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Supplemental Submission on Nuclear Power

The Challenge of Nuclear Waste

Executive Summary: Contrary to the submission of Professor Lee Chack-fan, Academician, Chinese Academy of Engineering, the problem of nuclear waste (radwaste) disposal and storage is not a simple one. It truly requires an active commitment of tens of thousands of years of safeguarding; something which simple common sense tells us is beyond human ability and a legacy and burden for future generations on an unprecedented scale.

Professor Lee's Submission

Towards the end of the second session before the Legislative Council Panel on Environmental Affairs on Friday 29 April 2011, Professor Lee Chack-fan made an oral submission on the problem of nuclear waste that went something as follows: *First*, he noted that low level radwaste tends to be bulky, un-concentrated, and of short half-life so that burial for a few decades tends to handle the problem. *Second*, high level radwaste, especially spent nuclear fuel, he implied is not really that big a problem. You seal it in a container along with some liquid absorbing material and bury it in the desert far from ground water for "a few hundred years". My apologies to Professor Lee if I have accidentally mischaracterized his submission but this is what my notes, taken down at the time, reflect.

Unfortunately, as it stands, this is a rather naïve view at best and so requires a detailed rebuttal.

> Note: nuclear technology is filled with scientific and technical concepts, which can easily overwhelm the reader. Part of the on-going problem with this debate is that it takes a bit of study to get a handle on this so the typical citizen gives up in deference to the "expert". That is not the way to address the problem. The public needs to be educated in order to make conscious and informed decisions. What follows is hopefully self-explanatory. However, should the reader get lost, they are invited to read the accompanying appendix which attempts to explain some of the most basic concepts while the conclusions section is basically an argument of common sense.

The Challenge of Nuclear Waste

Most nuclear power plants are run on what is called low enriched uranium (LEU). In nature, the two predominant isotopes are U^{235}, i.e. uranium defined by 92 protons and having 143 neutrons (92 + 143 = 235) and U^{238} (146 protons). U^{235} is fissionable and makes up ~0.7% of natural uranium, the rest being U^{238} which is not (but which is the seed material for producing a form of plutonium (Pu^{239}) which is. A practical reactor typically requires enrichment on the order of 3 to 5% U^{235}. Nuclear bombs like the one dropped on Hiroshima make use of highly enriched uranium (HEU) on the order of 80% or higher. The two most popular nuclear power plant designs, the boiling water reactor (BWR) (Fukushima) and the pressurized water reactor (Three-Mile-Island and Daya Bay), can be run for 18 months or so until the build up of byproducts which includes neutron absorbers make the fuel unusable.[1] This is known as spent nuclear fuel (SNF) and the major source of high-level radwaste.

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[1] Refueling instead every few months helps prevent the build up of Pu^{240} thus increasing the purity of Pu^{239}, which can be used in nuclear bombs. Weapons grade plutonium is defined as containing no more than 7% Pu^{240}.

You can't just instantly turn off a nuclear reactor. Once started up and then shut down, it takes many months to cool down. When all of the control rods are reinserted, absorbing the neutrons and thus quenching the nuclear fires, initially the residual heat from the radioisotopes produced will still be on the order of 6% that of the operating plant. This is why typical catastrophic nuclear power plant accidents are loss of coolant accidents (LOCA), common to Three-Mile Island, Chernobyl, and Fukushima. Cooling water needs to be actively circulated both through the reactor core as well as through cooling pools external to the core where SNF is housed for a decade or two. Temperatures are so high, that should the material become partially uncovered, the core will melt potentially right through the bottom of the containment vessel releasing radioactive materials into the environment. This is the classical reactor "meltdown". It is not uncommon to build nuclear reactors in pairs so that in principle one is operation while the other is cooling down and being recharged with fresh fuel rods.

The products of nuclear power are a true witches' brew of radioactive poisons. They basically break down into three categories, fission products, trans-uranium elements (also known as "actinides" after the branch they occupy on the Periodic Table of the Elements), and activation products created when structural materials, etc. absorb neutrons. All are highly dangerous to life processes in one way or another and the game that needs to be played is called "containment", i.e. never ever let them out into the environment because once released, like the furies fleeing Pandora's box, they can't be put back in.

When radioactive material does break into the biosphere, it is of course taken up according to its chemistry, not its radioactivity characteristics. For example, the two iodine (53 protons) radioisotopes I^{131} and I^{129} will both be taken up by the thyroid gland, which preferentially absorbs iodine but respectively have half-lives of 8 days and 15.7 million years so the challenges they present are quite different. Thus it makes sense to characterize radwaste, irrespective of its chemistry, according to half-life, into short-term (decades), medium-term (hundreds of years), and long-term (10,000 to a million years).

Short-term [scale of decades]

Short-term radioactivity is primarily due to fission products with half-lives on the order of a year or much less. The rule of thumb says that you need to wait 10 half-lives to reduce an initial mass down by 99.9%. Of course that may still be higher than normal background radiation, which is the biological measure for when the residual material is no longer of concern so in practice you may have to wait even longer.

Typically the longest-lived isotope in this category is Pm^{147} (promethium, 61 protons) with a half-life of 2.6234 years so a wait on the order of 26 years or so is in order. Such material is highly radioactive and because of the rapid decay thermally hot requiring active cooling in on-site SNF reactor pools. Should the spent fuel rods be partially uncovered, the temperature can become high enough for the zirconium cladding (protective container) to react with the water displacing hydrogen degrading the cladding.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$

The free hydrogen mixing with oxygen in the air will then explode with the resultant plume carrying all of the available isotopic poisons into the atmosphere. This was the sort of thing observed repeatedly in the Fukushima incident.

Medium-term [scale of hundreds of years]

Medium-term radioactivity occurs from fission products with half-lives on the order of 30 years, especially Cs^{137} (cesium, 55 protons) and Sr^{90} (strontium, 38 protons) which have half-lives respectively of 30.17 and 28.90 years. These two isotopes tend to dominate the regime because they are both produced in relative abundance in about 6% of all fissions. They were common constituents in the fallout found in atmospheric bomb tests in the past.

Cesium is nasty in the sense that at room temperature, like mercury (80 protons), it is a liquid and so readily evaporates into the air. It is in the same period as potassium and sodium and so readily substitutes for these and like them reacts with water producing the hydroxide, which in turn, as a base, reacts with any available acid producing a water soluble salt. Entering the human body, it distributes throughout and Cs^{137} is a dangerous gamma ray emitter. It is the principle source of radiation in the zone of alienation around Chernobyl and found in the radioactive plumes emanating from Fukushima.

Strontium is chemically similar to calcium so easily substitutes for it concentrating in bone. Children drinking contaminated milk are especially vulnerable. The Chernobyl incident contaminated a large area of Eastern Europe with Sr^{90}.

Our rule of thumb would thus require radwaste in this category to be contained for at least 300 years.

Long-term [scale of tens of thousands of years]

There are no fission products with half-lives between 100 and 100,000 years. Instead, this is where the actinides or trans-uranium isotopes dominate, most notably those of plutonium, americium, and curium as summarized in the following table:

Element	Symbol	Proton (Atomic) Number	Mass Number	Half-life (thousands of years)
Plutonium	Pu	94	239	24.1
			240	6.5
Americium	Am	95	241	0.4322
			243	7.37
Curium	Cm	96	245	8.5
			246	4.73

Plutonium is often considered to be the most poisonous substance known to man which readily oxides in the air or water and accumulates in bone marrow directly causing leukemia. Pu^{239} is fissionable. It was the explosive source of both the world's first nuclear bomb (Trinity) and the Nagasaki bomb. Radwaste containing it is a prime source for nuclear proliferation. The original Indian bomb (Smiling Buddha) in 1974 was produced from plutonium created in a civilian reactor supplied by both Canada and the U.S. in violation of the understanding that the reactor was to be solely used for peaceful purposes.

Both Americium and Curium are selectively taken up in the bones and liver.

Applying our rule of thumb to a rough half-life of 10,000 years gives a figure on the order of at least 100,000 years that this material would have to be safeguarded. Admittedly the intensity of radiation per unit mass is much lower with long-lived than short-lived radioisotopes but given effects such as bio-concentration, you really do not want this material to be released into the environment. In the U.S., the current debate is whether or not the government should be held liable for safeguarding it for 10,000 years or one million years into the future.[2] That fact alone should communicate how crazy the entire notion of nuclear power is!

On scales greater than 100,000 years, the long-lived isotope Tc^{99} (technetium, 43 protons) dominates, making up about 6.1% of fission products (for U^{235} fuel) with a half-life of 211 thousand years. Technetium compounds do not bind well to the surfaces of minerals and so are prone to be washed away into the larger environment. Inhalation is a significant lung cancer risk.

Technically, containing any of this material over such approximately geological times is daunting. Various schemes of “vitrification” (sealing in glass) and deep burial in so-called geologically stable strata have been proposed, none declared as universally satisfactory. The U.S. with over a hundred nuclear power plants has no established long-term nuclear waste system in place and it is not for a lack of trying.

It is not the business, as was claimed by Professor Lee, of simply burying it in a container for a few hundred years away from ground water. Designing an atomic bomb is technically the easier challenge.

Conclusion

Let’s assume that the technology is eventually established to safely contain spent nuclear fuel for at least 10,000 years. Who is going to actively safeguard it least the likes of al-Qaeda decide to use it as a mine for raw material to produce a dirty bomb? The Medieval priesthood of the Knights Templar lasted less than two hundred years (from 1129 to 1307 AD). In the whole history of our species, when has an organization remained stable for more than a few hundred years yet alone 10,000?

The problem of nuclear power, of which the safeguarding of nuclear waste is but an example, is that the scale of almost every dimension (space, time, energy, materials standards, construction reliability, ability to anticipate problems, shutdown time, operator reliability, reaction time to cascading problems, etc.) is *beyond human scale* and effective human control. The ultimate failure of the dream is not technological but the reality and limits of the behavior of our own species.

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[2] See the Testimony of Robert Meyers, Principal Deputy Assistant Administrator for the Office of Air and Radiation U.S. Environmental Protection Agency before the Subcommittee on Energy and Air Quality Committee on Energy and Commerce U.S. House of Representatives (July 15, 2008).

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Appendix on Basic Nuclear Science Concepts and Developmental History

Hopefully in high school chemistry, we learned that our normal material world is made up of chemical elements, the smallest representative of which is an atom (Greek for "indivisible"). Chemistry is the study of the natural reactions among elements and compounds (of elements). Structurally an atom consists of a very small positively charged nucleus surrounded by a negatively charged cloud. The positive charges are due to heavy protons and the negative charges light electrons. An electron has a mass of only about 0.00054th that of a proton. Overall, an atom is electrically neutral. Each proton and electron has exactly a unit (electron) charge.

In 1919, Rutherford discovered the nucleus as a tiny central concentration of protons typically only 0.0001 to 0.00001th the diameter of the overall atom. Indeed, an atom is mostly empty space. Ben Franklin taught us that like charges repel so the question was why didn't the nucleus of the atom fly apart (and rather strongly at that given the closeness of the protons to each other)? The puzzle was solved in 1932 by Chadwick with his discovery of the neutron, which in a very crude sense acts as the mediator of the strong nuclear force, which on the very short scale of the nucleus overcomes the force of electrostatic repulsion. The neutron is electrically neutral (hence its name) and slightly heavier than a proton. Free of the environment of a nucleus, it spontaneously decays to a proton and an electron (plus a kinetic energy release imparted to the particles equal to the difference in mass according to Einstein's famous formula $E = mc^2$) with a half-life of 14.8 minutes (the time it takes for half of a sample to decay away).

Thus a chemical element is characterized by the number of protons (its atomic number) in its nucleus (or in a neutral atom the number of electrons which is the same). Chemical reactions are essentially the exchange or sharing of the outermost electrons of an atom with each element having a different story (chemistry) although these properties tend to repeat themselves (hence the *Periodic* Table of the Elements).

However, it is possible for a given chemical element to have different nuclei by having more or less neutrons than average (for the element). Such combinations are known as isotopes (Greek *iso* "same" + *topos* "place", i.e. they occupy the same place in the Periodic Table). Some of these combinations are unstable and spontaneously decay with a measurable half-life. These are known as radioisotopes and are the source of nuclear radiation. Virtually all of the matter making up our everyday world within which life on Earth evolved and thrives is made up of stable isotopes (i.e. not radioactive) so what is the normal condition for life processes is the *absence* of radiation.

There are two primary forms of radioactive decay, *alpha* and *beta* radiation. Alpha particles are heavy, consisting of two neutrons and two protons. This is the nucleus of a helium atom (atomic number 2) and has a charge of plus two. When an atom looses an alpha particle, it drops down two in atomic number becoming a lighter weight element. Beta decay comes about when a neutron decays within a nucleus giving off a proton and an energetic electron (the beta particle) with a charge of minus one. Thus with beta decay, the atomic number goes up by one.

Following the discovery of the neutron, scientists realized that it might be possible to make heavier weight elements which are not known to naturally occur by firing slow neutrons (spending more time near a nucleus thus enhancing the probability of an interaction) into uranium (the naturally occurring element with the highest atomic number, 92), some of which may then undergo subsequent beta decay. That occurred but what they also discovered accidentally was nuclear fission. In some rare cases, an unstable nucleus is produced which splits or "fissions" into two lighter weight nuclei, energy in the form of heat and gamma (hard X-ray) radiation, and importantly multiple neutrons. This is the source of nuclear power, the mass loss again following Einstein's formula.

All three forms of radiation, alpha, beta, and gamma are dangerous to life processes, which need to be shielded from them. "Exposure" is the term used for when one is in the presence of such radiation. The accumulative effect is called the "dose". "Contamination" is the term used when radioactive material adheres to one's clothing or skin, is inhaled, or ingested, then you become a radioactive source of concern for others while you yourself receive a continuous dose of additional radiation.

Should enough fissionable material be brought together, the excess neutrons given off can go on to spilt further nuclei, etc. potentially in a runaway "chain reaction". Neutron absorbing material introduced into the system can control this at a sustained (constant rate). Under very special circumstances, in the absence of neutron absorbing material, if a "critical mass" of very pure fissionable material is rapidly brought together (a "critical assembly"), you will have a nuclear explosion. This is not possible in a nuclear power plant but of course is the heart of a nuclear bomb.