Spent Nuclear Fuel is not the Problem

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Fig. 1. ***Photograph of a typical light water reactor fuel assembly, prior to insertion in a nuclear reactor (credit: U.S. Nuclear Regulatory Commission).***

Why are terms like "dread," "danger," and "intractable" applied to describe the management of the spent nuclear fuel produced by today's commercial nuclear reactors? The small mass and compact form of this spent fuel are the most positive attributes of nuclear power, when compared to the massive volumes of waste we discharge when fossil fuels are burned.

In 2014, nuclear reactors operating worldwide produced 2410 TWh of electrical power [1], 10.5% of world electricity generation, and equivalent to the combustion of 1 billion tons of coal. For a typical fuel utilization of 45 GWd/ton and plant efficiency of 33%, these reactors produced approximately 6800 tons of spent fuel that year. If collected on a U.S. football field, the fuel assemblies used to fuel all of these reactors for one year would fill a volume 1.3 m high (in contrast, the corresponding height of the billion-ton pile of coal would be 230 km). These nuclear fuel assemblies (Fig. 1) are mechanically robust in storage, because they are designed to survive over four years of exposure to the very severe radiation, thermal, and chemical conditions inside nuclear reactors.

After being removed from reactors and cooled for several months in water-filled pools so shorter lived radionuclides can decay, these spent fuel assemblies provide effective, corrosion-resistant containment of the remaining radioactive byproducts produced by fission reactions. After being transferred from water storage into dry casks (Fig. 2), this spent fuel can be stored safely for decades. Whether or not this spent fuel is recycled, the volume involved is sufficiently small that deep geologic disposal is both practical and affordable.

And the costs for interim storage and for ultimate disposal—ranging from around 0.1 cents per kWhr in the United States to 0.5 cents per kWhr in Sweden—are remarkably small compared to the value of the electricity generated.

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Since the first study of nuclear waste disposal by the U.S. National Academy of Sciences in 1957, strong scientific and technical consensus has emerged that deep geologic disposal, in a variety of different geologic media, can provide safe and effective long-term isolation of hazardous wastes [2]. The worst case consequences of poor safety performance of deep geologic disposal involve the potential for isolated contamination of ground water.

As an example, the regulatory requirement for the U.S. Yucca Mountain repository restricts the maximum annual dose to any individual using ground water (assuming no public health measures to monitor and remediate contamination) to be under 0.15 mSv (15 mrem) for 10 000 years, and under 1.0 mSv (100 mrem) for the remaining one million years. Predicted doses would be much lower, with a mean annual dose of 0.005 mSv (0.5 mrem) [3], a modest fraction of natural annual background exposures that range from 1 to 13 mSv (100 to 1300 mrem) around the world [4].

Understanding of these risks continues to evolve, as it should. The scientific and public understanding of the hazards of bacteria has changed greatly in the last two decades, as the complexity of human microbiomes has become better understood [5]. Similarly, the understanding of the complex role of exposure to radiation at natural background levels continues to change, particularly in understanding the hazards and benefits of medical applications of radiation for imaging and therapy [6].

So how can we place the near and long-term risks of deep geologic disposal of nuclear waste into perspective? There are two important dimensions. First, naturally occurring, permanently hazardous chemicals such as arsenic [7] and the wider variety of hazardous chemicals that humans release directly in the environment or place in shallow land disposal [8] already contaminate vastly larger amounts of groundwater than deep geologic disposal facilities could ever harm in the future. The most important questions for future access to safe groundwater resources are not about isolated contamination by nuclear waste disposal facilities, but instead center on maintaining basic public health measures to test and remediate groundwater to protect against all hazardous substances [9]. Second, the dominant role of nuclear power plants has been to displace the base load use of coal, explaining why the carbon intensity of France's electricity in 2012 was 83 g_{co2}/kWh, compared to 536 g_{co2}/kWh in Germany [10]. Here the context is stark—future isolated contamination of limited quantities of groundwater by geologic disposal facilities for nuclear waste, juxtaposed with the discharge of gigatons of fossil combustion wastes into the biosphere resulting in global and persistent change in the chemistry of the Earth's atmosphere and oceans, creating risks of climate disruption, sea level change, and potential extinction of many marine organisms [11].

Using nuclear energy, instead of fossil fuels, results in large reductions in hazardous particulate air pollution. Quantitative analysis estimates that the substitution of nuclear energy for fossil fuels had already prevented 1.8 million human deaths between 1971 and 2009, along with avoiding 12 gigatons of CO_2 emissions [12]. An additional 351 000 deaths and 13 gigatons of CO_2 emissions were prevented between 2010 and 2014 [13].

Why then is spent nuclear fuel still commonly viewed with fear, when dry-cask storage, transportation, and deep geologic disposal provide high safety under any reasonable, logical standards for comparison with fossil fuels?

More specifically, what are the incentives that cause some technical experts and some public interest organizations to seek to amplify the public's fear of spent fuel and of deep geologic disposal? The Oxford Dictionary defines "fearmongering" as

Fig. 2. ***Dry cask storage for spent nuclear fuel (credit: U.S. Nuclear Regulatory Commission).***

"the action of deliberately arousing public fear or alarm about a particular issue." In the broader context, how should we react to claims about "danger" that have little basis in science or fact, and that could be considered to be fearmongering if made deliberately, but are embedded inside much more complex societal questions?

Experience has proven that the siting, development, and licensing of deep geologic disposal is a slow and difficult process. This is fine in the case of commercial spent fuel—there exists no need to rush because dry cask storage is safe, and strong scientific and technical consensus exists that safe deep geologic disposal is feasible in the longer term. Moreover, it is not known today whether existing commercial spent fuel is a waste or a resource.

Far more urgent is the need to reduce the current rate of consumption of fossil fuels, particularly coal, because the future geoengineering [14] that would be required to remove or remediate fossil emission wastes has little current scientific foundation, and transfers larger risk and cost to future generations [15].

Presume, for the sake of argument, that you believe that the storage, transport, and disposal of spent nuclear fuel can be safe, and that claims to the contrary involve fearmongering. Then why might others "fearmonger," either deliberately or sincerely? If you believe that spent fuel is not the problem, then what is? And how might scaring people about the wrong problem (spent fuel) result in poor decisions and policy?

Four dimensions of nuclear energy involve real problems, and the need for real solutions. First, the earliest applications of nuclear fission were to produce plutonium for nuclear weapons. The chemical processing of these fuels generated large volumes of waste, including sludge and salt stored in underground tanks, which have created major challenges. U.S. policy has assumed that these materials will be put into a repository that requires conversion into glass waste forms. But disposal of this tank waste in deeply bedded salt (as at the U.S. Waste Isolation Pilot Plant) would avoid the need to perform vitrification in glass, because the waste acceptance criteria for salt repositories have no limitations on waste-form leachability. In contrast to commercial spent fuel, for defense high level waste the early selection and development of geologic disposal is important, and the selection of salt for defense waste disposal could greatly reduce disposal costs.

Second, nuclear fuel is substantially more hazardous when it is in an operating power reactor and when it is being handled during refueling, than it is after being cooled and placed into dry casks for interim storage. The engineering of reactors for safety is far more complex than the engineering of dry storage casks, because operating power reactors contain very large inventories of short-lived fission products. Under reactor accident conditions, heat from these fission products can damage fuel, and in water cooled reactors hazardous cesium-137 and iodine-131 can mobilize as fine aerosol particles.

While the major reactor accidents that have occurred to date have had small public health consequences compared to fossil energy [12], long-term off-site ground contamination by cesium-137 has proven highly disruptive to societies. Passive safety and evolution toward non-water-cooled reactor options are appropriate directions for future evolution of reactor technology. Passive safety also greatly reduces the complexity and cost of physical and cyber security for reactors.

Third, some technologies used in civil nuclear energy systems overlap those used in the production of materials for nuclear weapons. A major benefit of civil nuclear energy has been the wide ratification of the Nuclear Nonproliferation Treaty, enabling the United Nations to establish an agency and system to monitor the activities of almost all nations to verify peaceful use of nuclear technologies. Access to civil nuclear energy remains a key carrot in efforts to strengthen this monitoring, particularly to strengthen measures to detect clandestine production facilities, as evidenced in the most recent international agreement with Iran.

Fourth, historically some civilian power reactors have used highly enriched uranium (HEU) or separated plutonium as fuels. Going forward, there exists no economic logic to continue the use of either HEU or separated plutonium in commodity nuclear energy production. Because these materials can be used directly in nuclear explosives, they require highly effective and expensive physical protection to prevent potential theft. HEU is completely unnecessary for commercial nuclear energy production, and no current or planned commercial power reactors use it.

The logic for using separated plutonium is determined by fuel technology, where some fuels (including water-cooled reactors) require complex equipment to fabricate, for example, to grind oxide pellets to precise diameters. Complex equipment requires direct-contact maintenance, so must be placed in glove boxes. This in turn creates a requirement that the recycled plutonium has very high decontamination, which increases the complexity and cost of chemical separations (and of physical security). Significant differences exist for advanced reactor fuels that use simple fabrication processes, such as metal and molten salt fuels. For these fuels fabrication can occur using remote handling inside hot cells, with minimal chemical processing of recycled spent fuel. The question of whether such advanced reactors might be commercialized in the future is also the question of whether existing spent fuel is a resource or a waste.

Nuclear energy is distinguished from fossil energy by the remarkably small volume of spent fuel that nuclear energy generates, by the availability of practical technology to store and transport this spent fuel, and by the practicality to use deep geologic disposal to provide safe, long-term isolation. For the young generation today who must do most of the work to fix our energy infrastructure, it can be eye opening to work through the comparisons needed to place different risks into context. In doing this, they can rapidly find that analysts who describe spent fuel and the deep geologic disposal of radioactive waste as being "dangerous" never make comparisons to risks posed by permanently hazardous chemicals. Placing risk into context is the first step in figuring out what the real problems are, and then getting to work to solve these problems and save the planet.

APPENDIX

Calculations for CO_2 emissions from French and German Electricity in 2012

Electricity Output (TWh) (pg. 90) [11]:
Germany: 623.2
France: 555.3

CO_2 Emissions, Electricity Sector (million tons) (pg. 54) [11]:
Germany: 334.4
France: 46.3

Ratio:
Germany: (334.4x1012 g)/(632.2x109 kWh) = 536 g/kWh
France: (46.3x1012 g)/(555.3x109 kWh) = 83 g/kWh

Volume of spent fuel produced worldwide in 2014

PWR dry cask diameter (m): 1.73
PWR dry cask height (m): 4.32
PWR dry cask volume (m3): (4.32)Ⓟ(1.73)2/4 = 10.12
Number of PWR assemblies in cask: 24
Mass of uranium in one PWR assembly (t): 0.423
Specific volume of spent fuel (t/m^3): (0.423)(24)/(10.12) = 1.00
Total mass of spent fuel (t): 6800
Football field dimensions (ft x ft): 360 x 160
Football field dimensions (m x m): 109.7 x 48.8
Football field area (m^2): 5351
Depth of spent fuel on a football field (m): (6800)/(1.00)(5351) = 1.27
Density of uranium fuel (t/m3): 10.95
Depth of uranium fuel on a football field (m): (10.95)/(1.00)(5351) = 0.12
Coal density (t/m^3): 0.8
Coal mass (t): 109
Depth of coal on a football field (m): (109)/(0.8)(5351) = 233601m = 233 km

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