Nature of the Hazard

Background Document

NWMO Workshop on

The Nature of the Hazard of Used Nuclear Fuel

What Needs to be Managed, For How Long and Why

January 31, 2005

Nuclear Waste Management Organization

CONTENTS

NWMO has compiled an overview of some scientific facts as background briefing. We recognize that other data are available and we encourage participants to bring additional reference materials to the Workshop for discussion.

1. CANADIAN USED NUCLEAR FUEL – CHARACTERISTICS

In Canada, used nuclear fuel consists primarily of used CANDU fuel which is generated at commercial nuclear power reactors in Ontario, Quebec and New Brunswick. In addition, there are very small quantities of used fuel from research and isotope-producing reactors in Canada (*Asking the Right Questions?*, NWMO Discussion Document 1 or DD1) (NWMO 2003). In many respects, these other nuclear fuel types are similar to the commercial nuclear fuels and they are commonly used at other research facilities around the world. Also, some of the Canadian nuclear utilities have proposed slight modifications to the composition of the nuclear fuel (e.g., slightly enriched uranium). Nevertheless, all of the used nuclear fuel in Canada will need to be addressed in an appropriate manner during implementation of a long-term management approach.

For the purposes of this Workshop on the Nature of the Hazard, the focus will be on used CANDU fuel from commercial reactors in Canada.

In a nuclear-powered electricity generating station, heat is produced by fission, which occurs in a fuel bundle when a neutron is absorbed by certain heavy elements (such as uranium-235 or plutonium-239). The characteristics and radionuclide content of used CANDU fuel for long-term management has been described in several reports such as AECL (1994) and Tait et al. (2000).

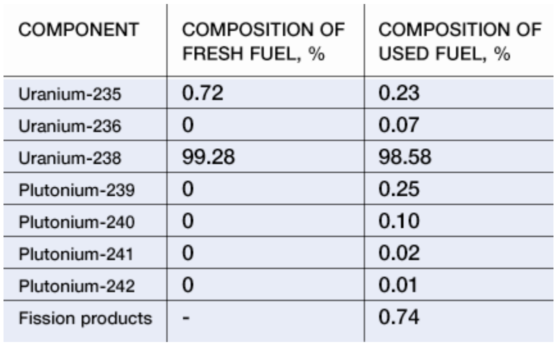
In the CANDU system used in Canada, each fuel bundle contains about 19 kg of natural uranium, in the form of high-density uranium dioxide ceramic pellets. These pellets are sealed inside zirconium alloy tubes, about 0.5m long, arranged in a circular array 10 cm in diameter (see Figure 1). Heat is removed by passing liquid heavy water over the many bundles in the reactor. In turn, the heavy water coolant passes through boilers which transfer the heat to ordinary water, producing steam. The cooled heavy water is then pumped through the reactor again in a closed loop in order to retain the heavy water. The steam from the boilers drives a turbine generator, producing electricity.

When an atom is split and neutrons are released, one neutron goes on to split another atom, and so on, keeping the nuclear reaction going. Another 1.3 neutrons (on average) are absorbed by the non-fissionable materials in the fuel and the reactor core. As the process continues, the concentration of fission products increases until their neutron absorption capacity becomes so large that the nuclear reaction begins to be impeded. At this stage, after about 18 months, the fuel is removed both because of the partial depletion of the fissile material as well as the build-up of neutron-absorbing fission products and actinides.

Figure 1: CANDU fuel bundle.

Unirradiated CANDU fuel consists primarily of ceramic uranium dioxide pellets. CANDU fuel is composed of natural uranium which is approximately 99.28% uranium-238 and 0.72% uranium-235 (NWMO 2003). Irradiated or used CANDU fuel consists of approximately 98.58% uranium-238, 0.23% uranium-235, 0.27% plutonium-239 and hundreds of other radioactive fission products and minor actinides (see Table 1).

Table 1: Composition of Fresh and Used CANDU Nuclear Fuel. (Ref. DD1, p. 26)



COMPONENT	COMPOSITION OF FRESH FUEL, %	COMPOSITION OF USED FUEL, %
Uranium-235	0.72	0.23
Uranium-236	0	0.07
Uranium-238	99.28	98.58
Plutonium-239	0	0.25
Plutonium-240	0	0.10
Plutonium-241	0	0.02
Plutonium-242	0	0.01
Fission products	-	0.74

When the used fuel is removed from the reactor, it is highly radioactive, although the radioactivity depends on the burn-up in the reactor. The radioactivity decreases substantially with time due primarily to the decay of short-lived radionuclides. The radioactivity of used fuel (Bq/kg U) decreases to about 1% of its initial value after 1 year, decreases to about 0.1% after 10 years and decreases to about 0.01% after 100 years (AECL 1994). After about 1 million years, the radioactivity in used fuel approaches that of natural uranium (AECL 1994; NWMO 2003; McMurry et al. 2004).

The total radioactivity of a used CANDU fuel bundle as a function of time out of reactor is illustrated in Figure 2. Over a million year time period, the activity of used fuel drops by about six orders of magnitude. The total radioactivity of used fuel then becomes comparable to the total radioactivity associated with natural uranium ore deposit. This is considered by some people to be a useful benchmark. However, radiotoxicity considerations must also be considered (see following sections on regulations and radiotoxicity).

Much of the emitted radiation is absorbed as heat by the fuel and surrounding materials. When a bundle is discharged from the reactor, the heat output is about 37,000 watts (AECL 1994). The heat output drops to 73 watts after 1 year, 5 watts after 10 years and 1 watt after 100 years. After about 1 million years, the decay heat from used fuel approaches that of natural uranium and its associated products (AECL 1994).

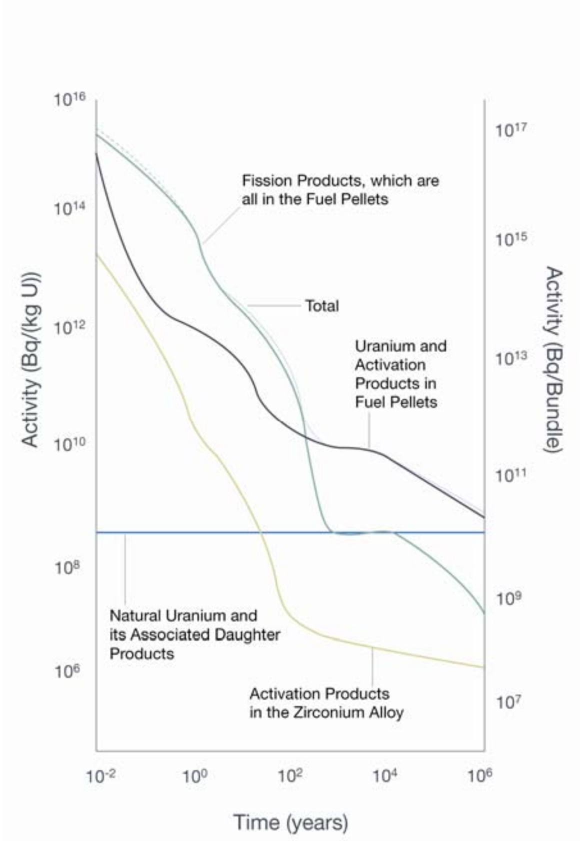


Figure 2: Total activity of used CANDU fuel as a function of time out of reactor. (Ref. DD1, p. 27)

2. CANADIAN RADIATION PROTECTION REGULATIONS AND LICENCES

The Canadian Nuclear Safety Commission (CNSC) has set an annual radiation dose limit of 1 mSv/a for members of the public (Government of Canada 2000). For comparison, the average annual background radiation dose to members of public in Canada is approximately 3 mSv (Sutherland 2003). The typical sources of radiation exposure are illustrated in Figure 3. They include radon gas from the earth's crust, radioactivity in the air, food and water, cosmic radiation and medical exposures such as dental x-rays.

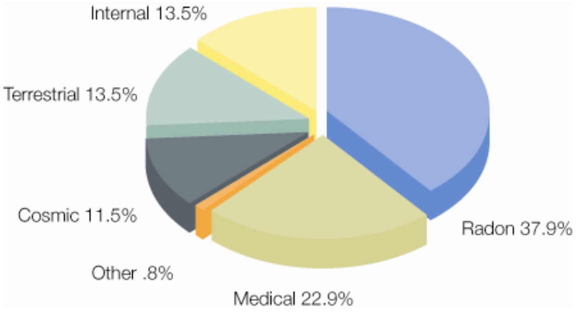


Figure 3: Sources of background radiation exposure in Canada.

In public radiological safety analyses, the critical benchmark is the CNSC dose limit of 1 mSv/a. As well, the average annual background radiation exposure of 3 mSv/a is sometimes used as a point of reference in safety assessments (e.g., Gierszewski et al. 2004).

For nuclear energy workers over a five year period, the annual radiation dose limit is 20 mSv/a.

The CNSC's Radiation Safety Data Sheet for uranium-238 indicates that a licence would be required for possessing more than 1 x 10^7 Bq of uranium-238 in a non-dispersible form (see CNSC website at www.nuclearsafety.gc.ca). Given a specific activity uranium-238 of 1.2 x 10^7 Bq/kg, a CNSC licence would be required to possess about 1 kg of uranium.

3. MAIN HAZARDS

3.1 RADIOTOXICITY AND CHEMICAL TOXICITY OF USED NUCLEAR FUEL

Used nuclear fuel is a potential source of both external radiation and internal exposure to humans and the natural environment. The health effects and dose rate factors from exposure to ionizing radiation have been studied over the years and documented in numerous publications such as BEIR (1990), ICRP (1991) and UNSCEAR (2000), and recently summarized in Sutherland (2003). There is on-going debate on the potential biological effects of radiation on humans and non-human biota, health risks and dose models associated with low and high doses, low and high dose rates (e.g., see ECRR 2003). There is also on-going debate on the potential benefits from low doses of radiation (hormesis), the apparent conservatism of the linear-no-threshold hypothesis for calculating risk and whether or not regulations set to protect humans are sufficient to protect non-human biota. While these debates will undoubtedly continue for some time, there is general agreement that radiation exposure needs to be controlled and regulated to protect humans and the environment.

The radiotoxicity of used nuclear fuel depends on the exposure pathway, the dose associated with each radionuclide and the time out of reactor. A common radiotoxicity index is based on the dose or risk calculated from ingestion (Mehta et al. 1991; OECD 2004). Similarly, drinking water guidelines are usually based on the water ingestion pathway (2 L/day), dose conversion factors for individual radionuclides and a dose limit set at 10% of the public dose limit (0.1 mSv/a). The Health Canada *Guidelines for Canadian Drinking Water Quality* were recently published in April 2004 (see Health Canada website at www.hc-sc.gc.ca/hecs-secs).

The Health Canada maximum acceptable concentration (MAC) for selected radionuclides which are important in used nuclear fuel is listed in Table 2. The principal chemical in used fuel is uranium and the MAC for uranium is limited by its chemical toxicity value of 0.02 mg/L which corresponds to a radionuclide concentration of about 0.5 Bq/L.

The radiotoxicity analysis for used CANDU fuel suggests that this material is a potential internal exposure health risk for more than 1 million years (Mehta et al. 1991; AECL 1994).

Similar analysis for used pressurized water reactor fuel (PWR) with enriched uranium-235 suggests that the radiotoxicity of used fuel becomes equal to the equivalent uranium ore after about 130,000 years (IAEA 2004). Other analysis suggests the time period is between 500,000 and 1 million years (OECD 2004). (*Note, due to enrichment of uranium-235 in light water reactor (LWR) fuel from 0.72% to up to 5%, 1 tonne of PWR fuel can be derived from about 7 tonnes of uranium ore*).

Table 2: Canadian Drinking Water Guidelines – Maximum Acceptable Concentration (Ref. Health Canada, April 2004)

Radionuclide	Half Life (years)	Ingestion Dose Conversion Factor (Sv/Bq)	MAC (Bq/L)
Uranium-235	704,000,000	3.8×10^{-8}	4[a]
Uranium-238	4,470,000,000	3.6×10^{-8}	4[a]
Plutonium-239	24,100	5.6×10^{-7}	0.2
Radium-226	1,600	2.2×10^{-7}	0.6
Cesium-137	30.2	1.3×10^{-8}	10
Carbon-14	5,730	5.6×10^{-10}	200
Iodine-129	16,000,000	1.1×10^{-7}	1

[a] Note, the MAC for uranium based on chemical toxicity is 0.02 mg/L or about 0.5 Bq/L.

3.2 EXTERNAL RADIATION FROM USED NUCLEAR FUEL

The external radiation field from a CANDU bundle depends on burn-up, time out of reactor and exposure distance from the fuel, which is typically measured from 0.3 to 1 metre from the source (Sutherland 2003). The external radiation fields for various fuel ages for an average burn-up of 7,800 MW days per tonne of uranium were taken from Sutherland (2003) and are listed in Table 3. The exposure time to reach the public radiation dose limit of 1 mSv/a is also given.

Table 3: External Radiation from Used CANDU Fuel as a Function of Time

Age of Used CANDU Fuel (years)	Unshielded External Radiation Field at 0.3 m (mSv/h)	Exposure Time to Reach Public Dose Limit of 1 mSv
50	1,150	3 seconds
100	360	10 seconds
200	37	97 seconds
500	0.82	1.2 hours
1,000,000	0.009	110 hours

The analysis in Table 3 indicates that at 50 years, the external radiation dose from unshielded used nuclear fuel would present a significant health risk. At a dose rate of 1,150 mSv/h, unshielded nuclear fuel would give a potentially fatal dose of 5 Sv after about 4 hours of exposure. While the external radiation from used fuel declines rapidly with the passage of time, it could still be considered significant from a public dose perspective far into the future since exposure to million-year old fuel (or unirradiated fuel for that matter) could potentially reach the public dose limit of 1 mSv/a after about 110 hours.

4. LONGEVITY

Based on the above discussion, one could conclude that uranium ore, fresh nuclear fuel or million-year old used nuclear fuel would be a potential external exposure health risk if left uncontrolled at the surface. (The internal exposure pathways would likely be more restrictive).

5. CITIZEN INPUT TO THE NWMO ON NATURE OF THE HAZARD

The following table presents a brief overview of the range of comments which have been received over the course of dialogue. Although most people agree that radiation from the used fuel can represent a significant hazard or risk to human health and the environment, we heard from Canadians different perspectives on the nature of the hazard or risk, and the time period over which the material is hazardous and needs to be managed.

Several suggested that as time goes by, the nature of the hazard and the associated risks change. Some indicated that the risk from external exposure to radiation is initially large but it is the risk of internal radiation through ingestion that remains a major concern over time. Some suggested that at some point, the hazard and risks will become very low and the requirement for management will diminish. Others remarked that there is no safe level of exposure to radiation, and high management standards will be required until monitoring results clearly indicate otherwise. Some suggested that even low levels of radiation are a concern. Others suggested that low levels of radiation might actually have a beneficial effect.

In Table 4 we list a sample of this diverse input and other reference material for review and consideration by participants in the Workshop.

Table 4: Input to NWMO on the Nature of the Hazard

Comments which have been made by participants over the course of the dialogue.

Input to NWMO on Nature of the Hazard
"Perceived Timeframe of Nuclear Fuel Hazard: Canadians believe that the hazard from nuclear waste is less than 10 years (8%), between 10 and 100 years (19%); between 100 and 1,000 years (15%); between 1,000 and 10,000 years (6%); greater than 10,000 years or forever (21%); don't know (31%)".
"There is a lot of misconception that needs to be cleared up, such as the belief that the fuel waste is toxic forever". "Some say the danger is around 500 years, others for 10,000 and a million years. Is there not a scientific consensus on the danger?"
"Considering the very long time that this waste would be dangerous for release to the environment (Hundreds of thousands of years) …" "A time scale that shows when radioactivity of used nuclear fuel approaches that of uranium ore should be developed".
"There is an assumption that nuclear materials are hazardous until the end of time and believed that low level radiation is just as dangerous as high level radiation".
"Over a period of hundreds of years, the hazard from used fuel will greatly diminish".
"Some of the radioisotopes in this waste will need to be contained virtually forever".
"Given the large stockpile of high level nuclear wastes that already exists in Canada and that will be hazardous for thousands of years …"

Input to NWMO on Nature of the Hazard
“It is generally accepted that high level radioactive waste must be kept isolated from the environment for a very long periods of time … in the order of hundreds of thousands of years”.
“Reactors create radioactive wastes that are extremely toxic even in minute quantities and which will remain extraordinarily dangerous for millions of years”. “Spent nuclear fuel is so radioactive that it can never be handled by human hands”. “Uranium … is particularly dangerous when brought to the surface”.
“An unprotected individual standing one metre from a CANDU fuel bundle just out of the reactor would receive a lethal dose in seconds”. “Due to the presence of these toxic materials, spent fuel remains extremely dangerous for millions of years”.
“Toxic chemicals are toxic forever. Radioactive waste over the million year time frame is no different to other chemicals. As a radiological hazard the toxicity of the waste decays to the same level it was when first mined in 300 to a 1000 years. Beyond that there are 2 or 3 radioactive species which would have to be ingested (like other toxic chemicals) to cause a biological hazard”.
“Your time-frame for radioactive decay is only true for external, penetrating radiation, which is roughly 0% of the concern with radioactive waste disposal. For toxicity, the time-frame is at least in the OOM [order of magnitude] of 100,000 years before the material’s toxicity drops to the level of the ore”.
“Spent fuel contains roughly 350 different nuclides, about 200 of which are radioactive. Its level of activity per unit mass declines to that of natural uranium and its associated daughter products after about one million years”.
“Used CANDU fuel … is radioactive and contains some chemically toxic elements. Humans and other organisms are protected by isolating the used fuel from the natural environment, shielding humans and other organisms from its radiation, and cooling it to remove the heat produced by radioactive decay”.
“After about 100,000 years the radiological toxicity of one tonne of Swedish spent fuel is on a par with the radiological toxicity of the natural uranium ore from which it was derived”. “One million years is the period of principal concern”. “There are no ethical arguments that justify imposing a definite limit to the period addressed by safety assessments, in spite of the technical difficulties that this can present to those conducting such assessments”.
“Spent [LWR] fuel … takes 130,000 years before the radiotoxicity reaches the reference level [7.83 tonne U in equilibrium]”.
“The general and widely publicized belief about spent fuel is that it is dangerously radioactive for millions of years ... this perception is incorrect”. “With radioactive decay, the dose rate associated with any radioactive material decreases with time. By the time 1,000 years have passed, there are no significant fission nuclides present, and the dose rate reflects the natural uranium content and the remaining transuranic nuclides”.
“After 100,000 years, the radiotoxicity of the fuel is the same as that of an equivalent amount of enriched uranium. That’s why 100,000 years is a guideline we set for how long the repository should function”.
“The waste contains radioactive elements … that emit radiation with the potential to cause severe injury. It is therefore dangerous to man, whether he be within range of a source of outside radiation … or affected through having ingested or inhaled radioelements. Adequate high-performance barriers must therefore be positioned between the waste and the environment, which isolate or ‘contain’ the radioelements and any toxic chemicals associated with them”.
“The management of radioactive waste is a difficult environmental problem because of the very long timescales involved. Some wastes remain radioactive and continue to present a potential hazard to the environment for millions of years to come”.
“Used nuclear fuel is highly radioactive and is very dangerous to humans and the environment if it is not properly managed”.

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APPENDIX 1

NWMO started to address this important question in its first discussion document, *Asking the Right Questions?* We direct you to pages 25 – 29 of this document, which contain NWMO's initial description of the nature of the hazard. The document is available on NWMO's website at: http://www.nwmo.ca/adx/asp/adxGetMedia.asp?DocID=1027,1026,20,1,Documents&MediaID=2018&Filename=NWMO_DD1_e.pdf

APPENDIX 2

As part of a suite of background papers which NWMO commissioned for its three-year study, NWMO commissioned a background paper on the topic of the health hazard posed by used nuclear fuel. This paper (Background Paper 3-2: Human Health Aspects of High-Level Radioactive Waste, by John Sutherland) is available on NWMO's website at: http://www.nwmo.ca/adx/asp/adxGetMedia.asp?DocID=228,208,199,20,1,Documents&MediaID=757&Filename=32_NWMO_background_paper.pdf

APPENDIX 3

As part of NWMO’s dialogue activities, a workshop was held with specialized groups to discuss and receive comment about NWMO’s first discussion document, *Asking the Right Questions?* As part of this dialogue, a number of gaps were identified in NWMO’s description of the nature of the hazard. The discussion of the nature of the hazard is summarized on pages 7 and 8 in the report of this session (Report on National Stakeholder and Regional Dialogues, DPRA), and in Appendix 4 of the report. The main report and Appendix is available on the NWMO web site at: http://www.nwmo.ca/Default.aspx?DN=1082,995,988,20,1,Documents