8
Gentilly-2	44.0	1.3	17.0	1.9	0.91

Effluent emissions for Nuclear power in the United States are regulated by 10 CFR 50.36(a)(2).

Boron letdown

Towards the end of each cycle of operation (typically 18 months to two years in length), each pressurized water reactor reduces the amount of boron in its primary coolant system (the water that flows past and cools the nuclear reactor core). As a consequence, some of this irradiated boron is discharged from the plant and into whatever body of water the plant's cooling water is drawn from. The maximum amount of radioactivity permitted in each volume of discharge is tightly regulated (see above).

Tritium Effluent Limits

Country	**Limit (Bq/L)**

Australia	76,103
Finland	30,000
WHO	10,000
Switzerland	10,000
Russia	7,700
Ontario, Canada	7,000
United States	740
European Union	1001
California Public Health Goal	14.8

Tritium

A leak of radioactive water at Vermont Yankee in 2010, along with similar incidents at more than 20 other US nuclear plants in recent years, has kindled doubts about the reliability, durability, and maintenance of aging nuclear installations in the United States.

Tritium is a radioactive isotope of Hydrogen that emits a low-energy beta particle and is usually measured in Becquerels per Liter (Bq/L). Tritium becomes dissolved in ordinary water when released from a nuclear plant. The primary concern for Tritium release is the presence in drinking water, in addition to biological magnification leading to Tritium in crops and animals consumed for food.

Legal concentration limits have differed greatly to place to place (see table right). For example, in June 2009 the Ontario Drinking Water Advisory Council recommended lowering the limit from 7,000 Bq/L to 20 Bq/L. According to the NRC, Tritium is the least dangerous radionuclides because it emits very weak radiation and leaves the body relatively quick. The amount released by any given plant also varies greatly; the total release for plants in the United States in 2003 was at least counted to be 0 and at most 2,080 Curries.

Uranium mining

Uranium mining can use large amounts of water - for example, the Roxby Downs mine in South Australia uses 35 million litres of water each day and plans to increase this to 150 million litres per day.

Risk of cancer

There have been several epidemiological studies that claim to demonstrate increased risk of various diseases, especially cancers, among people who live near nuclear facilities. Among recent studies, a widely cited 2007 meta-analysis of 17 research papers was published in the *European Journal of Cancer Care*. It offered evidence of elevated leukemia rates among children living near 136 nuclear facilities in the United Kingdom, Canada, France, United States, Germany, Japan, and Spain. Elevated leukemia rates among children were also found in a 2008 German study that examined residents living near 16 major nuclear power plants in Germany. These recent results are not consistent with many earlier studies that have tended not to show such associations. But no credible alternate explanations for the recent findings have so far emerged.

Comparison to coal-fired generation

In terms of net radioactive release, the National Council on Radiation Protection and Measurements (NCRP) estimated the average radioactivity per short ton of coal is 17,100 millicuries/4,000,000 tons. With 154 coal plants in the United States, this amounts to emissions of 0.6319 TBq per year for a single plant.

In terms of dose to a human living nearby, it is sometimes cited that coal plants release 100 times the radioactivity of nuclear plants. This comes from NCRP Reports No. 92 and No. 95 which estimated the dose to the population from 1000 MWe coal and nuclear plants at 490 person-rem/year and 4.8 person-rem/year respectively (a typical Chest x-ray gives a dose of about 6 milli-rem for comparison). The Environmental Protection Agency estimates an added dose of 0.03 milli-rem per year for living within 50 miles (80 km) of a coal plant and 0.009 milli-ren for a nuclear plant for yearly radiation dose estimation.

In short, nuclear power plants have more radioactivity than coal-fired power plants, but since they use shielding, coal power plants emit more.

Unlike coal-fired or oil-fired generation, nuclear power generation does not directly produce any sulfur dioxide, nitrogen oxides, or mercury (pollution from fossil fuels is blamed for 24,000 early deaths each year in the U.S. alone). However, as with all energy sources, there is some pollution associated with support activities such as manufacturing and transportation.

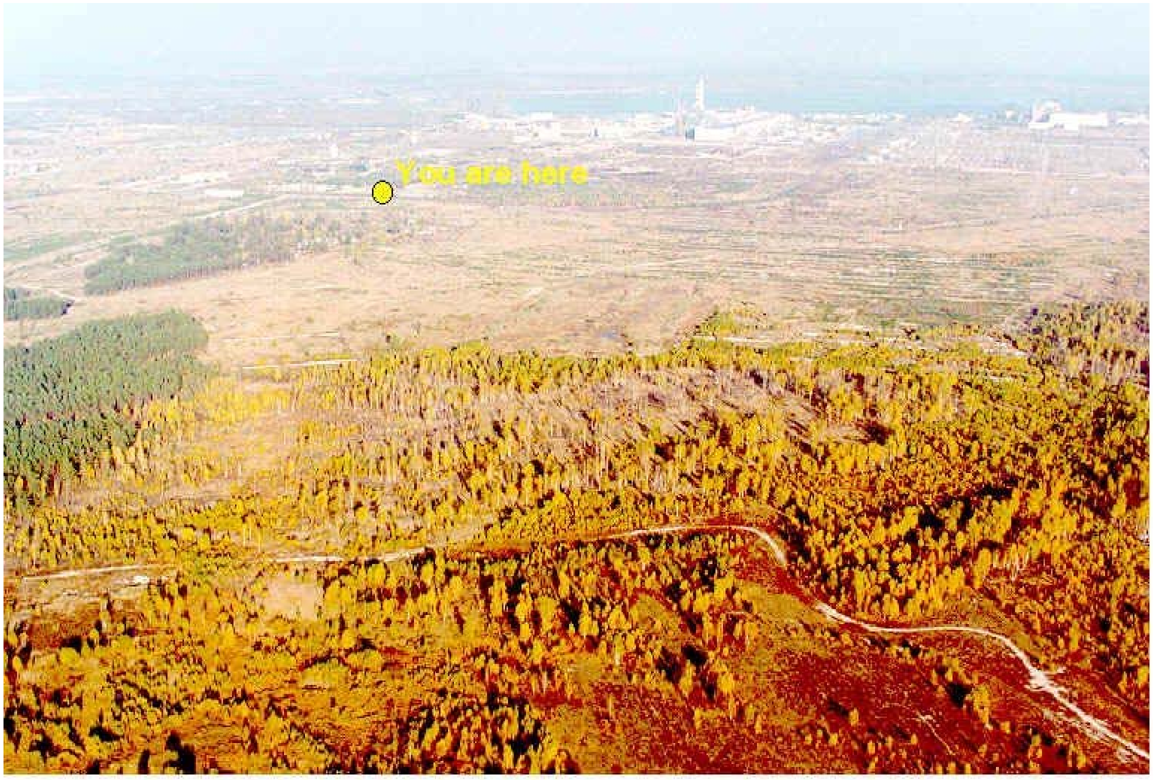
Contrast of radioactive accident emissions with industrial emissions

Proponents argue that the problems of nuclear waste "do not come anywhere close" to approaching the problems of fossil fuel waste. A 2004 article from the BBC states: "The World Health Organization (WHO) says 3 million people are killed worldwide by outdoor air pollution annually from vehicles and industrial emissions, and 1.6 million indoors through using solid fuel." In the U.S. alone, fossil fuel waste kills 20,000 people each year. A coal power plant releases 100 times as much radiation as a nuclear power plant of the same wattage. It is estimated that during 1982, US coal burning released 155 times as much radioactivity into the atmosphere as the Three Mile Island accident. The World Nuclear Association provides a comparison of deaths due to accidents among different forms of energy production. In their comparison, deaths per TW-yr of electricity produced from 1970 to 1992 are quoted as 885 for hydropower, 342 for coal, 85 for natural gas, and 8 for nuclear.

Environmental effects of accidents

The worst accidents at nuclear power plants have resulted in severe environmental contamination.

Chernobyl disaster



The major plume of radiation released by the Chernobyl Nuclear Accident was carried directly over what is now called the Red Forest. Radioactive particles settled on trees, killing areas of pine forest.

The 1986 Chernobyl disaster in the Ukraine was the world's worst nuclear power plant accident, resulting in an estimated 4,056 deaths. Large amounts of radioactive contamination were spread across Europe, and cesium and strontium contaminated many agricultural products, livestock and soil. The accident necessitated the evacuation of 300,000 people from Kiev, rendering an area of land unusable to humans for an indeterminate period. The habitability of the area for animals, however, has been less clear - some researchers have claimed to have detected depressed numbers of insects and spiders, while others have claimed that wildlife has flourished due to the absence of humans.

Windscale fire

On October 8, 1957, the Windscale fire in the U.K. ignited the plutonium "piles", resulting in the contamination of surrounding dairy farms. The main sources of radioactivity were cesium-137 and iodine-131. Overall, the accident resulted in 33 cancer deaths and US$78 million in property damage. The primary cause of the accident had been the second nuclear heating, applied too soon and too rapidly. It was triggered to release Wigner energy.

Water usage

Waste heat

The North Anna plant uses direct exchange cooling into an artificial lake.

As with some thermal power stations, nuclear plants exchange 60 to 70% of their thermal energy by cycling with a body of water or by evaporating water through a cooling tower. This thermal efficiency is somewhat lower than that of coal fired power plants, thus creating more waste heat.

The cooling options are typically once-through cooling with river or sea water, pond cooling, or cooling towers. Many plants have an artificial lake like the Shearon Harris Nuclear Power Plant or the South Texas Nuclear Generating Station. Shearon Harris uses a cooling tower but South Texas does not and discharges back into the lake. The North Anna Nuclear Generating Station uses a cooling pond or artificial lake, which at the plant discharge canal is often about 30°F warmer than in the other parts of the lake or in normal lakes (this is cited as an attraction of the area by some residents). The environmental effects on the artificial lakes are often weighted in arguments against construction of new plants, and during droughts have drawn media attention.

The Turkey Point Nuclear Generating Station is credited with helping the conservation status of the American Crocodile, largely an effect of the waste heat produced.

The Indian Point nuclear power plant in New York is in a hearing process to determine if a cooling system other than river water will be necessary (conditional upon the plants extending their operating licenses).

It is possible to use waste heat in cogeneration applications such as district heating. The principles of cogeneration and district heating with nuclear power are the same as any other form of thermal power production. One use of nuclear heat generation was with the Ågesta Nuclear Power Plant in Sweden. In Switzerland, the Beznau Nuclear Power Plant provides heat to about 20,000 people.. However, district heating with nuclear power plants is less common than with other modes of waste heat generation: because of either siting regulations and/or the NIMBY effect, nuclear stations are generally not built in densely populated areas. Waste heat is more commonly used in industrial applications.

During Europe's 2003 and 2006 heat waves, French, Spanish and German utilities had to secure exemptions from regulations in order to discharge overheated water into the environment. Some nuclear reactors shut down.

Uranium mining

Uranium mining can use large amounts of water - for example, the Roxby Downs mine in South Australia uses 35 million litres of water each day and plans to increase this to 150 million litres per day.

Greenhouse gas emissions

Nuclear power plant operation emits no or negligible amounts of carbon dioxide. However, all other stages of the nuclear fuel chain – mining, milling, transport, fuel fabrication, enrichment, reactor construction, decommissioning and waste management – use fossil fuels and hence emit carbon dioxide. There has been a debate on the quantity of greenhouse gas emissions from the complete nuclear fuel chain.

Many commentators have argued that an expansion of nuclear power would help combat climate change. Others have pointed out that it is one way to reduce emissions, but it comes with its own problems, such as risks related to severe nuclear accidents the challenges of more radioactive waste disposal. Other commentators have argued that there are better ways of dealing with climate change than investing in nuclear power, including the improved energy efficiency and greater reliance on decentralized and renewable energy sources.

Various life cycle analysis (LCA) studies have led to a large range of estimates. Some comparisons of carbon dioxide emissions show nuclear power as comparable to renewable energy sources. On another hand, a 2008 meta analysis of 103 studies, published by Benjamin K. Sovacool, determined that renewable electricity technologies are "two to seven times more effective than nuclear power plants on a per kWh basis at fighting climate change".

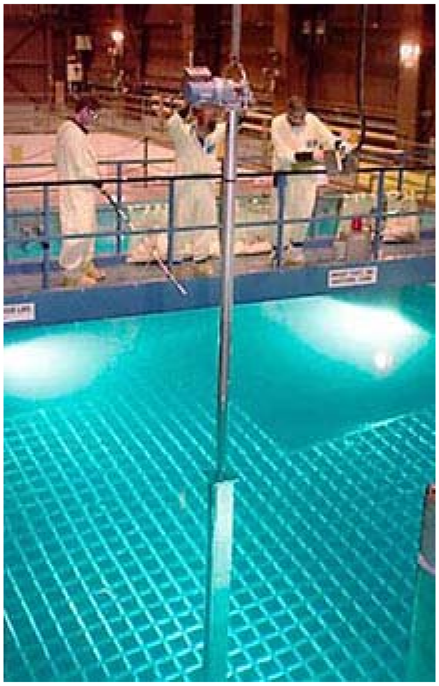
Decommissioning

Both nuclear reactors and uranium enrichment facilities must be carefully decommissioned using processes that are occupationally dangerous, and hazardous to the natural environment, expensive, and time-intensive.

Chapter- 2

Waste Streams

Spent nuclear fuel



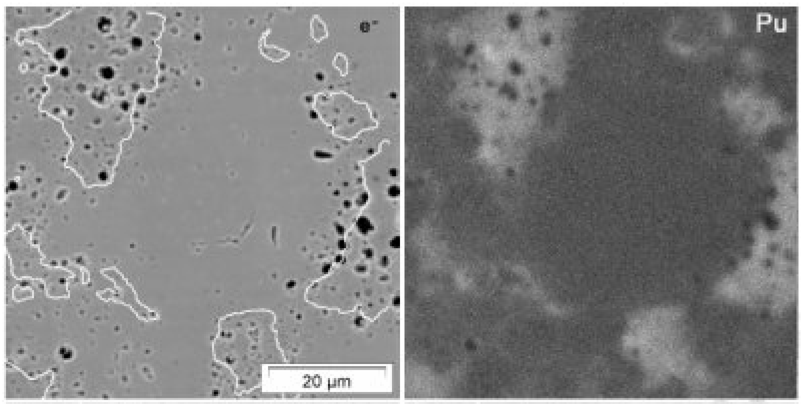
Spent fuel pool at a nuclear power plant.

Spent nuclear fuel, occasionally called **used nuclear fuel**, is nuclear fuel that has been irradiated in a nuclear reactor (usually at a nuclear power plant) to the point where it is no longer useful in sustaining a nuclear reaction.

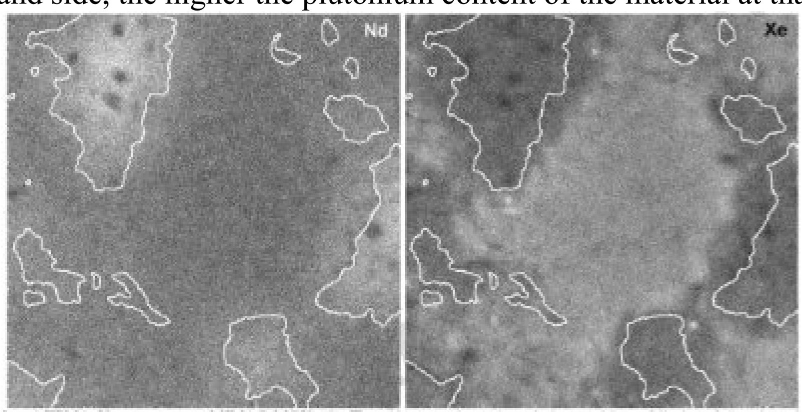
Nature of spent fuel

Nanomaterial properties

Spent low enriched uranium nuclear fuel is an example of a nanomaterial that existed before the term nano became fashionable. In the oxide fuel, intense temperature gradients exist which cause fission products to migrate. The zirconium tends to move to the centre of the fuel pellet where the temperature is highest, while the lower-boiling fission products move to the edge of the pellet. The pellet is likely to contain lots of small bubble-like pores which form during use; the fission xenon migrates to these voids. Some of this xenon will then decay to form caesium, hence many of these bubbles contain a large concentration of ^{137}Cs.



A used MOX which has 63 GW days(thermal) of burnup and has been examined with a scanning electron microscope using electron microprobe attachment. The lighter the pixel on the right hand side, the higher the plutonium content of the material at that spot



A used MOX which has 63 GW days(thermal) of burnup and has been examined with a scanning electron microscope using electron microprobe attachment. The lighter the pixel, the higher the neodymium (left) or xenon (right) content of the material at that spot

In the case of the MOX the xenon tended to diffuse out of the plutonium-rich areas of the fuel, and it was then trapped in the surrounding uranium dioxide. The neodymium tended to not be mobile.

Also metallic particles of an alloy of Mo-Tc-Ru-Pd tend to form in the fuel. Other solids form at the boundary between the uranium dioxide grains, but the majority of the fission products remain in the uranium dioxide as solid solutions. A paper describing a method of making a non-radioactive "uranium active" simulation of spent oxide fuel exists.

Fission products

3% of the mass consists of fission products of ^{235}U and ^{239}Pu (also indirect products in the decay chain); these are considered radioactive waste or may be separated further for various industrial and medical uses. The fission products include every element from zinc through to the lanthanides; much of the fission yield is concentrated in two peaks, one in the second transition row (Zr, Mo, Tc, Ru, Rh, Pd, Ag) and the other later in the periodic table (I, Xe, Cs, Ba, La, Ce, Nd). Many of the fission products are either non-radioactive or only short-lived radioisotopes. But a considerable number are medium to long-lived radioisotopes such as ^{90}Sr, ^{137}Cs, ^{99}Tc and ^{129}I. Research has been conducted by several different countries into segregating the rare isotopes in fission waste including the "fission platinoids" (Ru, Rh, Pd) and silver (Ag) as a way of offsetting the cost of reprocessing; however, this is not currently being done commercially.

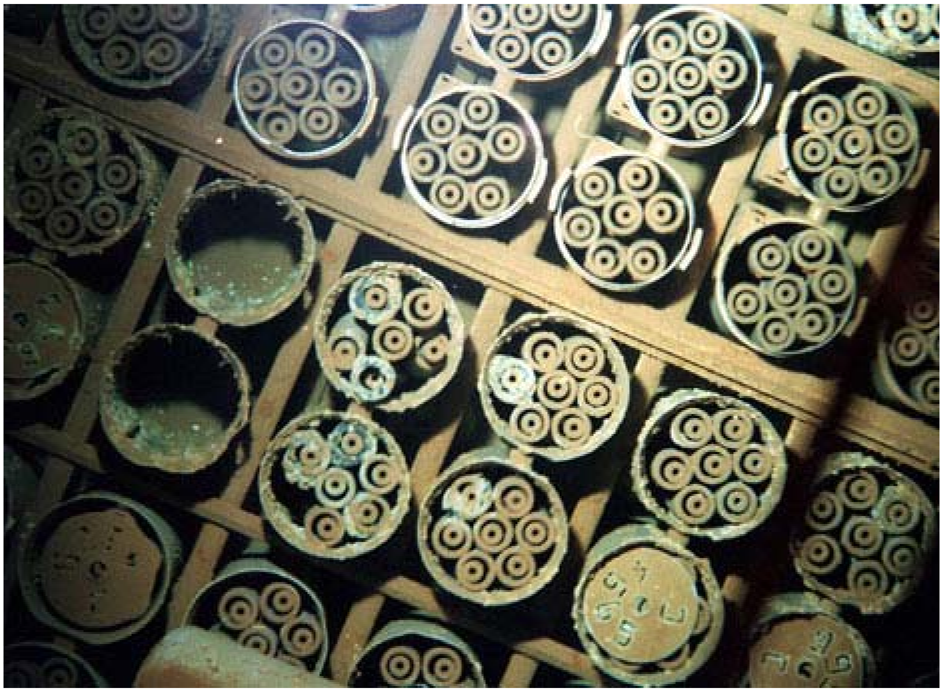
The fission products can modify the thermal properties of the uranium dioxide; the lanthanide oxides tend to lower the thermal conductivity of the fuel, while the metallic nanoparticles slightly increase the thermal conductivity of the fuel.

Table of chemical data

The chemical forms of fission products in uranium dioxide

Element	Gas	Metal	Oxide	Solid solution
Br Kr	Yes	-	-	-
Rb	Yes	-	Yes	-
Sr	-	-	Yes	Yes
Y	-	-	-	Yes
Zr	-	-	Yes	Yes
Nb	-	-	Yes	-
Mo	-	Yes	Yes	-
Tc Ru Rh Pd Ag Cd In Sb	-	Yes	-	-
Te	Yes	Yes	Yes	Yes
I Xe	Yes	-	-	-
Cs	Yes	-	Yes	-
Ba	-	-	Yes	Yes
La Ce Pr Nd Pm Sm Eu	-	-	-	Yes

Plutonium



Spent nuclear fuel stored underwater and uncapped at the Hanford site in Washington, USA.

About 1% of the mass is ^{239}Pu and ^{240}Pu resulting from conversion of ^{238}U, which may be considered either as a useful byproduct, or as dangerous and inconvenient waste. One of the main concerns regarding nuclear proliferation is to prevent this plutonium from being used by states, other than those already established as nuclear weapons states, to produce nuclear weapons. If the reactor has been used normally, the plutonium is reactor-grade, not weapons-grade: it contains much ^{240}Pu and less than 80% ^{239}Pu, which makes it less suitable, but not impossible, to use in a weapon. If the irradiation period has been short then the plutonium is weapons-grade (more than 80%, up to 93%).

Uranium

96% of the mass is the remaining uranium: most of the original ^{238}U and a little ^{235}U. Usually ^{235}U would be less than 0.83% of the mass along with 0.4% ^{236}U.

Reprocessed uranium will contain ^{236}U, which is not found in nature; this is one isotope which can be used as a fingerprint for spent reactor fuel.

If using a thorium fuel to produce fissile U-233, the SNF will have U-233, with a half-life of 159,200 years. This will have an impact on the long-term radioactive decay of the spent fuel. If compared with MOX fuel, the activity around one million years in the cycles with thorium will be higher due to the presence of the not fully decayed U-233.

Minor actinides

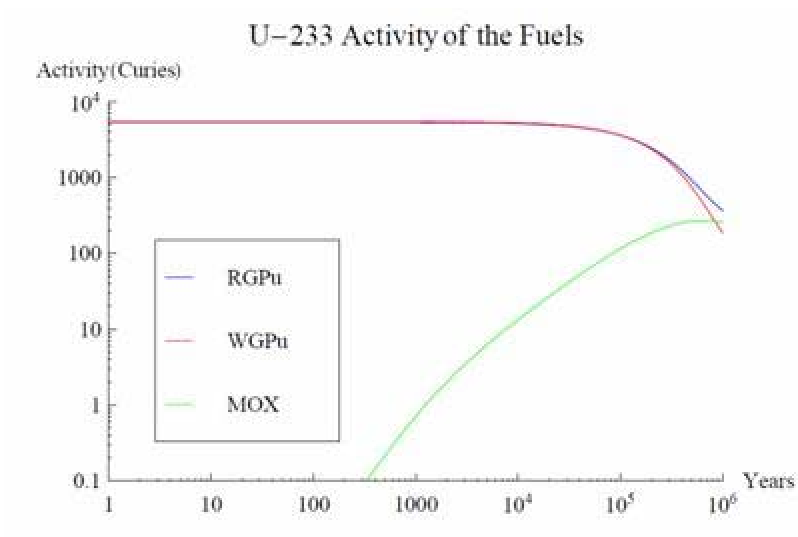
Traces of the minor actinides are present in spent reactor fuel. These are actinides other than uranium and plutonium and include neptunium, americium and curium. The amount formed depends greatly upon the nature of the fuel used and the conditions under which it was used. For instance, the use of MOX fuel (^{239}Pu in a ^{238}U matrix) is likely to lead to the production of more ^{241}Am and heavier nuclides than a uranium/thorium based fuel (^{233}U in a ^{232}Th matrix).

For natural uranium fuel: Fissile component starts at 0.71% ^{235}U concentration in natural uranium. At discharge, total fissile component is still 0.50% (0.23% ^{235}U, 0.27% fissile ^{239}Pu, ^{241}Pu) Fuel is discharged not because fissile material is fully used-up, but because the neutron-absorbing fission products have built up and the fuel becomes significantly less able to sustain a nuclear reaction.

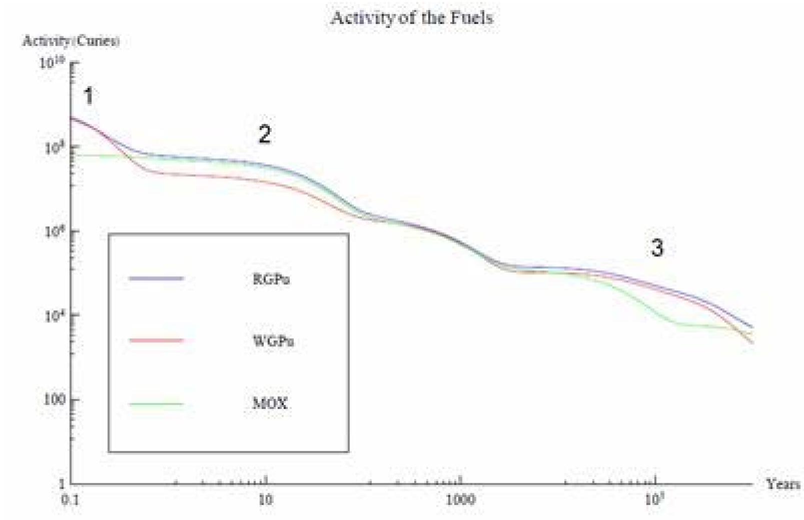
Some natural uranium fuels use chemically active cladding, such as Magnox, and need to be reprocessed because long-term storage and disposal is difficult.

For highly-enriched fuels used in marine reactors and research reactors, the isotope inventory will vary based on in-core fuel management and reactor operating conditions.

Fuel composition and long term radioactivity



Activity of U-233 for three fuel types



Total activity for three fuel types

Long-lived radioactive waste from the back end of the fuel cycle is especially relevant when designing a complete waste management plan for SNF. When looking at long-term radioactive decay, the actinides in the SNF have a significant influence due to their characteristically long half-lives. Depending on what a nuclear reactor is fueled with, the actinide composition in the SNF will be different.

An example of this effect is the use of nuclear fuels with thorium. Th-232 is a fertile material that can undergo a neutron capture reaction and two beta minus decays, resulting in the production of fissile U-233. The SNF of a cycle with thorium will contain U-233, an isotope with a half-life of 160,000 years. Its radioactive decay will strongly influence the long-term activity curve of the SNF around 1,000,000 years. A comparison of the activity associated to U-233 for three different SNF types can be seen in the figure on the top right.

The burnt fuels are Thorium with Reactor-Grade Plutonium (RGPu), Thorium with Weapons-Grade Plutonium (WGPu) and Mixed Oxide fuel (MOX). For RGPu and WGPu, the initial amount of U-233 and its decay around 10E5 years can be seen. This has an effect in the total activity curve of the three fuel types. The absence of U-233 and its daughter products in the MOX fuel results in a lower activity in region 3 of the figure on the bottom right, whereas for RGPu and WGPu the curve is maintained higher due to the presence of U-233 that has not fully decayed.

The use of different fuels in nuclear reactors results in different SNF composition, with varying activity curves.

Spent fuel corrosion

Noble metal nanoparticles and hydrogen

According to the work of the corrosion electrochemist Shoesmith the nanoparticles of Mo-Tc-Ru-Pd have a strong effect on the corrosion of uranium dioxide fuel. For instance his work suggests that when hydrogen (H_2) concentration is high (due to the anaerobic corrosion of the steel waste can), the oxidation of hydrogen at the nanoparticles will exert a protective effect on the uranium dioxide. This effect can be thought of as an example of protection by a sacrificial anode, where instead of a metal anode reacting and dissolving it is the hydrogen gas which is consumed.

Disposal of

Nuclear reprocessing can separate spent fuel into various combinations of reprocessed uranium, plutonium, minor actinides, fission products, remnants of zirconium or steel cladding, activation products, and the reagents or solidifiers introduced in the reprocessing itself. In this case the volume that needs to be disposed of is greatly reduced.

Alternatively, the intact Spent Nuclear Fuel (SNF) can be disposed of as radioactive waste.

The United States has planned disposal in deep geological formations, such as the Yucca Mountain nuclear waste repository, where it has to be shielded and packaged to prevent its migration to mankind's immediate environment for thousands of years. However, on March 5, 2009, Energy Secretary Steven Chu told a Senate hearing that "the Yucca Mountain site no longer was viewed as an option for storing reactor waste."

Radionuclide

A **radionuclide** is an atom with an unstable nucleus, which is a nucleus characterized by excess energy which is available to be imparted either to a newly-created radiation particle within the nucleus, or else to an atomic electron. The radionuclide, in this process, undergoes radioactive decay, and emits a gamma ray(s) and/or subatomic particles. These particles constitute ionizing radiation. Radionuclides may occur naturally, but can also be artificially produced.

The number of radionuclides is uncertain because the number of very *short-lived* radionuclides that have yet to be characterized is extremely large and potentially unquantifiable. Even the number of long-lived radionuclides is uncertain (to a smaller degree), because many "stable" nuclides are calculated to have half lives so long that their decay has not been experimentally measured. The nuclide list contain 90 nuclides that are theoretically stable, and 255 total stable nuclides that have not been observed to decay. In addition, there exist about 650 radionuclides that have been experimentally observed to decay, with half lives longer than 60 minutes. Of these, about 339 are known from nature (they have been observed on Earth, and not as a consequence of man-made activities).

Including artificially produced nuclides, more than 3300 nuclides are known (including ~3000 radionuclides), including many more (> ~2400) that have decay half lives shorter