

A New Generation Nuclear Fission?

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I have been asked to give a presentation on the prospects for nuclear fission probably because I wrote with four other authors a paper titled “A Nuclear Solution to Climate Change?” in May 2000 in *Science*.¹ The question mark on that paper title and on this one is related to the public opinion about nuclear energy. Bob Krakowski spoke on nuclear fission the last time this meeting was held and one of his overall conclusions was that the growth of nuclear power will be governed by public opinion.² If what he said is true, then I am probably one of the least qualified people in the world to speak on the subject, because as a nuclear engineer, I am basically not qualified to speak on public opinion questions. I was on sabbatical at Stanford from Los Alamos the year that the *Science* paper was written, and I also wrote two more papers tying nuclear power, climate change and nuclear non-proliferation concerns together.^{3,4}

Because I am not an expert on all the areas covered in this talk, I have obtained help from several people, including, Erich Schneider and Jim Tape of Los Alamos, Matt Bunn of Harvard, David Wade of Argonne, Steve Fetter of the University of Maryland, Dave Bodansky of the University of Washington and Chaim Braun of Stanford.

Nuclear Power Overview

Nuclear power is different from the other technologies discussed at this conference – it is old. Some important events in the history of nuclear power include Eisenhower’s speech to the UN General Assembly in 1953 titled “Atoms for Peace,” for which he received a standing ovation. In 1957 the International Atomic Energy Agency was founded, as a result of Eisenhower’s speech.

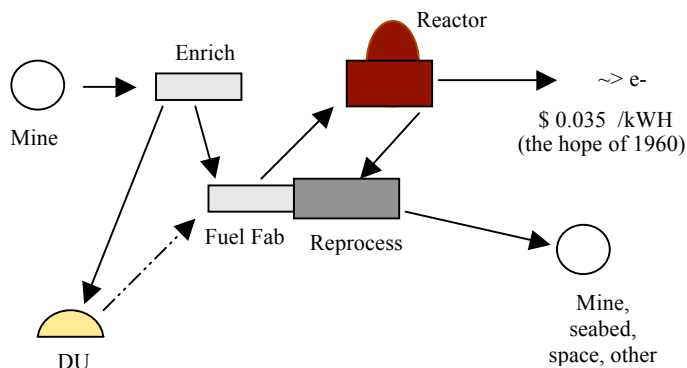


Figure 1. The “complete” nuclear fuel cycle as envisioned in 1960. The cost goal was one cent per kilowatt-hour (translates to 3.5 cents today). Reprocessing and/or plutonium breeding was assumed.

Shown in Figure 1 is a “complete” nuclear fuel cycle of 1960. By this time many different reactors and fuels had been researched and tested. These include light water reactors, heavy water reactors, graphite reactors, molten salt reactors and liquid metal cooled fast reactors. The fuel was first fed into the reactor and then the discharge fuel was to be reprocessed and recycled into new fuel. The purpose of this is to build up the concentration of plutonium in the fuel, because the neutron-balance properties of plutonium are better than uranium, so that eventually the reactor could be replaced with something like a fast breeder reactor. It was assumed that uranium was scarce and that reprocessing costs would be very low. Also, stockpiling plutonium would alleviate the need for enrichment. The hope of that era was a penny per kilowatt-hour, which I have shown in the figure as 3.5 cents after correcting for inflation.

The reprocessing option in the US was discarded because of greatly escalating costs and concerns about proliferation. France, England and Russia continued with reprocessing and plutonium stockpiling, ignoring cost overruns and lack of escalation in uranium prices. England now has 50 tons of plutonium and no reactors that burn plutonium. Japan is currently completing a huge reprocessing facility at Rokashomura that will be the most expensive facility to build and operate yet. I like the American system the best, because we were able to get rid of an unnecessary part of the fuel cycle and not hang on to it for bureaucratic reasons.

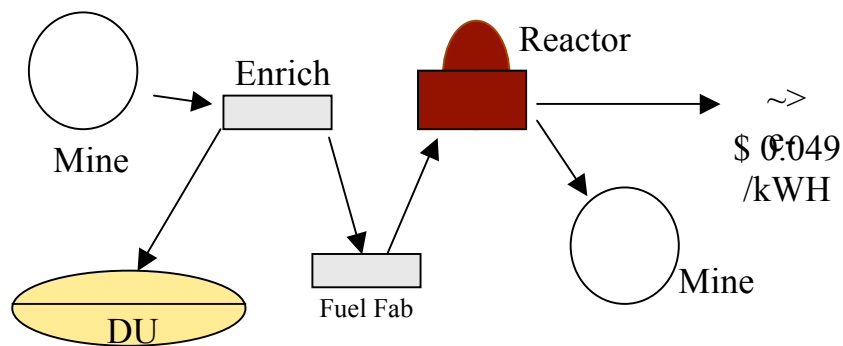


Figure 2. The current US “once-through” fuel cycle without spent fuel reprocessing. Cost estimate for electricity for new plants constructed today, from IAEA.

Figure 2 shows 4.9 cents per kilowatt-hour for the cost of electricity for a once-through fuel cycle, new advanced LWR, 36 month construction time 11% return on capital (after taxes). Operations and maintenance costs are taken as 0.5 cents per kw-hr (experience is higher than this), and fuel costs 0.8 cents per kw-hr. Computed carbon abatement costs are \$50 per ton versus coal. These numbers are off the IAEA web page and I hope that they are somewhat familiar to you.⁵ I have very little to add to this except that we should be building these plants now.

Fuel Cycle

Because the organizers of this conference asked me to speak about fast reactors, and they indicated that the talk should be “researchy” I have included a somewhat lengthy discussion here.

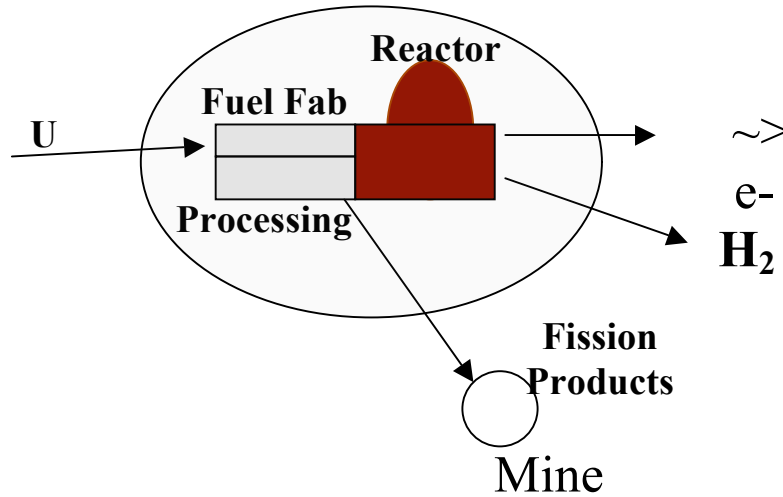


Figure 3. The Ultimate Fast Reactor fuel cycle. The feed is uranium and the outputs are fission products, electricity and possibly hydrogen. No mining is required because there is already enough uranium above ground. The reactor and fuel facilities are integrated with one another.

Shown in Figure 3 is a fuel cycle and reactor system that comes closer to Herman Daly-type sustainability – I have called it the “Ultimate Fast Reactor Fuel Cycle.” A small amount of uranium enters the system, and electricity and possibly hydrogen leave the system. No mining is required because we have enough uranium above ground for a very long time. Fission products (only) go to the waste stream. The system itself contains the reactor, fuel fabrication facility and fuel reprocessing facility. It is completely self-contained and possibly has a tall barbed-wire fence around it. In the case of the fast reactor, criticality can be maintained because there is a steady-state inventory of plutonium inside the plant that provides the “seed” for the uranium to continually burn. Such systems, which are not economical now, are much of what the DOE “Generation IV” initiative is about.⁶ There are six different candidate systems that would take the place of the unit shown in the grey area in the figure. In my talk I shall mostly cover just the fast reactor (FR) concept.⁷ In promoting the FR, and other fuel cycles that use reprocessing, two points are usually mentioned. The first is the alleged short supply of uranium and the second is the short supply of nuclear waste repository space.

Uranium Availability

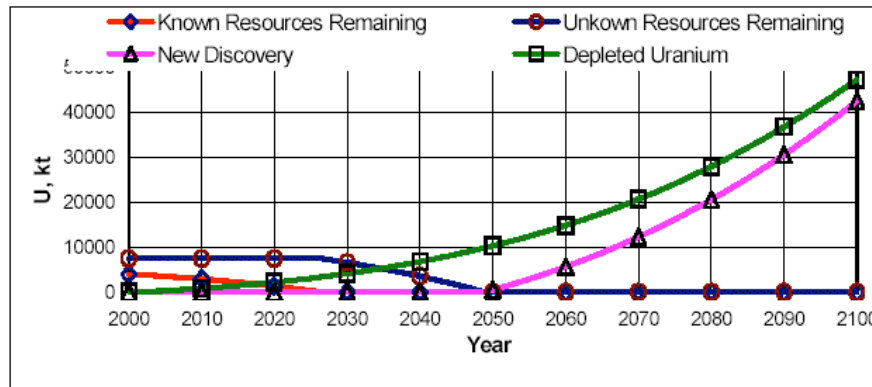


Figure 4. Uranium resource usage under a high-growth nuclear scenario using the once-through fuel cycle (from David Wade, Argonne National Lab)

Shown in Figure 4 is a reactor deployment scenario for LWR's using a once-thru fuel cycle. This graph is taken from Dave Wade of the DOE's Generation IV Fuel Cycle Crosscut Group. The world growth rate of demand for nuclear electricity production was taken from Case B of the World Energy Council/International Institute of Systems Analysis study published in 1998. In that case the nuclear deployment grew from 350 GWe in year 2000 to 2000 GWe in year 2050 to 6000 GWe in year 2100. The known uranium reserves remaining in the world is shown in orange, starting at 2.1 million tons and going down from there. Speculative reserves are shown in blue, starting at about 10 million tons and falling to zero at year 2050. The line in pink is the amount of new uranium discoveries that must be made.

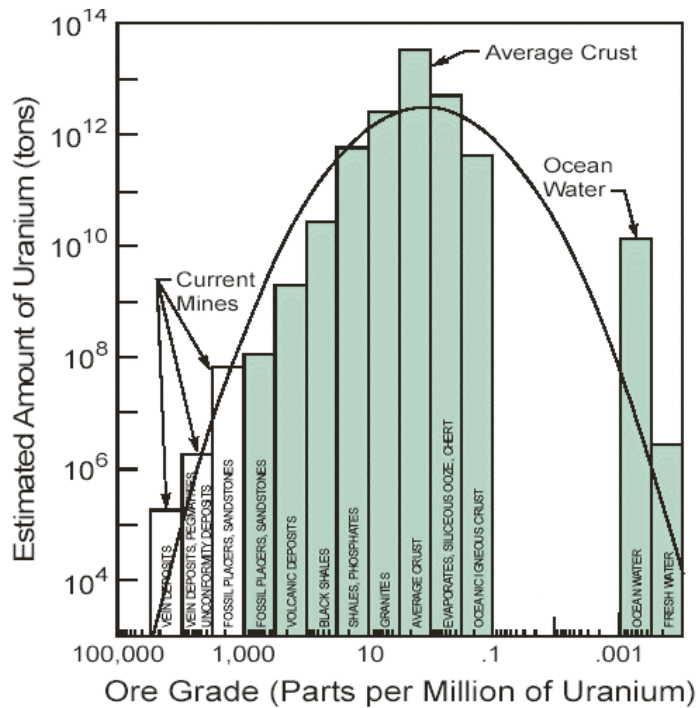


Figure 5. Theoretical abundance of uranium on earth. As we use more uranium, our sources would tend to go from the left to the right on the abscissa. Sources at 200,000 are still being cataloged.

Let's look at the uranium resource argument. This graph, Figure 5, taken from an older (1980) issue of Scientific American,⁸ breaks down the uranium abundance into amounts that are theoretically available versus ore grade and type. Currently, uranium is mined in veins, fossil placers and sandstones. Lower grades of ores could be used with practically no limit, as we would climb up the curve until reaching the average crustal abundance of uranium. The area under this curve is over 10^{13} tons. In a sense, you could look at this as something like a Fourier transform of the Hubbert curve, which is used for oil. We are nowhere near the peak and probably never will be. In fact, in Canada, mining of ores of 200,000 ppm, that are off the scale to the left is taking place now in veins found since this graph was made.

The fact that there has been virtually no exploration for uranium in years reflects the low demand because of few new nuclear plant orders. New nuclear plant orders would start exploration again, revising the Red Book numbers upwards.

Table 1. Uranium resource extrapolation according to $R/R_0 = (p/p_0)^x$, where p is the price in \$/kg for uranium, R_0 is the “Red Book” number at $p_0 = \$40/\text{kgU}$.

Organization	Exponent x	R @ \$130/kgU	R @ \$260/kgU
DOE Gen IV FCCCG	2.35	30 M tons	200 M tons
Princeton, 1978	2.74	50 M tons	400 M tons
U Information Center	3.32	100 M tons	1000 M tons

The expansion of resources with increase in price is called the “long term elasticity of supply” by economists and is commonly a power law. In Table 1 we use the Red Book reserve number at \$40/kg of 2.1 million tons as a calibration point. Matt Bunn has found three locations in the literature from which the exponent could be determined. One of them is Dave Wade’s Generation IV Fuel Cycle Crosscut Group, who obtained an exponent of 2.35. Other groups, including the Australian uranium industry’s trade group, have obtained higher exponents. I believe that at a price of \$260/kg there may be as much as a billion tons of uranium available.

Would U prices actually go up or down? Looking at 200 years of copper prices, for instance, it appears that the answer is down. Productivity increases in the mining industry have outpaced copper resource depletion. There are spikes in the price, which cause increased exploration, but the general trend is down. In fact, this is a general trend in all mineral commodity prices, downwards, when corrected for inflation.⁹

Waste Disposal

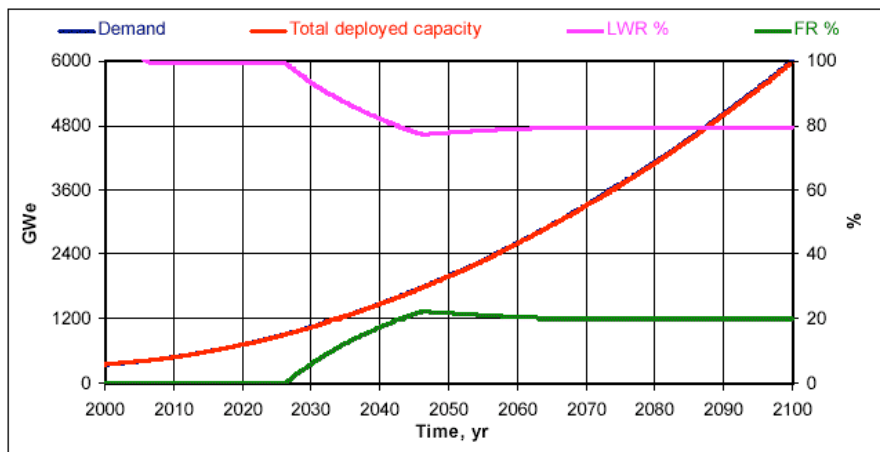


Figure 6. Growth scenario with Light Water Reactors (LWR’s) combined with Fast Reactors (FR’s).

Another argument in favor of reprocessing and fast reactor deployment is the possibility of “burning up” or transmuting some of the most toxic species headed for a repository. Figure 6 shows the nuclear power contribution under the same growth scenario, but with fast reactors becoming ultimately 20% of the nuclear capacity. The orange line shows the growth in nuclear power total capacity, the pink line the fraction associated with light water reactors and the green line the fraction with fast reactors, which comes up from zero starting at about 2025, rising to 20% by 2050. Under this scenario, the total amount of spent fuel above ground in storage (shown in dark orange, Figure 7) rises to a maximum of about 250,000 tons in 2010 but goes down from there as the fuel is reprocessed to make new fuel for the fast reactor fleet. It is noted that the legislated capacity of the Yucca Mountain repository is only 70,000 tons. In this

scenario, under perfect process conditions, the only wastes to be disposed of are fission products and fuel cladding and structural materials.

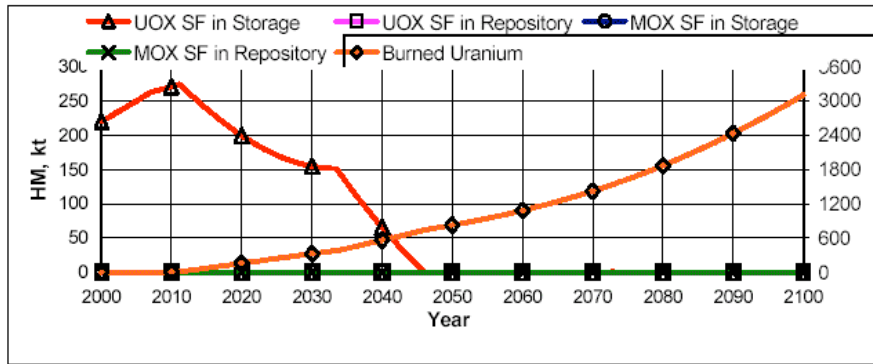


Figure 7. The growth and decline of the amount of spent nuclear fuel under the same FR deployment scenario is shown in the dark orange curve. Reprocessing and FR deployment decreases need for spent fuel storage and limits the maximum amount above ground.

Under these circumstances, the Yucca Mt repository may have a much easier job to do. Since there is no neptunium, plutonium, americium or curium (collectively called TRU, or transuranic species) the performance of the repository in the time frame between 100,000 and 1,000,000 years is better defined.¹⁰ Additionally, the species ¹²⁹I, ¹⁴C and ⁹⁹Tc can be made into special waste forms, such as alloys, that will render them insoluble in water. These species, especially the ⁹⁹Tc are important contributors to the projected releases from the repository in the 1000 to 100,000 year time frame. The only other species that would go to the repository would be species such as ⁵⁹Ni, ⁹³Zr and some other species that are not soluble in water. Because of the lower heat load and these other advantages, it is possible that the repository could hold the waste output from ten times as many GW-years of operation as is currently planned.

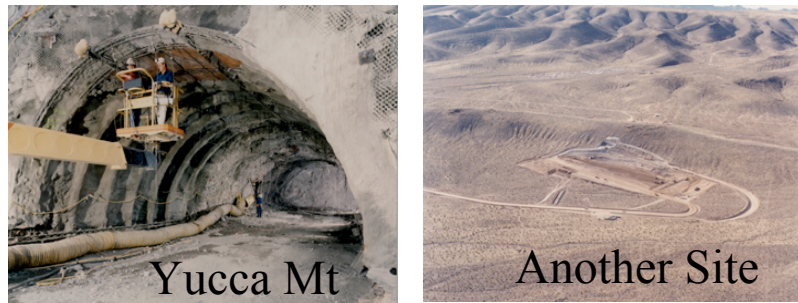


Figure 8. If reprocessing is used to reduce the burden on the Yucca Mountain repository (left), another site would be required (right) to hold the millions of curies of very radioactive species ¹³⁷Cs and ⁹⁰Sr that would be removed from the Yucca Mountain waste stream.

Another storage facility would have to be built for the extremely radioactive and hot species ¹³⁷Cs and ⁹⁰Sr. See Figure 8. It is hard to overstate how radioactive the interior of this storage facility would be if it were to store the output from thousands of power reactors. It can only be imagined that it would be built at some remote location and it would be a few hundred feet below ground. If human entry was required as part of the design, then the shielding around the sources would consist of thousands of tons of heavy material. However, it is to be

remembered that this facility does not have to meet a 10,000-year performance standard like Yucca Mountain. There would be some sort of cooling system and after a few hundred years the remaining ^{135}Cs would be put into a permanent repository (this isotope of cesium has a very long half-life and would not be separated from the more-radioactive ^{137}Cs prior to storage).

There are several important downsides to the FR story. First and most important is that the processing of the spent LWR fuel to make the FR fuel would be enormously expensive, based on experience with spent fuel reprocessing around the world. Essentially, if the FR's were sized at 1 GWe, the new fuel in each one would cost something like the cost of the reactor, 2.5 billion dollars. In other words, adding the cost of the new fuel to the capital cost of the reactor effectively doubles the capital cost of the FR versus an LWR under the generous assumption that the FR (minus fuel) would be built for the same cost as the LWR. The FR then produces electricity at about 9 cents per kilowatt-hour, versus 5 cents for the LWR. Here we have neglected some other important costs associated with the FR, such as the reprocessing facilities for making discharge FR fuel into new FR fuel.

The fuel in the FR would necessarily contain a mixture of uranium, plutonium and higher TRU species, but there is little experience with fuels of this composition – most fuels to date have either been made of uranium or uranium/plutonium mixtures. An extensive fuel research program would be required and it is not certain that the fuel produced as a result of the R&D program would have the same safety characteristics as existing fuels.

Much of the chemistry that is required for the system to work as planned has not been demonstrated on an industrial scale. For the described scheme to work, the processing of the LWR fuel, which is mostly uranium, must produce an extremely “clean” product. Traces of TRU that exceed 100 nCi/g will require the uranium to go to a repository. Typical reprocessing schemes that are in commercial use today cannot decontaminate the uranium to this extent. Additionally, fuel cladding materials are in general contaminated with TRU species and would go to the repository containing these contaminants.

Starting with spent LWR fuel and processing it to reduce the amount of TRU species does not necessarily reduce the release rate of TRU species from the repository unless the waste is very clean. This is because, in any case, the release rate is governed by the solubility of the TRU species in the groundwater. Only complete (or nearly complete) removal of the TRU guarantees a reduction in TRU release from the repository in future years. This level of cleanliness applies to the sum of all of the waste streams going to the repository and it has not been demonstrated yet. Until this demonstration, it cannot be said that reprocessing results in a repository better able to contain TRU releases.

The FR also requires reprocessing facilities for making new FR fuel from old FR fuel. Similar problems exist for the waste streams exiting these facilities, except that the FR fuel processing technology is almost in its infancy. It is also unknown what quantity of low-level wastes would be continually produced in these facilities, but it is expected to be large.¹¹ Waste streams contaminated to beyond 100 nCi/g with TRU species must be sent to a repository.

Routine gaseous and liquid releases from the reprocessing facilities are unavoidable and would have negative (though small) public health consequences in the near term. These negative consequences are to be weighed against the long-term benefits to the repository, which are not certain. If future deaths from repository releases to the environment are discounted versus deaths caused by reprocessing wastes in the present time, the net benefits of reprocessing can

be negative. Also, if the entire fuel processing infrastructure is included in a cost/benefit analysis, and all near-term negative consequences of operating the infrastructure are included, including non-radiological consequences, the net benefit to the public can be negative even without discounting.¹²

Implementation of a scheme like the one described will necessarily imply the need to site, license, and construct LWR fuel processing facilities, FR and FR reprocessing and fuel fabrication facilities. These types of facilities have proven to be controversial with the public, and therefore the benefits to the repository would only be achieved at the cost of having to face multiple contentious policy, siting and licensing issues elsewhere.¹³ We have to ask the question that if nuclear energy becomes so wildly popular that thousands of plants are being built (as per the scenario) how hard could it be to license a few more repositories after Yucca Mountain? It does not seem that the FR option necessarily makes nuclear power more acceptable to the public, but rather the scenario assumption has assumed that nuclear power has already made a turn-around in public acceptance.

On the other hand, look at the situation where an enormous amount of up-front investment is made to deploy a FR fleet. If the FR ends up being uneconomic or if other energy production methods were to undercut it in the market, the cost of scuttling the FR system would be huge. We would be stuck with the FR for many years, regardless of its competitiveness, because a new set of nuclear waste repositories would have to be built to accept the FR spent fuel.

Here is the source of the problem. The 12,000 ton supply of mixed TRU species that would have been buried with the LWR spent fuel has not gone away; it is still above ground in the year 2100, in the cores of the FR's. The need to dispose of these species has not been removed – it has been postponed.

Some of the problems that the proposed fuel cycle seems to solve can be attended to in different ways, without reprocessing any fuel. At this point it is instructive to remember that the FR requires a radioactive material “sequestration” facility to store the very-radioactive species ¹³⁷Cs and ⁹⁰Sr for a few hundred years before placement of the remaining ¹³⁵Cs in a repository. This hypothetical site, possibly build at the US Government's Nevada Test Site, would be underground to protect against thieves or curiosity-seekers and self-guarding because the radiation levels (it would also have a guard force). It would probably require some sort of cooling system but would not have to be licensed for a 10,000 year performance requirement like the Yucca Mountain repository.

Alternatively, a spent fuel storage facility with a similar description could be used with the once-through fuel cycle. Spent fuel is stored underground, safe from thieves, terrorists, or the curious, protected by its own radiation shield (and thousands of tons of uranium). The fuel would cool down over a few hundred years before disposal in a permanent repository. Research could continue at Yucca Mountain, and a large amount of spent fuel could be tested for burial while the repository is kept open for a number of decades as a “waste disposal laboratory.” As time progressed, and the inventory of fuel cooled off due to the decay of ¹³⁷Cs and ⁹⁰Sr, much more waste could be packed into Yucca Mountain. If all the tests went well, the repository could be sealed after a few hundred years.

While this “plan” for Yucca Mountain sounds quite different than the plan presented to the public, I believe that it is similar to one the will eventually be adopted. While there is a very good reason to have an underground storage facility for wastes, and a laboratory for waste

disposal, there is no reason why these two must be forced into one facility. There is also no real reason to seal the repository at any time soon. This latter point has already been recognized by the DOE.

Proliferation

There is also another reason to be wary of uneconomical fuel cycles, especially those involving spent fuel reprocessing. In Figure 9 a “fuel cycle” is shown (only a slight modification of the reprocessing fuel cycle) that produces plutonium metal that can be used for nuclear weapons. This fuel cycle was selected by India, Israel and North Korea to make nuclear weapons. In each case they told elaborate cover stories about the need for domestic energy independence and the need for nuclear power. In all three cases the weapon came before any significant amount of electricity was made from nuclear power. Israel, for instance, is said to have a large nuclear arsenal, but not a single nuclear power plant. In fact, none of these countries could economically use the nuclear fuel cycle that they selected. Iraq also tried this path to obtain weapons with its Osireq reactor, which was destroyed by Israel in 1981.

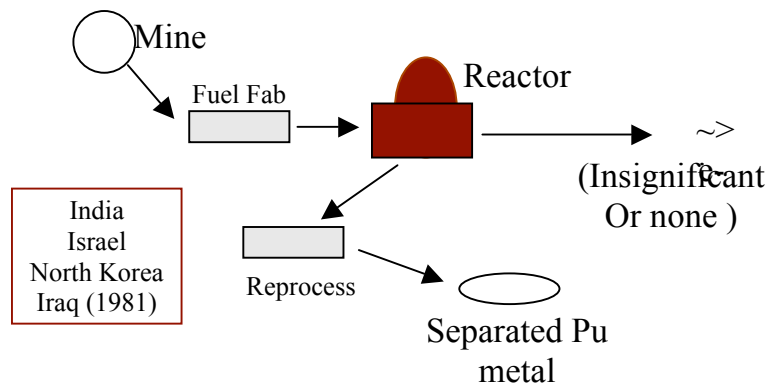


Figure 9. A reprocessing nuclear fuel cycle used as a cover story for nuclear weapons development in India, Israel, North Korea and Iraq.

For the last two or three decades the US has been part of the nuclear suppliers’ cartel, which has effectively blocked the spread of reprocessing facilities to many would-be new nuclear weapon states. Because of the effectiveness of the cartel and the norms of the international non-proliferation regime, nuclear proliferation has slowed down (especially compared to expectations) during the years 1975-today. For the future, the US role with respect to reprocessing needs to be as a world anti-proliferation leader, showing that this uneconomical fuel cycle is not legitimate, thereby reducing its value as a cover story. An accelerated program in reprocessing fuel in the US is inconsistent with this role.

The latest trend in nuclear proliferation should be pointed-out for the sake of completeness. Shown in Figure 9 is a diagram that illustrates the strong indication that Pakistan, North Korea and Iran have become trading partners in uranium enrichment and missile technology. Pakistan’s nuclear weapon program has been based on centrifuge technology stolen from the European company EURENCO in the late 1970’s through espionage. Some nuclear weapons design help may have been provided by China. If Pakistan is indeed selling the knowledge and even the hardware to the highest bidder this is indeed a very negative turn of events.

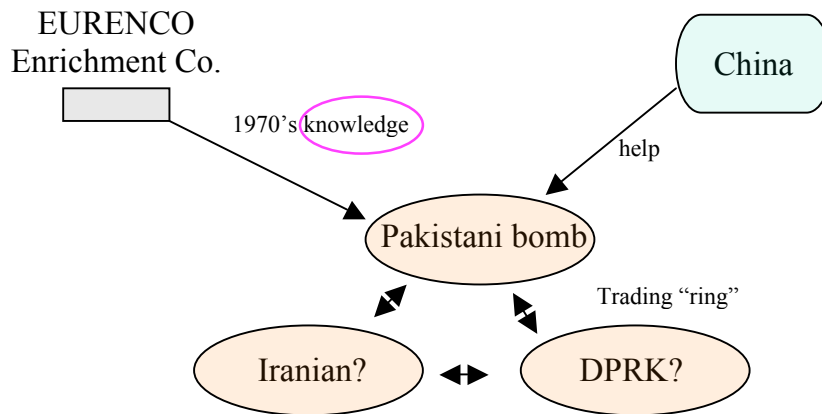


Figure 9. Pakistan has apparently begun to sell weapon-related knowledge and/or hardware to other nations such as Iran and North Korea (DPRK). The information was obtained via espionage from the European enrichment company EURENCO and via help from China.

Lastly consider Iran who has a partially completed uranium enrichment plant at Natanz probably obtained with the help of Pakistan. The IAEA has a long list of questions for Iran, who claims that they are only interested in building a peaceful nuclear energy infrastructure. The main concern is that Iran may have tested an enrichment pilot plant with uranium feed without notifying the IAEA in advance. Iran also has an uncompleted Russian-build power reactor at Bushear, which does not seem to have a direct weapon connection. Hence, there is plausibility to the peaceful cover story if the IAEA’s questions are resolved. It is disturbing to think that Iran would buy a complete power reactor just for the purpose of providing a cover story for its uranium-enrichment-based nuclear weapon program.

The best that the US can do now is to steer weapon-relevant knowledge and technology that is out there in the world into channels that are of maximum peaceful applicability. We should deal with Iran (and the all potential proliferators), if it comes clean with the IAEA. A deal can be struck where we provide assistance with energy technology for Iran in exchange for adherence to safeguards requirements (Iran, per se, cannot be given nuclear energy assistance by the US because of its status as a State Sponsor of Terrorism). For countries that are in compliance with their safeguards obligations (other than Iran) nuclear power assistance can be provided if weapons pathways are renounced.

Conclusions

Nuclear power can be expanded with the once-through fuel cycle to as much as 2-3 TW_e by the year 2050 without significant uranium resource constraint. If uranium prices follow the observed trend seen for other mineral commodities over this last century, it should be expected that uranium prices will be even lower than they are today after such an expansion. Nuclear power could then be expanded by another factor of two by 2100, probably also without uranium price constraints. The amount of spent fuel generated will depend on the specific type of reactors deployed and their efficiency at fuel utilization. As much as million tons of spent fuel could be generated by mid century. The best way to handle the spent fuel is by long-term (multi-century) underground storage followed by permanent disposal.

Alternatives fuel cycles that require the reprocessing of spent LWR fuel in general increase the cost of nuclear energy significantly, and are unlikely to be less troubled by regulatory

problems. Advocates of reprocessing have been proclaiming the shortage of space in the nuclear waste repository at Yucca Mountain as a reason to reprocess spent fuel. However, if nuclear power is to expand at all, the climate of public opinion must change. In a climate where nuclear power is seen as beneficial to the environment, nuclear waste storage and disposal shall become much easier. The space constraint claim is therefore inconsistent with nuclear growth scenarios that must assume that the public is positive to nuclear power. A rational nuclear spent fuel storage strategy combined with continued nuclear waste disposal research is a far more cost-effective option than reprocessing that also leaves open the possibility of increased use of nuclear energy in a future carbon-constrained world.

Some real constraints on nuclear power growth, besides gaining public support for the growth, are in the lack of human capital. Nuclear energy requires a highly skilled work force for design, construction, quality control and regulation. Such an infrastructure would take time to grow, especially in the developing world. Keeping nuclear energy as an option in the Kyoto Protocol's Clean Development Mechanism (CDM) would help to insure that a nuclear expansion in the developing world would be done to the highest safety standards possible. Otherwise, an expansion not involving the assistance of the developed nations could result in compromised nuclear safety.

Article IV of the Nuclear Non-Proliferation Treaty (NPT) states that "All Parties to this Treaty undertake to facilitate, and have the right to participate in, the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy. Parties to the treaty in a position to do so shall also cooperate in contributing alone or together with other States or international organization to the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States Party to the Treaty, with due consideration for the needs of the developing areas of the world." It is therefore entirely consistent with the NPT that the CDM be used to provide funding for an expansion of unambiguously peaceful nuclear energy.

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⁶ DOE, *Generation IV Roadmap: Report of the Fuel Cycle Crosscut Group (FCCCG)*, March 18, 2002, available at <http://nuclear.gov/reports/GenIVRoadmapFCCG.pdf>.

⁷ D. C. Wade, "Goals for Nuclear Energy Systems and Fuel Cycle Concepts Proposed for the Generation IV Roadmap", presented at U of Michigan Symposium on Energy and the Environment: The Role of Nuclear Power, Oct. 2-4, 2002.

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⁹ J. L. Simon, "The Amazing Theory of Raw-Material Scarcity," Chapter 1 of *The Ultimate Resource 2*, Princeton University Press, Princeton, NJ, 1996.

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¹¹ T. H. Pigford, "Actinide Burning and Waste Disposal," an invited review for the MIT International Conference on the Next Generation of Nuclear Power Technology, October 5, 1990, UC Berkeley Dept of Nuclear Engineering, UCB-NE-4176.

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