Don't Reprocess Spent Fuel from Light-Water Reactors

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Abstract

Although reprocessing and recycle is strictly necessary for breeder reactors, and for the "thorium fuel cycle," it adds to cost and hazard and it wastes potentially valuable plutonium if the separation is done before there is an active and growing population of breeder reactors. The better approach is to store used LWR fuel elements in dry-cask storage for as long as 100-150 years, for eventual disposition in mined geological repositories, unless breeder reactors are developed that are as safe and are more economical than LWRs. In the meantime, there is plenty of uranium to be mined and enriched in support of an expanded population of light-water reactors.

Introduction

Nuclear power is a technically proven approach to the concentrated generation of electrical power and has negligible emission of greenhouse gases. Although it is not the lowest cost option in many areas, its financial cost is affordable to most societies.

Nuclear power has a major problem in that the consequences of an accident in an operating nuclear reactor, in spent fuel “pools,” or in a reprocessing plant for nuclear fuel can be devastating in terms of loss of land for dwelling, commerce, and agriculture, although the expected deaths and illness from even the most severe reactor accident are small compared with the environmental consequences and even accidental deaths from other energy sources. Most of the world’s nuclear power comes from light-water reactors (LWR)—either of the boiling water reactor (BWR) or pressurized water reactor (PWR) variety. In both, the reactor operates at very high pressure because water is the heat transfer fluid from the ceramic fuel that is heated by fission in the nuclear chain reaction, and water is used to transfer the energy to a steam turbine coupled to an alternator. The steam from the turbine is condensed to water and pumped back into the reactor or into the steam generator/heat exchanger in a closed cycle. Electrical power is transmitted via a generator step-up transformer onto the grid at very high voltage, and the waste heat (about two-thirds of the fission energy) is communicated via the steam condenser to a neighboring body of water, or to the atmosphere.

A typical reactor producing 1000 megawatts of electrical power (1000 MWe or 1 GWe) fissions about 1000 kg of uranium or plutonium per year. For the LWR, the uranium is supplied as~5% U-235 so that about 20 tons of low enriched uranium (LEU) in the form of UO_2 ceramic pellets containing about one ton (metric ton) of U-235. The fuel remains in the reactor and average of four years, with about one-third of the reactor core replaced every 18 months with fresh fuel. The “spent fuel” is removed and placed immediately in a deep pool (“swimming pool”) next to the reactor or even within the same building.

The origin of reprocessing.

With the recognition of fission in December 1938 and the arrival of Fermi and his family in New York January 2, 1940, Fermi and Leo Szilard, and others, began to work on fission and on nuclear reactors, driven by Szilard’s vision of nuclear weapons employing the fission of U-235. In May, 1940, Szilard received a letter from Louis A. Turner of Princeton University proposing that the capture of neutrons in the reactor in U-238 would produce an isotope, Pu-239, after two beta decays, that would be as fissile as U-235. This led Szilard immediately to conjecture that uranium could support a “breeder” reactor, in which one of the several neutrons from each fission would go on to provide another fission in that reactor, while another neutron would be captured in the abundant U-238 to form, ultimately, Pu-239. It turns out that this is feasible only for fast neutrons with the U/Pu breeding cycle. Clearly, a breeder is key to utilization of U-238, non-fissile with thermal neutrons, and at the beginning of the nuclear age this was regarded as important, in view of the presumed scarcity of uranium resources. The idea of the breeder, and of reprocessing irradiated fuel in order to remove fission products, to refabricate properly structured fuel, and to allow the addition of more natural uranium, has a fundamental appeal to engineers and physicists. Such breeders have been built in several countries, with no commercial success. They are operating now in Russia, as the BN-600, which has spent most of its life fueled with enriched uranium, rather than Pu fuel. Russia's BN-800 has gone into operation along with the BN-600. The BN-800 has a mostly MOX core[1].

[1] IBFM blog, at http://fissilematerials.org/blog/2015/12/russian_bn-800_fast_breed.html

France, with its centrally directed civil nuclear power program, as well as an active military nuclear weapons program, early-on designed breeder reactors and even scaled them into the commercial range with Superphénix, which was a technical and commercial failure and is now in the course of being dismantled. Although a breeder reactor might be built with fuel that would be used once and not reprocessed, that puts great stress on the physical integrity of the fuel form, and it is only natural to want to reprocess, in order to save and reuse the concentrated energy still in the uranium and transuranics of the spent fuel. With the failure of the commercial breeder venture, France decided to recycle Pu into its PWR fleet, replacing as much as one-third of the uranium oxide ("UOX") core with mixed-oxide ("MOX") fuel. France has done an excellent technical job on reprocessing and fuel fabrication, but at increased cost over what would have been the case without all of the attendant costs and hazards of reprocessing and MOX fabrication.

Reprocessing and recycle in France.

All LWR UOX fuel from French reactors (but not irradiated MOX fuel) is reprocessed at the AREVA NC plant at La Hague, Normandy, and the separated Pu shipped by truck to Marcoule in the South of France for fabrication into MOX. Although external radioactivity from fresh MOX fuel is low, because of the excellence of the separation of fission products, Pu-239, with its half-life of 24,000 years, is 30,000 times more radioactive than U-235 and is a potent hazard for inhalation or ingestion. However, the cost of reprocessing dominates the very high cost of the Pu fuel cycle. Those who conduct and support recycle in LWRs make the argument, increasingly unsustainable, that reprocessing and recycle reduces the volume of waste that needs to go to the mined geologic repository ("MGR") and thus reduces the cost of permanent disposal. I have long published papers showing that this is not true, because the repository loading is limited not by volume of the fuel elements to be disposed of, but by the heat generation from radioactivity in the spent fuel, and this decay heat over the decades, centuries, and millennia, is dominated by the "transuranics"—plutonium and curium, among them.

Thus, a 2011 MIT Study, "The Future of the Nuclear Fuel Cycle[2]," notes (p. 80), *"1 kgHM of spent MOX fuel has a larger repository requirement (1/0.15 or 6.7 greater) than 1 kgHM of spent UO2 fuel."* This results from its increased content of higher transuranics—not a larger amount of heat-producing fission products.

[2] "MIT Study on the Future of the Nuclear Fuel Cycle," at https://energy.mit.edu/wp-content/uploads/2011/04/MITEI-The-Future-of-the-Nuclear-Fuel-Cycle.pdf

Since 5 kgHM (kilograms of heavy metal—that is, of uranium atoms) of spent UOX fuel are used to produce 1 kgHM (kg of atoms of uranium, plutonium, or other transuranics) of fresh MOX fuel, there is no saving in repository space, but very substantial additional cost and risk in the use of MOX fuel in LWRs.

The proper role of the breeder reactor.

Indeed, for those who hope, work, and expect ultimately that civil nuclear energy will use breeder reactors, and thus be able to consume economically high-cost terrestrial uranium, the consumption of LWR-produced Pu in LWRs is a tax on the future.

On the other hand, responding to those who think it might be desirable in the future to rapidly deploy a fleet of breeders,[3] the

[3] "The Role of the Breeder Reactor," a chapter for the book, Nuclear Energy and Nuclear Weapon Proliferation, ed. F. Barnaby, et al., pp. 141-153. Publisher: Taylor and Francis, Ltd., London 1979, at http://fas.org/rlg/sipri-rbr.pdf

only option for rapid growth of a breeder population is to invest such reactors with an initial core of enriched uranium—most suitably, < 19.9% U-235, because the world will not have forgotten how to separate uranium isotopes, and enrichment capability is widespread. The gas centrifuge is a highly evolved tool for separation, and its technology is perfectly adequate to provide fuel for breeders, and is a very difficult economic standard to surpass.

Depending on the fuel form—metal or ceramic; oxide, carbide, or nitride—different approaches to reprocessing of breeder fuel can be taken, especially if the choice is made, as it should be, to use automatic means for fabricating MOX fuel, rather than to push separation to such an extreme that human workers with glove boxes can be used for the fuel fabrication process. For this reason, I have long advocated a world breeder reactor laboratory or its virtual equivalent, in an April 2009 presentation[4] long posted on the Garwin Archive,

"Tremendously important, though, is informed analysis, as contrasted with R&D. That is, buyers and users need to model and to simulate their possible options. Some oppose the use of nuclear power because of its potential for the proliferation of nuclear weapons to additional states or to terrorist organizations. Others oppose it because of the potential for large-scale accidents or its vulnerability to terrorist attack. The nuclear power sector, however, is not homogeneous. Reactors themselves, if they operate with leased fuel so that there is no need for enrichment and no need for disposal of spent fuel locally, do not contribute to nuclear proliferation. For years I have urged changing laws and custom to permit disposal of spent nuclear fuel outside the borders of the

[4] "R&D OPPORTUNITIES AND NEEDS FOR THE ECONOMIC TRANSITION" by Richard L. Garwin, Apr 30, 2009, at https://fas.org/rlg/042209%20R&D_Opportunites_and_Needs2.pdf

country in which it was generated, and the licensing and supervision by the International Atomic Energy Agency—IAEA—of competitive, commercial, mined geologic repositories. These would accept, for a fee, spent fuel in IAEA-approved disposal casks or reprocessed spent fuel in similarly approved overpacks.

"I also recommend the equivalent of a world breeder reactor laboratory, with the purpose of working on three quite specific choices of breeder reactor, including their fuel form and fuel cycle. This laboratory would develop and use an advanced and evolving state-of-the-art suite of computer simulations tools, with the purpose of providing reliable simulation and modeling of the performance of each of the reactor types. If, after 10 or 20 years, the effort yielded a proposed system that was demonstrated in credible simulation to be as safe as existing light-water reactors and economically competitive with them, then a prototype could be built to verify the simulations. I believe that this is the way to make

progress most rapidly in this important sector, but it is, obviously, only one of the approaches that we could have been following all these years, and it won't help at all for 20 years or more."

Current studies and fact finding regarding reprocessing in China.

Three recent studies are available that bear directly upon the future of reprocessing in China. The 2011 MIT Study, "The Future of the Nuclear Fuel Cycle" from which I have already quoted the lack of benefit in repository space, recommends,

> *"Integrated system studies and experiments on innovative reactor and fuel cycle options should be undertaken in the next several years to determine the viable technical options, define timelines of when decisions need to be made, and select a limited set of options as the basis for the path forward."*

The 2015 Report of the International Panel on Fissile Material,[5] indicates the great cost associated with reprocessing and recycle, especially by reference to the AREVA-built Rokkasho reprocessing plant in Japan. AREVA is reported (p. 23) to have proposed to the CNNC (China National Nuclear Corporation) the construction of a plant to reprocess 800,000 kgHM per year of irradiated LWR fuel, for an investment cost of € 20 billion.

And most applicable and most recent, "The Cost of Reprocessing in China,"[6] directly addresses the advisability of reprocessing in China. That report on p. 2 compares the cost of reprocessing with that of dry-cask storage of LWR fuel and finds the investment required for reprocessing much greater than for the widely practiced dry-cask storage,

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[5] "Plutonium Separation in Nuclear Power Programs. Status, Problems, and Prospects of Civilian Reprocessing Around the World," Report of the International Panel on Fissile Material, July 2015, at http://fissilematerials.org/publications/2015/07/plutonium_separation_in_nuclea.html

[6] "The Cost of Reprocessing in China," by Matthew Bunn, Hui Zhang, and LI Kang. Cambridge, Mass.: Project on Managing the Atom, Report, Belfer Center for Science and International Affairs, Harvard Kennedy School, January 2016, at http://belfercenter.ksg.harvard.edu/files/The%20Cost%20of%20Reprocessing-Digital-PDF.pdf

Table ES.1: **High and Low Estimates of Reprocessing Capital and Operating Costs**

Plant	Capital cost	Operating cost	40-year cost (no financing)	40-year dry storage cost
200 tHM/yr, Low	$3.20 B	$0.19 B	$10.80 B	$1.60 B
200 tHM/yr, High	$5.70 B	$0.34 B	$19.30 B	$1.60 B
800 tHM/yr, Low	$8.00 B	$0.48 B	$27.20 B	$6.40 B
800 tHM/yr High	$20.00 B	$1.50 B	$80.00 B	$6.40 B

On p.67 the 2016 Harvard Study approvingly cites the 2011 MIT Nuclear Fuel Cycle Study,

> *"The use of enriched uranium to start fast reactors with near unity conversion ratio provides a scheme to divorce the speed with which fast reactors can be deployed from the availability of TRU [transuranics] to fuel their initial cores. This facilitates a faster penetration of the nuclear energy system by fast reactors.*

The lower conversion ratio compared with breeders may also permit a greater range of FR technologies. In addition, such a route to fast reactors avoids the building of a large thermal fuel recycling capacity, which is the costly part of nuclear fuel recycling infrastructure.”

In addition to my 1979 paper, I gave a presentation in 2012,[7] which called specifically, as do the 2011 MIT fuel cycle Study and the 2016 Harvard Kennedy School Study, for a commitment to put LWR spent fuel into dry cask storage, thus relieving the cost and hazard of water-filled pool storage for spent fuel. This approach is well worked out, practiced the world over, affordable and much safer than pool-type storage. Moreover, the results of the group at the Argonne National Laboratory, quoted in my 2006 reports on

[7] "Reprocessing and Global (Energy) Security," by R.L. Garwin. Presentation in Panel II Session, Reprocessing and Global Security, Teaching the Nuclear Fuel Cycle, The Elliott School of International Affairs, George Washington University, Washington, DC, April 6, 2012, at http://fas.org/rlg/GWU%20_04_06_2012.pdf

GNEP (the still-born Global Nuclear Energy Partnership advocated by U.S. Department of Energy staff) and in this 2007 presentation[8]

[8] "GNEP: Leap before looking," by R.L. Garwin. Presented at session NUCL 61, American Chemical Society annual meeting, Chicago, Illinois, March 27,2007, at http://fas.org/rlg/GNEP_ACS_2Hf.pdf

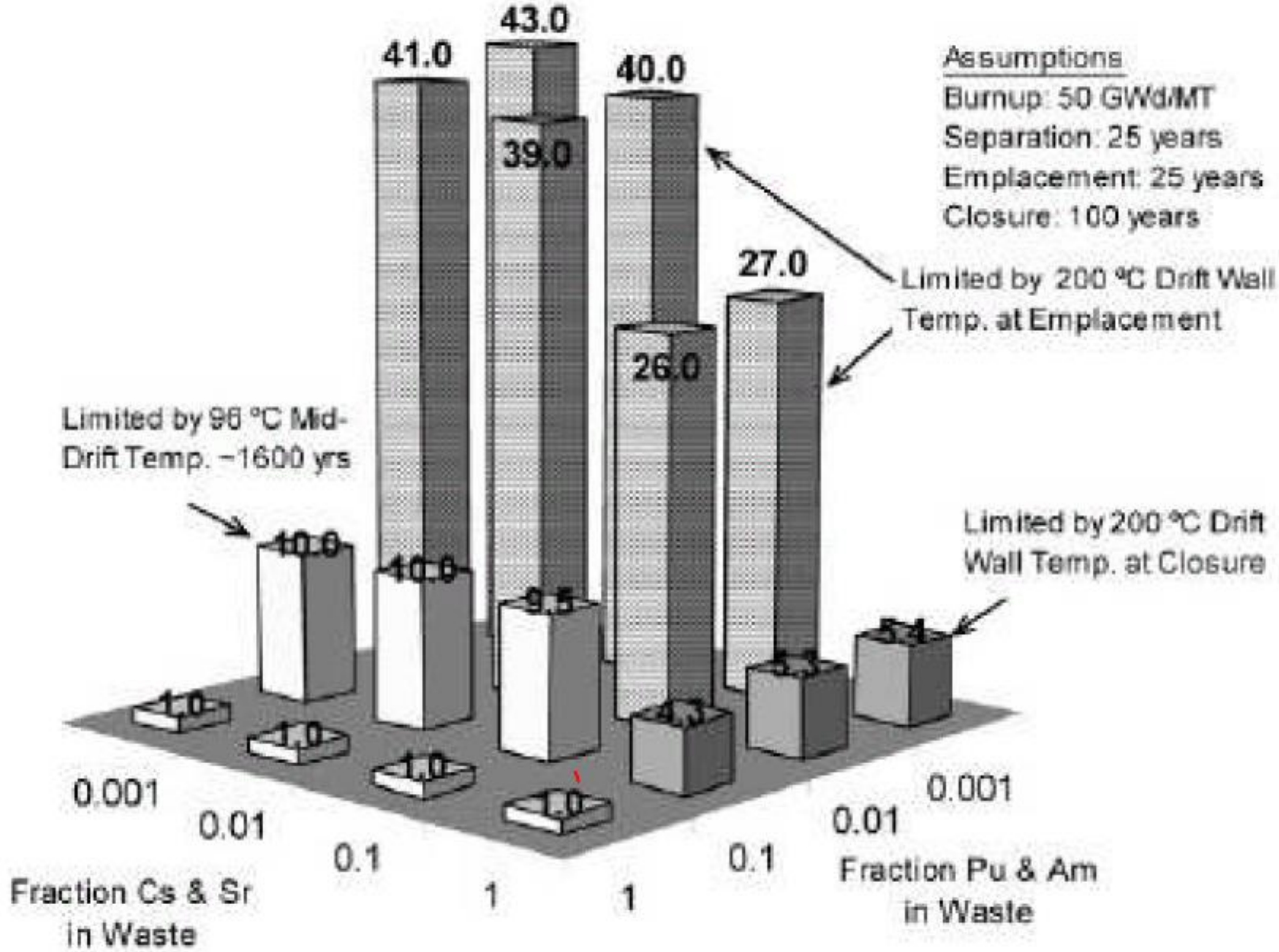

Fig. 7. Potential repository drift loading increase as a function of separation efficiency for plutonium, americium, cesium, and strontium.

assume that the Cs and Sr chemically removed from the repository-bound waste is safely stored elsewhere—for instance in dry-cask storage[9]. But why not do the obvious, and store the fuel elements themselves in dry-casks designed ultimately for emplacement in the repository?

Hazards to society and the nuclear power industry from reprocessing

As practiced in the United Kingdom, with the ill-fated THORP plant at Sellafield, reprocessing was (and is) a serious hazard from natural and routine accidents and events, and an enormously dangerous target for terrorists, as evidenced in my testimony of 2006 to the Irish Academy of Sciences, referenced in my 2010 presentation in China[10],

> *"There are fewer reprocessing plants than nuclear power reactors, but the plant may hold in much more accessible form*

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[9] Fig.7 is taken from "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," by R.A. Wigeland, T.H. Bauer, T.H. Fanning, and E.E. Morris, Nuclear Technology, vol. 154, pp. 95-106, (April 2006).

[10] "Nuclear Terrorism: A Global Threat," by Richard L. Garwin, as presented at the Harvard-Tsinghua Workshop on Nuclear Policies, Beijing, March 14, 2010, at http://fas.org/rlg/3_14_2010%20Nuclear%20Terrorism_A%20Global%20Threat_p2.pdf

the intense radioactivity not only for many decades of reactor operation but from multiple reactors. Thus the Sellafield plant in England reprocessed for more than 20 years fuel from Japan and Germany, in large part. Much of the fission products from most of those reactor-years of operation is present in the HAST-- highly active storage tanks. These are aboveground, spherical steel tanks, equipped with triply redundant cooling coils within the liquid itself. I have spoken of the vulnerability of these tanks[11]*. In brief, in 2002, 21 spherical tanks at Sellafield held a total of 1550 m^3 of Highly Active Liquor, with each m^3 of liquid containing 1.6 kg of Cs- 137. The 1986 Chernobyl accident liberated 26 kg of Cs-137 and gave an overall population exposure of some 600,000 person-Sv, corresponding to about 30,000 deaths from cancer. From a single B215 150-m^3 tank, 50% of the Cs-137 would be 120 kg—four times Chernobyl, or*

[11] In my presentation, "Major Accident or Terrorism Risks From Sellafield," to the 2002 conference of the Royal Irish Academy, "Making Sense of Sellafield."

120,000 cancer deaths according to the linear hypothesis (see "Megawatts & Megatons…" (2001), Ch. 4)."

Similarly, even the smallest (Pool D) of the reactor-fuel storage pools at La Hague can contain 3,500 tons of spent fuel; successful radiological attack that released half the Cs-137 capacity of this pool is assessed[12] to have an impact up to 67 times that of the release at Chernobyl.

Summary

Reprocessing of spent fuel is likely to be desirable and economical for the fast-neutron reactors of Conversion Ratio about 1.0 that might ultimately be deployed to supply a substantial fraction of the world's energy needs. R&D should be done in the context of integrated and detailed simulation of reactor concepts, their

[12] "Radiological Terrorism: Sabotage of Spent Fuel Pools" by Hui Zhang, December 2003, at http://belfercenter.hks.harvard.edu/publication/364/radiological_terrorism.html

associated fuel forms, and appropriate reprocessing. A world nuclear breeder reactor laboratory (or its virtual analog) should explore such possibilities with advanced computer simulation techniques. When such simulations of normal operation and all imaginable accidents show a breeder/fuel/reprocessing combination that is cheaper and safer than existing reactors, a prototype breeder should be built and operated to test the adequacy and accuracy of the simulation. There are many technical difficulties to be overcome, and success is not assured.

Reprocessing and recycle in light-water reactors is hazardous to the economics and safety of the public and of the nuclear industry.

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