March 13, 2021

Comments by Dr. Jeremy Whitlock on

“Questions and Answers about Used Nuclear Fuel – for the South Bruce NWMO CLC” (by Dr. Gordon Edwards, updated 2021 February 18 on South Bruce CLC website[1])

Background:

My name is Dr. Jeremy Whitlock. I am nuclear reactor physicist and manager with over 26 years' experience in the nuclear field (22 years in Canada mostly at Chalk River Laboratories, and since 2017 as a manager at the International Atomic Energy Agency (IAEA) in Vienna). I have a PhD in reactor physics from McMaster University, and I am a former President of the Canadian Nuclear Society, a professional organization representing Canadian nuclear science and technology. Since 2006 I have specialized in nuclear non-proliferation matters, both at Chalk River Laboratories in Canada and at the IAEA in Vienna.

During my career I have participated in many public discussions about nuclear power, striving for a balanced understanding of the risks, benefits, and history of this technology. Since 1997 I have maintained “The Canadian Nuclear FAQ” website, a question-and-answer resource dedicated to Canadian nuclear science and technology (www.nuclearfaq.ca).

Prior to my move to Vienna I had the pleasure of visiting several CLCs involved in the NWMO's siting process as a guest speaker. These were enriching opportunities to meet new communities, including several indigenous communities, and in the process I gained a better understanding of the key concerns facing those involved directly in the NWMO learning process.

Recently Dr. Gordon Edwards shared a “Questions and Answers” document with the South Bruce CLC as a follow-up to his November 5, 2020 presentation to the CLC[1]. Let me first say that I strongly support the efforts of NWMO CLCs to maintain a balance in the information they hear from speakers, as it is important that local communities be exposed to all sides of the debate.

At the same time, I know that this is a very complex and often frightening topic for people, and it can be difficult to separate facts from opinion. For this reason, I would like to offer the following observations on several comments from Dr. Edwards' paper that I feel were either incorrect, or simply misleading, to an extent that they would probably further confuse or frighten people.

I offer this additional context on Dr. Edwards' paper in the spirit of better understanding. I respect everyone's right to express an opinion, but not the right to misrepresent the facts – especially when directed at a vulnerable population faced with monumental questions affecting the future of its community and environment.

Dr. Jeremy Whitlock
jeremyjwhitlock@gmail.com
http://www.nuclearfaq.ca

---

[1] http://www.nuclearfaq.ca/qa-from-november-2020-south-bruce-clc-meeting-dr-gordon-edwards.pdf

Comments by Dr. Jeremy Whitlock on

"Questions and Answers about Used Nuclear Fuel – for the South Bruce NWMO CLC"
(by Dr. Gordon Edwards, updated 2021 February 18 on South Bruce CLC website[2])

This article will address the questions:

- *How can we have confidence in predictions of the long-term safety of a geological repository?*
- *How do medical radioisotopes from nuclear reactors help to equalize the global quality of life?*
- *How is radiation a natural part of our environment, and less dangerous than one might think?*
- *Does Canada have the expertise to safely handle and transport highly radioactive spent fuel?*
- *How are proliferation concerns for spent nuclear fuel addressed with a geological repository?*
- *Why is waste management actually one of the more attractive benefits of nuclear technology?*

For clarity each comment is arranged such that original text from Dr. Edwards' document is quoted in a shaded block in italics, followed by Dr. Whitlock's comments.

> **Item 1 (Section B1, page 1)**:
>
> *Unfortunately, the fission process also creates hundreds of varieties of unwanted by-products – radioactive elements never found in nature before 1940.*

The statement above incorrectly implies that radioactive fission products did not exist in nature prior to 1940. In fact, not only is uranium fission a natural process (which humans only happened to discover in 1939), but this fact is actually of immense importance to our confidence in the long-term safety of geological repositories.

First, some background on what we mean by uranium "fission" in nature: this isn't a reference to the more prevalent form radioactive decay of uranium, discovered at the beginning of the 20th century, whereby every uranium atom will at some point spontaneously shed a small amount of energy and mass, turning into new "daughter products", one after the other, through a chain that ends eventually at nonradioactive lead. This process is extremely slow (only about 1 in 10 billion uranium atoms will radioactively decay over a year), which is why half the uranium found on earth when the planet formed 4.5 billion years ago is still around, and still one of the more abundant elements in the earth's crust. (Interesting fact: The radioactive decay of uranium's chain of daughter products is largely responsible for the intense heat in the earth's interior – leading to, among other things, the planet's magnetic field that makes all life on the surface possible. That's correct: *radioactive decay makes life on earth possible.*)

But as slow as this 'conventional' decay process for uranium is, we also know that a much smaller fraction of uranium atoms (about two million times smaller) will instead choose to spontaneously 'fission' – i.e., split into two large, radioactive pieces called "fission products". Now, since uranium is found everywhere, including trace concentrations inside each of us, this process of spontaneous fission also happens

---

[2] http://www.nuclearfaq.ca/qa-from-november-2020-south-bruce-clc-meeting-dr-gordon-edwards.pdf

everywhere. (So yes, another interesting fact is that every one of the fission products found in used nuclear fuel is also created naturally inside our bodies – albeit in extremely low quantities.)

However – and this is the important part – we also know that roughly two billion years ago there was enough uranium and ground water in the Oklo region of Gabon, Africa to create several 'natural nuclear reactors' that operated sporadically over a period of a million years. As in any nuclear reactor, radioactive products were produced, including 6 to12 tonnes of fission products (the leftover 'half-pieces' of split uranium), and about 4 tonnes of plutonium. All of these have disappeared (through radioactive decay) by now, but their signatures remain, leaving a two-billion-year-old record of their migration behaviour. It can be determined, for instance, that the atoms of plutonium produced never moved from the grains of uranium where they were formed, and that widespread migration did not happen for most of the fission products - despite exposure to ground water movement for over two billion years.

These prehistoric natural "Oklo reactors" in Africa are thus much more than just interesting science trivia; they act as a *natural analogue* of the geological repository concept: a two-billion-year "experiment" that nature has conducted for us, from which we gain valuable knowledge. Although the analogue is not perfect (these natural reactors were obviously much different than an engineered used-fuel repository, both in layout and content), there are enough similarities to give us additional confidence in our simulations of the long-term behaviour of a repository.

Incidentally, there are several other natural analogues out there for a used nuclear fuel repository – one of the most useful is in Canada: the high-grade uranium ore deposit now being mined at Cigar Lake in northern Saskatchewan. Despite sitting in highly permeable sandstone host rock, the Cigar Lake ore deposit has survived roughly 1.3 billion years of geologic history, chiefly because of its natural clay buffer. The clay immobilizes the uranium by reducing both the penetration of groundwater into the deposit, and the diffusion of uranium atoms out of the deposit. Remarkably, the deposit has remained intact through several mountain-building episodes (the Rocky Mountains, the Appalachians), the trauma of continental drift, multiple ice ages, constant groundwater flow, and significant uplift caused by the erosion of over 2.5 km of overlying sedimentary rock. In fact, it is so stabilized in its position, currently 430 metres below the surface, that no chemical or radioactive signature can be detected on the ground above it. Since the NWMO's repository concept calls for a much less permeable host rock (either crystalline or sedimentary) and a superior clay buffer (bentonite clay, rather than Cigar Lake's illite clay), the barriers to water movement and radionuclide migration proposed in the Canadian plan are given added validation by Cigar Lake.

More information on these natural analogues and their significance to used fuel repository safety can be found in a background paper on the NWMO website: *Natural and Anthropogenic Analogues – Insights for Management of Spent Fuel*.

Finally, the claim about radioactive fission products 'never being found in nature' is not just incorrect, but an unnecessary distraction to the public discussion, since it creates uncertainty and fear about our ability to handle radioactive waste. It is 'unnecessary' since almost every object and material in our homes, offices, cars, and clothing is composed of molecules that didn't exist before the mid-20th century, and most would be toxic if ingested in hazardous concentrations (as are many naturally occurring elements and molecules, for that matter): the discussion of responsible waste management does not hinge on whether the items occur in nature.

In particular, all radioactive versions of elements, whether naturally occurring or not, have similar chemical properties to their non-radioactive cousins, and thus would undergo chemical reactions in a familiar manner within the environment. In addition to this we have had 75 years of experience with the analysis, handling, and regulation of radioactive products from the fission process, including numerous *in situ* underground tests at places like Chalk River Laboratories, which enhances our understanding.

Item 2 (Section B1, page 1):

A radioactive atom will explode or disintegrate, suddenly and violently, giving off a kind of subatomic shrapnel called "atomic radiation". Exposure to such emissions will damage nearby living cells. Some of those radiation-crippled cells will develop into cancers many years later.

This description of radioactive decay uses unnecessarily provocative imagery to describe a natural process that is a part of our life from the moment we're conceived. Within our own bodies, and within the environment around us, thousands of atoms are radioactively decaying into other atoms at every moment (almost 10,000 per second in an adult body alone): this is simply one of the many ways that nature exchanges energy. These atoms are not "exploding", the process isn't "violent", and the energy emitted is not "shrapnel".

Another way that nature exchanges energy is through the absorption of sunlight, and like sunlight, radioactivity presents a low risk at low exposures, and a higher risk at high exposures. At low levels of exposure – the levels that we encounter every day – our bodies have amazing mechanisms for dealing with the radiation around us, and within us: for example, we have about 30-40 trillion cells in each of our bodies (that's 30-40 *million million* cells), and every one of them will encounter an energetic ray or particle of natural background radiation at least once during our lifetime – some more than once. What additional cancer risk does this pose? The international risk standard[3] predicts that exposure to background radiation increases our lifetime probability of getting cancer by about 1% – compared with our overall probability of 50% for getting cancer during our lifetime (the extra 1% would be in the "noise" and undetectable). Our bodies are clearly adept at handling background levels of radiation.

At higher radiation exposures the risk increases proportionately, which is why, for example, X-rays are only administered when there is good justification for their use, and only with safety measures for both patient and medical staff. Fortunately, radiation, after over a century of use in medicine and industry, is one of the most well-understood agents in the environment, and one of the most controllable. This knowledge is reflected in comprehensive national regulation of any activity involving radiation, with dose limits set many times lower than what would be considered dangerous. As a member of the public, you can be confident that your health and safety takes precedence in the planning of such activities, including the transportation and management of used nuclear fuel.

---

[3] See ICRP-103, "The 2007 Recommendations of the International Commission on Radiological Protection".

Item 3 (Section Q3, page 6):

At present, there are no hot cells at any of the existing reactor sites, and neither OPG nor Bruce Power has ever built a hot cell. Also, none of the atomic workers employed at any of the operating nuclear reactors have had any prior experience working with hot cells. It will be an unusual experience for them, the closest encounter they have ever had with an individual, unshielded, highly radioactive fuel bundle, not submerged underwater as it is in a spent fuel pool, but up close and personal, just on the other side of the glass window. And they will have to process up to 300 used fuel bundles per day, 365 days per year, for 50 years or more.

In my view, the probability of accidental leakage is quite high. It will be a miracle if the environment surrounding the proposed DGR does not experience at least some degree of contamination. I find it amazing and irresponsible that NWMO has not explained to all of the candidate communities that used nuclear fuel cannot be put directly underground, it has to be repackaged first.

The author of the statement above is not a nuclear safety expert and has no qualifications for assessing the “probability of accidental leakage” for these repository surface-facility operations – he is simply playing on public uncertainty and fear. Furthermore, the NWMO has clearly explained to candidate communities in the “Learn More” process (including on the NWMO website) about all stages of used-fuel handling, including packaging in the surface facilities prior to transfer underground, and including the use of “hot cells” (shielded facilities for remotely handling radioactive materials).

Canada has a vast amount of experience in the safe packaging, transport, and handling of used-fuel bundles and other highly radioactive materials, gained over the 75 years of its nuclear program – including the use of “hot cells” and similar facilities. The equipment for the transfer and packaging of used nuclear fuel will be state-of-the-art using Canadian and global expertise, and operators will be highly trained to perform their tasks, as would be expected of this highly regulated and complex operation.

Item 4 (Section Q9, page 15):

Perhaps someone can tell me why we think that NWMO knows all the answers when in some cases they do not even seem to know the questions? or why NWMO uses the copper/steel combination when it is known that contact between two such metals will cause a current to flow that will accelerate any corrosion? or why NWMO chooses to use only 3 mm of copper when Sweden and Finland are using 50 mm of copper (17 times the thickness) and no steel at all? or why NWMO proposes a vertical shaft while others design a gently sloping ramp that spirals down into the rock formation, one that you can drive a bus on?

The author of the statement above is not a geochemist, engineer, or nuclear safety expert, and has no qualifications for assessing the long-term corrosion behaviour of copper, the pros and cons of various repository designs, or almost any other technical aspect of used nuclear fuel management. The NWMO, on the other hand, gets its information from experts working in these specialty areas of science and technology, and I would suggest starting with them for clarification on these design details.

Item 5 (Section Q10, page 15):

Q10. Written Question*. If a DGR is not a suitable solution for containing radionuclides, how do you explain the Oklo natural reactor in Africa? It "operated" for millions of years, and the radionuclides never travelled farther than a couple of meters in the surrounding rock.*

Answer*. What you say is not true. The event happened before there was any life on Earth. We have no idea where the radioactive iodine went, or the caesium, or the noble gases, but I am sure they did not just "stick around". One anecdote does not make a scientific safety case.*

The Oklo natural reactor site in Gabon, Africa, as described in the first section above (with a link to the NWMO's background paper on the topic), is one of the best analogues in nature for a used-fuel repository, providing valuable data to validate and enhance our models for long-term fuel and radionuclide behaviour. We know, for example, that chemical interactions prevented almost all of the radionuclides, including the plutonium, from migrating away from the reactor site, despite over two billion years of uncontained access to the surrounding environment.

We have other analogues as well, such as the Cigar Lake uranium deposit in Saskatchewan that only exists today because of a natural clay buffer with many similarities to the engineered buffer design proposed by the NWMO (see further details in the response to Item 1 above).

However, no natural analogue is exact, and certainly none are sufficient for an engineering safety case – which is why the safety case relies upon a substantial amount of additional research and development conducted in Canada and internationally over the past half-century, and continuing today.

That said, the analogues do go a long way to answering the question, "how can we have confidence that the science is on the right track?": because nature herself is showing us the way.

Item 6 (Section Q11, page 16):

It seems clear that plutonium requires active surveillance and strict security measures to prevent its theft or diversion for use in nuclear weapons. It cannot be simply abandoned, whether above ground or below ground. […] In the next century, or even the next millennium, science may discover a method of destroying the plutonium without simultaneously creating additional radioactive waste. Until then, we should keep an eye on it and make sure that it does not fall into the hands of desperate people.

The author of the above statement is not a nuclear safeguards expert and has no qualifications for assessing the proliferation risk of plutonium in a deep geological repository.

As part of international commitments under the Nuclear Non-proliferation Treaty (NPT), the International Atomic Energy Agency (IAEA) implements safeguards measures on all nuclear material in countries like Canada, in order to verify its continued use in only peaceful applications of nuclear technology. These safeguards extend to geological repositories, and consequently the IAEA is currently working with Finland

and EU authorities to develop practical measures to provide continual verification of the uranium and plutonium that will be placed in its used fuel repository now being completed at Olkiluoto, Finland (due to start receiving used fuel in 2025). The IAEA will similarly work with Sweden, Canada, and other countries developing repositories, to implement similar safeguards measures. The nuclear material in these repositories will not be abandoned, but will be monitored for as long as there is an IAEA and national institutions.

In the very long term one may conceive of a time when there is no longer an IAEA or national institutions. This is precisely the scenario envisaged in the concept of a deep geological repository, since it must necessarily recognize the reality of a post-glaciation future where signs and indicators of our current activities can no longer be relied upon by future civilizations. For safety and security reasons, the best place for used nuclear fuel will probably be in a deep repository designed to withstand the geologic upheaval of glaciation – in fact, since future glaciation will impact most of Canada, including our cities, it is very likely that the one toxic legacy that future civilizations will *not* have to worry about will be the used nuclear fuel stored responsibly in these repositories.

Item 7 (Section Q14, page 18):

As for medical isotopes, they serve a number of valuable functions, none of which are dependent in any essential way on nuclear reactors or the fission process. Isotopes can be and are being produced by particle accelerators such as cyclotrons and linear accelerators, without the need for uranium or reactors. Cobalt-60, which has been used in cancer treatment and to sterilize medical equipment, is being replaced by electron accelerators in both of these applications. The University of Saskatoon, where the first "cobalt bomb" was built for cancer treatment, has now replaced its cobalt irradiator with an electron accelerator.

The statement above reflects a lack of understanding of how medical radioisotopes are made and utilized on this planet. Some medical radioisotopes are best made in nuclear reactors, and some are best made in cyclotrons. The difference comes down to usage, cost, and national development level.

Nuclear reactors make "neutron-rich" radioisotopes used extensively in both radiotherapy (e.g. iodine-131, iodine-125, samarium-153, strontium-89, radium-223, cobalt-60) and imaging (e.g. technetium-99m).

Cyclotrons (a compact accelerator using rapidly rotating particle beams) make "proton-rich" radioisotopes that tend to be much shorter-lived (e.g. fluorine-18) and used mainly in imaging such as PET scanners – but increasingly for radiotherapy as well. The short half-life of most cyclotron radioisotopes tends to restrict their use to local distribution (often located in the same hospital as the PET scanner). Reactor-made and cyclotron-made radioisotopes have some overlapping and some distinct applications, and thus they complement each other.

Linear accelerators using high-energy electron beams have replaced most external radiotherapy applications of reactor-produced isotopes in developed countries (but not internal radiotherapy or imaging applications). The limitation to developed countries speaks to the important consideration of global availability, and the aspirational goal of equalizing the global quality of life. This consideration is further explored below.

One of the most common nuclear medicine procedures in the world uses technetium-99m to image blood flow and heart operation – this procedure accounts for 80% of all nuclear medicine procedures worldwide (about 40 million per year), and nuclear reactors are essential for the global availability of this radioisotope[4].

Some medical radioisotopes, like technetium-99m (or Tc-99m), can be also made less efficiently with particle accelerators (like a cyclotron): in fact, from a scientific viewpoint, just about any isotope can be made with a particle accelerator, if time and money are no object. Unfortunately, time and money are very much of importance to global access to medical radioisotopes, and this is why the only practical way that sufficient quantities of Tc-99m can be distributed and used around the world – particularly in the developing world – is through the use of nuclear reactors for production.

For the same reason of global availability, many cancer radiotherapy machines (which were first pioneered through a collaboration of the Canadian nuclear and medical communities in the mid-20th century) still use reactor made radioisotopes like cobalt-60, while newer models use linear electron accelerators: In order to implement an accelerator in place of a reactor-based radioisotope technology – whether for cancer therapy, or to supply an imaging and diagnostic scanner – you generally require more technical infrastructure (including stable electricity supply), financial investment, and expertise, which is why these tend to be first-world medical solutions today. In developing nations (accounting for about 70% of the world's population) cancer radiotherapy and diagnostic imaging using nuclear-reactor produced radioisotopes tend to dominate.

Yes, that's correct: nuclear reactors make life-saving medical procedures possible for most of the planet's population.

For this reason, it is short-sighted and first-world-centric to claim that nuclear reactors aren't needed for medical radioisotope production. In fact, reactors are an essential part of a suite of technologies that make advanced medical procedures accessible to people in all countries and from all backgrounds – and this legacy is, in fact, one of the greatest gifts that Canadian ingenuity in science and medicine gave the planet in the second-half of the last century.

---

[4] See, for example: "How Research Reactors Help Make Medical Imaging Possible," IAEA Bulletin, 2020 Aug 10, www.iaea.org/newscenter/news/how-research-reactors-help-make-medical-imaging-possible.

Item 8 (Section Q17, page 19):

The success of the nuclear industry is based on a number of fictions. First and foremost is the fiction that nuclear power has nothing to do with nuclear weapons. Second is the fiction that nuclear power is "clean" – a term that fooled many decision-makers into thinking that nuclear waste didn't exist.

These are strawman arguments: neither of these "fictions" have been propagated by the nuclear industry or broad nuclear community, whether in Canada or internationally.

Firstly, nuclear weapons: the entire nuclear industry and broad nuclear community in Canada exists within an international non-proliferation regime, verified through the Vienna-based International Atomic Energy Agency (IAEA), which Canada was instrumental in creating and maintaining for the past 50 years (see www.iaea.org). The fundamental tenets of this non-proliferation regime are (a) that nuclear technology and nuclear weapons are inextricably linked, (b) that countries wishing to make use of nuclear technology commit to never exploit this link, and (c) that these countries accept strict international verification measures (nuclear safeguards) which demonstrate this obligation.

<u>This is not an industry living in a "fiction" that nuclear power has nothing to do with nuclear weapons</u>: this is an industry striving to advance technologies that enhance and equalize the quality of life for all people on this planet, despite the reality of nuclear weapons (and doing so successfully for 75 years).

Secondly, clean energy: nuclear fission does not produce pollution from combustion (including greenhouse gases), and does not take up large tracts of land to extract energy from dilute energy sources. Its use, in combination with renewables, can lead to an almost pollution-free electricity generating system such as that found in the province of Ontario (60% nuclear, 35% renewable), and is recognized by the Government of Canada as essential to achieving "net-zero" greenhouse-gas emissions by 2050. This does not mean perfectly "clean", since nothing is – not solar panels, not wind turbines, not hydro dams, and not nuclear plants.

The majority of nuclear power's waste production is concentrated in its spent fuel: solid, low in volume relative to its energy content, and all in one place. It is highly radioactive and so must continue to be properly managed, but this is relatively easy given the fact that it is, in fact, solid, low-volume, and all in one place. In fact, Canada, like many other leading nuclear nations, has a plan to keep the spent fuel "all in one place" for a long time to come – protected over the coming millennia even from future glaciations – and in this respect nuclear is unique among the large infrastructure industries that enable our society's functioning.

In Canada this plan is 40 years in the making and today is implemented by the Nuclear Waste Management Organization (NWMO): a highly visible, government-mandated organization whose primary goal is a transparent, public process to collaboratively develop a spent fuel geological repository (see www.nwmo.ca).

<u>This is not an industry trying to fool decision makers that it makes no waste</u>: this is an industry working with decision makers and the public (including indigenous peoples) to implement a leading-edge solution

to this waste – and, in fact, the availability of a solution that uniquely addresses 100% of its long-lived waste in a responsible manner is one of the more attractive benefits of nuclear technology.

Item 9 (Section Q17, page 19):

[The safety case for nuclear waste management] can't really be proven. No principle of science allows one to verify predictions made over such an extraordinarily long period of time.

The above statement reflects a misunderstanding of how science works. The implication is that we cannot have confidence in scientific modelling of long-timescale processes, unless we stick around to see the end-result of the process to get "proof". By this logic, science should give up on attempting to predict the long-term modelling of our sun's lifecycle, the movement of continents, human population growth and genomic evolution, or environmental degradation – including global climate change.

In fact, science deals with many processes with long timescales, and some of these – like the ones listed above – are actually quite important to get right.

But what does "getting it right" mean? Does it mean 100% accuracy, or does it mean getting it "right enough" to provide us the confidence to make important decisions today, with any remaining uncertainty justified and minimal? That's actually where we are with climate change modelling today, by the way: predictions of the impact of atmospheric warming over the next 50 or 100 years are based upon imperfect scientific models and incomplete knowledge – therefore involving a level of uncertainty. Governments around the world have nevertheless judged this uncertainty to be low enough, relative to the risk of not making important decisions today, to justify acting upon these imperfect scientific models anyway.

In fact, science never knows an answer with 100% confidence, because there is always uncertainty. This is why asking a real scientist for a "yes/no" answer to anything can be aggravatingly unsuccessful: you will probably get a qualified answer, and in fact you would be wise to question when you don't get a qualified answer. (So, with reference to Item 8 above, one would be right to question a scientific response that nuclear power, wind power, electrical cars, or any technological process is "clean" – and ask for clarification, as provided in Item 8 above.)

So then, given the million-year timescale of nuclear waste management, how exactly does science gain confidence in the long-term safety case? The answer is threefold:

Verifying today's models

Learning from nature's past

Minimizing future uncertainty

Let's look at each of these in more detail:

1. Verifying today's models: We can't go forward in time to personally verify our predictions

for long-term processes, but we can verify the scientific models we use today to make these predictions. Whether we're modelling the long-term changing of the climate, or the long-term behaviour of spent nuclear fuel in a repository, we must consolidate data from the simulation of a large number of complex and interconnected environmental processes, each with their own assumptions, inputs, and individual uncertainties. We determine these individual uncertainties by testing against experiments or natural observations, and – importantly – continuously improving our understanding so we reduce these uncertainties as much as possible. The combination of these individual uncertainties is then extrapolated forward to give a range of overall uncertainty in our long-term predictions. Then, when a scientist later explains what we believe will happen to the climate in 100 years, or spent nuclear fuel in 1 million years, this inescapable uncertainty will always be part of the answer.

2. Learning from nature's past: We may not be able to go forward in time, but we can often go backwards – i.e., letting nature herself show us the results of long-timescale natural processes with sufficient similarity to help us verify our models. Just as climate modellers turn to historical records to better understand how the earth's climate and greenhouse-gas concentrations have evolved in the past, nuclear repository developers turn to historical geology to better understand how nature's own repositories of uranium and other radioactive elements have behaved underground for millions of years. As described in Item 1 above, nature was this planet's first nuclear engineer – even operating a natural nuclear reactor two billion years ago that created all the same waste radioisotopes produced by our reactors today. We learn a lot from these "natural analogues"; in particular, we verify our assumptions by analysing the natural mechanisms that isolated uranium and its radioactive products from the environment for millennia. More importantly, we can improve on nature's methods because we have the luxury of not being random – e.g., we can choose more favourable rock formations, regional seismicity, ground water conditions, and protective clays (in addition, of course, to having a robust starting containment around the uranium). For more information on these natural analogues, please refer to the NWMO's background paper linked in Item 1 above.

3. Minimizing future uncertainty: When forecasting far into the future it is particularly important to minimize uncertainties as much as possible. When so-called "chaotic processes" are involved – that is, processes where even a minor perturbation in behaviour today can lead to very large and unpredictable deviations in end results – minimizing uncertainty is even more important. This is one of the challenges facing global warming modellers, for example, since the natural processes of weather and climate involve a significant level of chaotic behaviour. In fact, you could say this is one reason that long-term spent fuel management looks to deep underground repositories – removing the inherent uncertainty introduced by future climate change (including glaciation, which we know will occur in Canada within the coming millennia). Other ways that scientists reduce the uncertainty include choosing a rock formation that is as homogenous as possible in order to simplify its characterization (e.g., uniform geochemical properties and no large fractures), as well as being low in seismic activity, groundwater transport, and probable human interest (i.e. no rare minerals). In addition, scientists reduce the impact of uncertainty by making conservative design assumptions wherever possible (i.e. "erring on the safe side") – for example, in forecasting the lifespan of the containers holding the spent nuclear fuel in

> the underground conditions, and including as many natural barriers as possible that complement our engineered barriers. An example of a natural barrier is the low groundwater transport properties of the host rock formation, which would slow the movement of radionuclides migrating from a repository such that the journey to the surface would take many hundreds of thousands of years – long enough for the radionuclides to naturally decay to background levels of radiation.

It is worth noting that the level of planning for the sustainable long-term management of spent nuclear fuel easily exceeds that accorded to any other industrial waste produced by humans – partly because society demands this, and partly because the unique features of spent nuclear fuel (solid, low-volume, and all in one place – see Item 8) make it possible. But nuclear fuel is far from the only toxic or long-lasting waste challenge facing modern society. Today, for example, we may be content to safely dispose of tonnes of toxic industrial waste in state-of-the-art engineered landfills, but the next glaciation will have no problem scouring these out and redistributing their contents across the post-glacial landscape. Future civilizations will certainly have many interesting chemical legacies to deal with, but one that they won't likely have to worry about – due to their ancestors' careful planning, learning from nature, and minimization of modelling uncertainty – will be historic spent nuclear fuel, still isolated deep within its rock repository.

Dr. Jeremy Whitlock
jeremyjwhitlock@gmail.com
www.nuclearfaq.ca

About the author:

Dr. Jeremy Whitlock is a nuclear reactor physicist and manager with over 26 years' experience in the nuclear field (22 years in Canada mostly at Chalk River Laboratories, and since 2017 as a manager at the International Atomic Energy Agency (IAEA) in Vienna). He has a PhD in reactor physics from McMaster University, and is a former President of the Canadian Nuclear Society. Since 2006 Dr. Whitlock has specialized in nuclear non-proliferation matters, both at Chalk River Laboratories in Canada and at the IAEA in Vienna. Dr. Whitlock is a speaker and author on nuclear issues, striving for a balanced understanding of the risks, benefits, and history of this technology. Since 1997 he has maintained "The Canadian Nuclear FAQ" website, a question-and-answer resource dedicated to Canadian nuclear science and technology (www.nuclearfaq.ca).