NPEC Nonproliferation Policy Education Center

A FRESH EXAMINATION

OF THE PROLIFERATION DANGERS OF

LIGHT WATER REACTORS

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October 22, 2004

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PREFACE

Even before the ink was dry on the Nuclear Nonproliferation Treaty (NPT) in l968, officials in the U.S. State Policy Planning staff had privately warned their superiors that non-weapons member states to the treaty could come within weeks of acquiring a nuclear arsenal by amassing nuclear weapons useable fuels claiming that these were intended for peaceful purposes. The advice was quietly filed away.[1] Six years later, with India's "peaceful" nuclear explosion, the warning seemed more salient. Still, even after a series of studies pointing out the military risks associated with proliferating civilian nuclear technology,[2] most policy makers believed that the danger was speculative and still, at worst, many years away.

Thirty years later, the danger seems much closer. Iran, in specific, has become a poster child for the problems spelled out three decades before.[3] Its nuclear enrichment program proceeded for years without the detection by the International Atomic Energy Agency (IAEA). When it and past plutonium recycling activities were finally discovered, moreover, Iran claimed it had a right to them and the entire fuel cycle. These activities, they argued, were all "peaceful", part and parcel of Iran's light water power reactor (LWR) program. They were protected, they insisted, under the NPT.

The U.S. and its allies are now trying to deny Iran the ability to enrich uranium out of fears it might use this capability to make bombs. The problem is that no country has yet clearly countered Iran's claim that it has a legal right to pursue all of its nuclear activities. A key reason why is the peaceful status the U.S. and others have long conferred upon the centerpiece of Iran's nuclear program -- the light water power reactor.

LWRs, in fact, produce and consume massive quantities of lightly enriched uranium and plutonium-laden spent fuel, materials that are quite useful to would-be bomb makers if they have reprocessing or uranium enrichment plants. Yet, for years, it was assumed that these plants and their construction could not be concealed from international inspectors or national intelligence agencies and that therefore, one could promote peaceful nuclear power with LWRs without risking the spread of nuclear weapons.

Supporters of nuclear power also have insisted that the plutonium LWRs produce could not be used to make nuclear weapons. This last point was debated throughout the l970s: Nuclear critics insisted that even "reactor-grade" plutonium could be used to make

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1. See, Avner Cohen, *Israel and the Bomb* (New York, NY: Columbia University Press, 1998), p. 299.
2. See, U.S. Arms Control and Disarmament Agency, *Peaceful Nuclear Power Versus Nuclear Bombs: Maintaining the Dividing Line (Publication 91, December 1976);* Albert Wohlstetter et. al., *Swords from Plowshare: The Military Potential of Civilian Nuclear Energy* (Chicago, IL: University of Chicago Press, 1979); Ford Mitre Nuclear Energy Study Group, *Nuclear Power Issues and Choices* (Cambridge, MA: Ballinger Publishing Company, 1977); and U.S. Department of Energy, *Nuclear Proliferation and Civilian Nuclear Power: Report of the Nonproliferation Alternative Systems Assessment Program* (Washington D.C.: U.S. Department of Energy, Assistant Secretary for Nuclear Energy, December 1979).
3. See, especially, Albert Wohlstetter, "Spreading the Bomb Without Quite Breaking the Rules," Foreign Policy (Winter 1976-1977).

workable, if not optimal, nuclear explosives. As for the inability to covertly reprocess or enrich, though, most nonproliferation analysts were all too willing to downplay or dismiss it. The reason why, in part, was to avoid the worst. At the time, many nuclear supporters insisted that "advanced" states should have the complete fuel cycle, including large reprocessing and enrichment plants. Yet, these bulk handling facilities were much more dangerous than having LWRs alone. Nuclear critics saw promoting LWRs without reprocessing or the further spread of enrichment plants, then, as the best path. Enrichment and reprocessing, they argued, would be difficult to hide and, therefore, could and should be discouraged.

The report that follows, which The Nonproliferation Policy Education Center first released September 27, 2004, constitutes a significant qualification of this given wisdom. Written by national authorities on nuclear chemistry, commercial nuclear power reactors, and nuclear weapons designs, the report makes clear that building and operating small, covert reprocessing and enrichment facilities are now far easier than they were portrayed to be 25 years ago.

A key reason why is the increasing availability of advanced centrifuge enrichment technology. This allows nations to make weapons-grade uranium with far less energy and in far less space than was required with older enrichment methods. It also allows them to distribute and hide their uranium enrichment facilities among a number of sites, something traditional gaseous diffusion uranium enrichment (the next most popular way to enrich uranium) does not permit. Another reason why is that nations can quickly separate out the plutonium contained in spent reactor fuel in relatively affordable facilities that can be quite small (as little as 65 feet square) and therefore, be easily hidden. The bottom line -- LWRs no longer should be given to any nation that might divert the reactor's fresh lightly enriched fuel or the plutonium-laden spent fuel to make bombs.

The report details how fresh and spent LWR fuel can be used to accelerate a nation's illicit weapons program significantly. In the case of a state that can enrich uranium (either covertly or commercially), fresh lightly enriched reactor fuel rods could be seized and the uranium oxide pellets they contain quickly crushed and fluoridated. This lightly enriched uranium feed material, in turn, could enable a would-be bomb maker to produce a significant number of weapons with one-fifth the level of effort than what would otherwise be required to enrich the natural uranium to weapons grade. As for spent LWR fuel, the report details how about a year after an LWR of the size Iran has was brought on line, as much as 60 Nagasaki bombs' worth of near-weapons grade material could be seized and the first bomb made in a matter of weeks. The report also details how the reliability of the bombs made of this material, moreover, is similar to that of devices made of pure weapons grade plutonium.

The running assumption today, of course, is that any nation diverting either the fresh or spent fuel from an LWR site would be detected by IAEA inspectors. This clearly is the premise of the deal the United Kingdom, France, Germany, and Russia are making to Iran: Russia will provide Iran with fresh reactor fuel if Iran promises to suspend

activities at its known uranium enrichment facilities and surrenders spent fuel from its LWR for transit and storage in Russia. What's not fully appreciated, however, is that Iran might well be able to divert these materials to covert enrichment or reprocessing plants and might well be able to do so without detection. Lengthy exposure to spent fuel that has just left an LWR of the sort required to package and ship long distances out of the country is quite hazardous. If Iran was set on making bombs, though, it might be willing to take the risks associated with a much shorter transit for quick reprocessing. The health hazards associated with diverting fresh LWR fuel, on the other hand, are virtually nil.

The IAEA currently does not have complete, real time camera monitoring of either fresh or spent fuel storage areas in Iran and only reviews camera tapes at these sites once every 90 days – a period within which Iran could divert this material to make its first nuclear weapon. Oddly, the IAEA is now considering expanding the intervals between these inspections (for nations other than Iran) from 90 days to a year as a way to rationalize its meager resources and to entice nations to allow the IAEA more intrusive inspection rights under the Additional Protocol.

The thinking here is that since it would take a nation about a year to construct an enrichment or reprocessing plant, the IAEA can afford to extend the time between inspections. This argument, however, assumes two things: First, that the IAEA can determine in advance which nations do not have covert enrichment and reprocessing plants and, second, that IAEA inspectors could detect covert reprocessing and enrichment plant construction in a timely fashion. Yet, neither assumption seems warranted.

Iraq's enrichment program was only discovered *after* the first war with the U.S. North Korea's and Libya's enrichment programs also totally escaped IAEA monitoring. South Korea's and Taiwan's production of laboratory quantities of nuclear weapons materials were only found out years after they had occurred. What compounds all of these shortfalls is the increasing availability, after the commerce A. Q. Khan promoted, of nuclear weapons and uranium enrichment centrifuge designs and hardware.

What, then, should be done to limit these risks? This question was raised at a workshop the day of the report's release. A number of useful suggestions were made.

First, the IAEA should tighten its rules and inspections. Instead of extending the interval in between reviewing camera tapes of the fresh and spent fuel storage sites, the IAEA should move toward more complete, real-time surveillance. It also should have a much more precise accounting for all spent and fresh reactor fuel. Such auditing would likely prove to be costly. One idea to defer these expenses would be to assess all nuclear facility users an inspection tax that would be sent to Vienna. In regards to spent fuel, the IAEA should pay particular attention to single-cycle and old spent fuel. The former contains near-weapons grade plutonium and the second is the easiest to move undetected for reprocessing.

It also would make sense for the IAEA to list uranium hexafluoride as a direct-use material (i.e., material that could be converted into weapons useable fuel in a relatively

short period of time) and to treat all of the related production technology as bulk handling equipment like that associated with reprocessing and enrichment. After the sales of Dr. A.Q. Khan, it is quite clear that the IAEA needs to do much better at accounting for the movement of materials and equipment associated with uranium enrichment.

Second, the U.S. and other advanced nuclear power providers should establish tough rules regarding the export of LWRs and try to persuade international bodies including the Nuclear Suppliers Group, the IAEA, and the United Nations Security Council to adopt them. One idea would be to discourage any nation from developing large reactors including LWR unless they were able first to secure a clean bill of health regarding the possible interest in or development of covert enrichment or reprocessing. In essence the IAEA currently attempts to make such distinctions as part of its promotion of integrated safeguards (i.e., reduced inspections) for nations it believes are not interested or able to make weapons usable fissile materials covertly.

Another suggestion made was to demand that all new large nuclear construction projects, including LWRs, be subjected to a basic free market competition test. Was the nuclear project in question competed against less risky and more economical non-nuclear alternatives (e.g., non-nuclear power generators, visitation to existing nuclear research centers, importation of radioisotopes, etc.)? Was the nuclear project economical enough to attract or be sustained by private financing? Certainly, if the answer to these questions was no, it could help highlight the project's suspect character well *before* it was built or put on line. Such a test would subject many nuclear projects in the advanced world to criticism but after 9/11 and the emergence of so many competitors to nuclear power, it's criticism arguably that's overdue.

Finally, the findings of the report highlight the criticality of enforcing the NPT's strictures against nuclear activities that cannot be safeguarded to prevent quick diversions from peaceful to military purposes. Without early detection and the real prospect of strong negative consequences for would-be bomb makers, the spread of nuclear weapons capabilities is only likely to increase. This, however, is not inevitable assuming policy makers fully appreciate the nexus between nuclear energy and nuclear weapons – a connection detailed graphically in this report.

Henry Sokolski
October 19, 2004

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Conclusions

- The Light Water Reactor (LWR), the standard power source for most nuclear power stations around the world and the likely design for future ones, is not nearly so "proliferation resistant" as it has been widely advertised to be. From a proliferation point of view the LWR is generally preferable to other types of power reactors but the differences are more blurred than was previously appreciated.

- With today's technology small, difficult to find, clandestine enrichment facilities or reprocessing plants could provide the reactor's owners with militarily significant quantities of nuclear explosives.

- We need therefore to revise the conventional wisdom that LWRs are a safe proposition for siting in just about any country so long as there are no accompanying commercial uranium enrichment facilities or reprocessing facilities.

- The principal "front end" concern relates to gas centrifuge enrichment plants. . It is now widely understood that even if such plants are safeguarded and designed to produce low enriched uranium (LEU) for LWR fuel, their owners could convert them quickly to produce highly enriched uranium (HEU) for bombs. It is less appreciated that if the owners divert some of the LEU produced by the declared plant and used as feed for a clandestine enrichment plant, they can reduce the needed plant capacity by a factor of five. Moreover, such LEU feed need not rely on the existence of an LEU plant; it could come from processing the fuel pellets of a fresh LWR fuel reload. The possibility of using centrifuges to produce HEU for bombs has been enhanced by recent revelations regarding Pakistan's spread of this technology to Iran, Libya, and North Korea, and possibly others, with the fabrication of parts in a number of other countries.

- It is also widely understood that reprocessing plants that separate plutonium from LWR spent fuel for later use as fuel could also provide plutonium for bombs. What is less understood, and emphasized in this report, is that small, clandestine reprocessing plants could provide the reactor's owners with militarily significant quantities of nuclear explosives. Such technology is well within the capabilities of countries like North Korea or Iran.

- Clandestine reprocessing is only half of the plutonium concern. The other is that contrary to conventional wisdom LWRs can be copious sources of near-weapons grade plutonium that can be used to make powerful nuclear weapons. The widely debated issue of the usability for weapons of plutonium from LWR fuel irradiated to its commercial limit has diverted attention from the capacity of an LWR to produce large quantities of near-weapons grade plutonium from partially irradiated spent fuel. The characteristics of bombs based on this material would not be significantly different than those based on weapons grade plutonium.

Recommendations

- *We need to reassess the role of LWRs in international programs.* They are not for everyone and we should be cautious about promoting their construction in worrisome countries. This is not a benign technology. At a minimum we should not support such technology where it is not clearly economic.
- *Clandestine enrichment and reprocessing*. The IAEA and national intelligence has constantly to be on the lookout for clandestine plants because they can rapidly change the security equation. There needs to be much closer accounting of LEU fuel in view of its significance as possible feed for clandestine enrichment.

- *IAEA inspection of LWRs*. IAEA inspection activities for LWRs to check on fuel inventories and refueling need adjustment upward in countries of concern from the point of view of potential bomb-making to take account of possible undiscovered clandestine reprocessing. Because of inevitable IAEA resource limitations it is necessary for the agency to concentrate the inspection where they are most important. It would help to gain support for such a system if it were possible to develop some objective way of defining "countries of concern." The IAEA should take greater account of the presence of weapons-grade plutonium or near weapons-grade plutonium in spent fuel pools and storage in devising its inspections.

- *Enforcement*. The NPT members must enforce the IAEA inspection system. An important purpose of IAEA safeguards is to deter nuclear weapons activities—of would-be nuclear weapon countries—by the threat of early detection. This assumes there will be a strong reaction to such an early detection of illicit activity. If would-be bomb-makers conclude they have nothing to fear because the international community is not likely to react to their violations, the whole system of control falls apart.

A FRESH EXAMINATION OF THE PROLIFERATION DANGERS OF LIGHT WATER REACTORS

LWRs become the nuclear power workhorse around the world

From the beginning of the nuclear age American efforts to shape the worldwide development of nuclear energy were driven in part on US interest in limiting the possibilities for diversion of civilian facilities to military purposes. US policy went through stages, at each one of which it appeared as if a particular technological or institutional approach to nuclear energy could tame it sufficiently to allow world-wide commercial use without spreading access to nuclear weapons. But in time the real world poked holes in one rationale after another. The subject of this report involves one of these technological policy initiatives, the consequences of which we are living with today—encouraging the spread, starting in the 1960s, of US light water reactor (LWR) technology as the basic nuclear power workhorse throughout the world.[4]

In the 1950s, before the advent of nuclear power plants, the United States tried to control the uranium market by buying up uranium at high prices. This naturally encouraged exploration that demonstrated that uranium was plentiful and negated the US effort at control. With easy access to uranium but lacking indigenous uranium enrichment facilities, Britain, France, and Canada, opted for reactor designs that utilized natural uranium fuel and heavy water or graphite as the neutron moderator. In the late 1950s and early 1960s, they interested Italy, Japan, India, and other countries in heading in this direction. Not only did this threaten America's competitive position but it also threatened to spread a type of reactor that lent itself easily to production of plutonium. In fact the first British and French power reactors were based on their military plutonium production reactors.

America's advantage was two-fold. The United States had developed a compact, and therefore relatively low-cost, LWR design based on a naval propulsion reactor design. And the United States had invested heavily in gaseous diffusion plants in Tennessee, Kentucky, and Ohio to enrich uranium for weapons.

[4] As nearly every interested person knows by now, light water in this context is just plain water, so called in the early days of the nuclear era to distinguish it from heavy water, in which the hydrogen atom is replaced by deuterium. LWRs come in two basic types—Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). In a PWR the nuclear core heats a pressurized primary water loop that passes through a steam generator that boils a secondary water loop to provide steam to the electric turbines. In a BWR the water boils in the nuclear vessel and passes directly to the steam turbine. Most of the LWRs in the world are PWRs. For our purposes the differences between PWRs and BWRs are not significant.

The LWR could only operate on enriched uranium, that is, uranium more concentrated in the active uranium-235 isotope than natural uranium.[5] By virtue of its huge enrichment capacity, the United States had an effective monopoly on the production of this fuel. Moreover, as the cost of the plants had been largely assigned to the military budget, the United States decided to sell the stuff at low prices that did not defray the massive investment. It was a price that at the time no other country could even hope to offer in the future. From the point of view of customers, it was a deal that was hard to refuse, even if it came with US control conditions. Ultimately, the amount of engineering invested in these designs and the depth of experience with them overwhelmed any conceptual advantages other reactor types may have had. While not the exclusive choice—Canada and India continued developing the natural uranium/heavy water designs that evolved into the CANDU reactor—the LWR became the standard reactor type around the world. In the late 1960s France switched to LWRs, and Britain did later. Other European manufacturers in Germany and Sweden chose LWRs. The Soviets eventually did, too. There are now over 350 LWRs in operation in the world today.[6]

From the point of view of proliferation, the advantages of the LWR were considerable as compared with natural uranium-fueled reactors. US policy makers thought that the most important security advantage of LWRs was that the LWR customers knew that they risked losing their reactor fuel supply if they misused the reactors for military purposes. There appeared to be detailed technical advantages, as well. For a given size of reactor, the LWRs produced less plutonium. The plutonium was, generally speaking, more difficult to extract from the LWR fuel by chemical reprocessing because the fuel is irradiated for a longer period of time, i.e., it has a higher fuel burn-up, and hence is more radioactive, necessitating more shielding of the separation process. LWRs also had to be shut down for refueling which makes for easier oversight of the fuel, whereas most natural uranium reactors are refueled online and continually so it is harder to keep track of the fuel elements. It was widely believed through the 1970s—even by the top people in the International Atomic Energy Agency in Vienna—that it was not usable at all.

It is important to correct one widely held belief about LWR spent fuel. The isotopic characteristics of spent fuel from LWRs are about the same as that from spent fuel from heavy water reactors such as the CANDU (see Table 1 on p. 62) even though the LWR burnup is much higher. This is because of the differences in the enrichment levels of the two types of fuel. The weapons usability of plutonium from either fully irradiated LWR spent fuel or fully irradiated CANDU spent fuel would be comparable.

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[5] Natural uranium contains about 0.7% uranium-235 and 99.3% uranium-238. LWR fuel is normally enriched to about 4%, while bomb material is usually enriched to about 90% uranium-235.

[6] There are LWRs in Armenia, Belgium, Brazil, Bulgaria, China, Czech Republic, Finland, France, Germany, Hungary, India, Japan, South Korea, Mexico, Netherlands, Russia, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Taiwan, UK, and the US.

Even the intrinsic technical advantages of the LWRs themselves do not now appear as significant as they once did. While LWRs do not produce as much plutonium as natural uranium-fueled reactors of the same size, the modern LWRs are so much bigger than the older natural uranium plants that they are also prolific plutonium producers.[7] A standard size LWR with an electrical generating capacity of about 1000 megawatts produces about 250 kilograms of plutonium per year. (That has to be compared with the nominal 5 kilograms of plutonium per warhead.)

Worldwide spread of enrichment technology eases access to nuclear weapons

In any case, the proliferation benefits of worldwide deployment of LWRs gradually attenuated. Just as the market for uranium encouraged exploration that negated US control, so the spread of LWRs and the consequent market for enrichment encouraged both the reinvention by others of the gaseous diffusion enrichment process, originally developed by the US during World War II, as well as the development of the gas centrifuge enrichment process, broke the US monopoly on the supply of enrichment for LWRs.

In particular, France built a large gaseous diffusion plant, and the UK, West Germany, and the Netherlands established the Urenco consortium which supplies enrichment services from gas centrifuge plants in each of these countries. While the gaseous diffusion plants in France and the US continue to operate, both countries have announced plans to replace them with new gas centrifuge plants. Moreover, Russia long ago abandoned the gaseous diffusion process in favor of gas centrifuge, and is now a major competitor for enrichment supply on the international market. Other countries, which already rely or plan to rely on nuclear power to a significant extent, notably Japan and China, respectively, have also built gas centrifuge plants, although at present they do not supply enrichment services to the international market.

Global attention on the proliferation implications of centrifuge enrichment has been focused recently as a consequence of the revelations about Pakistan's role in spreading this technology. The activities of A. Q. Khan and his associates in trading the centrifuge technology he stole from Urenco to Iran, North Korea, Libya and possibly other countries has underlined the "front-end" vulnerability of the LWR once-through fuel cycle.

An important advantage of the gas centrifuge process is that it is much less energy intensive than gaseous diffusion. The trend towards using gas centrifuge instead of gaseous diffusion for commercial enrichment has also been driven by improvements in centrifuge performance. The newer models are much more reliable and have a larger unit enrichment capacity. Gas centrifuge plants are also inherently much more flexible than gaseous diffusion plants to accommodate different

[7] For example, the two LWRs promised North Korea in a 1994 US-DPRK agreement were nearly ten times the size of the indigenous natural uranium reactors they were supposed to replace and therefore had a plutonium production capacity about twice that of the natural uranium reactors.

combinations of feed enrichment, tails (waste) concentration, and product enrichment. Large centrifuge enrichment plants can be thought of as many smaller centrifuge plants in parallel, so the small modular units can be shifted around fairly easily, or one can stand by itself. In other words, gas centrifuge technology lends itself to small-scale operation.

Unfortunately, these characteristics also make the gas centrifuge process a much bigger proliferation risk than, say, gaseous diffusion technology. That applies both to (1) the possibility that the owner of an existing, declared LEU plant would modify it to also produce HEU and (2) that someone would construct a small clandestine HEU plant.

It is now generally appreciated that gas centrifuge plants for LEU can fairly easily be turned into plants for HEU. It is less appreciated that LEU at, say, 4 percent enrichment, is about 80 percent of the way to HEU. It takes comparatively little additional "separative work" to upgrade LEU to HEU. It would be difficult for the IAEA to keep close enough track of all the LEU to stay ahead of any such conversion.

Having a gas centrifuge plants producing LEU makes it much easier to construct and operate a clandestine one. The presence of the larger plant would mask many of the intelligence indicators and environmental indications of a clandestine one so it would harder to find.

But even in the absence of any commercial enrichment—in the case of a country with one or more stand alone LWRs—the presence of LWRs means that a substantial supply of fresh LWR fuel would also be present at times. That such fresh fuel can provide a source of uranium for clandestine enrichment is another possibility that has received essentially no attention in proliferation writings. Since the fuel is already low enriched uranium, a much smaller gas centrifuge plant would suffice to raise the enrichment to bomb levels than would be the case if the starting point is natural uranium. By starting with such LEU fuel pellets, which are uranium oxide (UO_2), the enricher would be able to skip the first five processes required to go from uranium ore to uranium hexafluoride gas, the material on which the gas centrifuge operate. To go from the uranium oxide pellets to uranium hexafluoride the would-be bomb-maker would crush the pellets and react the powder with fluorine gas. Suitably processed, the LEU pellets could provide feed for clandestine enrichment.

We elaborate on gas centrifuge proliferation issues in Appendix 1.

Worldwide spread of reprocessing technology for plutonium separation

By contrast to the heavy attention recently directed at the possibility of clandestine uranium enrichment, there has been relatively little attention directed at the possibility of clandestine reprocessing to separate plutonium from LWR spent fuel. It is a principal concentration of this paper.

In previous debates on the subject the point was made that (1) plutonium contained in LWR spent fuel is unsuitable for weapons; that anyhow (2) anything short of a high-investment commercial reprocessing plant—beyond the means and capabilities of most countries—would not provide access to the plutonium contained in the LWR spent fuel; and (3) such reprocessing would be detected by international inspectors. We believe these bars to using LWRs as a source of plutonium for weapons are very much exaggerated.

Partial cores removed from an LWR after one fuel cycle (rather than the conventional three) have lower burnup and hence contain plutonium with a higher Pu-239 content than the plutonium in spent fuel of the full design burnup. Such plutonium is sometime called fuel grade, as distinguished from weapons grade at one end and reactor grade at the other. In practical effect such plutonium is near-weapons grade. The characteristics of simple fission weapons using this material are not very different from those using weapons grade plutonium. The fuel grade plutonium is markedly superior for weapons use than reactor grade plutonium from spent fuel of the design burnup. The arguments surrounding the usability of LWR plutonium for weapons deal with the high burnup reactor grade material and so are irrelevant for the present discussion.

Reprocessing of LWR spent fuel is not particularly difficult for a country with modest technological capabilities. Witness North Korea's reprocessing of its plutonium production reactor spent fuel. While reprocessing LWR fuel is harder than reprocessing low burnup natural uranium fuel, the feasibility of small-scale, and possibly "quick and dirty" reprocessing of LWR fuel has been known for thirty years.

It is more difficult to make categorical statements regarding the ability of IAEA inspectors to detect a hypothetical clandestine reprocessing plant. Such a plant could likely remain hidden until it is put to use—until spent fuel is withdrawn from a reactor and the reprocessing operation begins. Even if the start of operation would be detected promptly, which is by no means sure, especially as to location, it is possible that the operator of the clandestine plant, could manage to produce militarily significant quantities of plutonium, and weapons, before the international system can react effectively.

Our more detailed views on the technical difficulties involved in clandestine reprocessing of low burnup LWR fuel are presented in Sections 3 and 4, and Appendices 2 and 3. To place these issues in context, we first summarize the evolution of US policy on the proliferation implications of commercial reprocessing.

1974 Indian nuclear explosion sparks policy debate over LWRs and reprocessing

The reasons for addressing these matters now—the reason for a fresh look—are that firmly held but erroneous views on the facts underlie important US policies on

LWRs. Until 2001, the State Department defended putting LWRs in North Korea as part of the 1994 US-DPRK Agreed Framework on the grounds that LWRs were "proliferation resistant"—that North Korea would find it difficult if not impossible to reprocess LWR spent fuel. Even now, that US-supported project is only suspended, not terminated.

The State Department's Russian counterparts made similar arguments, and continue to make them, in supporting the Russian construction of Bushehr reactors in Iran. And even in arguing against the Russian power reactor project at Bushehr on proliferation grounds the United States says only that the civilian project could provide cover for a clandestine Iranian bomb effort, not that the plant itself is inherently dangerous.

The LWR issues also have much wider significance. The idea that plutonium from LWRs is essentially unusable for bombs is an essential underpinning of the commercial drive for worldwide deployment of LWRs.

It has long been understood that the most difficult hurdle for a country seeking nuclear weapons is getting the nuclear explosive materials—either highly enriched uranium (HEU) or plutonium. By comparison the design and fabrication of the nuclear weapon itself poses a less difficult obstacle. That is why the technologies that extract the nuclear explosive material—uranium enrichment and reprocessing—are designated as "sensitive" technologies in the polite international discussions over nuclear controls against proliferation. In plain language, "sensitive" means dangerous.

The 1974 Indian nuclear explosion alerted the United States to the ease with which a country that had reactors and reprocessing could progress to nuclear weapons.[8] It also alerted those concerned with the spread of nuclear weapons to the extent to which reprocessing technology had spread and was spreading further. Even though it was equally dangerous, the United States had never restricted its reprocessing technology the way it had restricted enrichment technology. Perhaps this was because the United States could hope to maintain a commercial monopoly on uranium enrichment whereas that was unrealistic in the case of reprocessing. It was assumed in the early days of nuclear power that uranium was scarce and that reprocessing was an essential part of all reactor operation. In the background was the near-universal notion that the future of nuclear power lay in plutonium-fueled reactors, that uranium-burning reactors were just a transition phase, so cutting off access to plutonium was thought tantamount to putting a lid on the expansion of nuclear energy.[9]

[8] There was an additional cause for alarm and chagrin. India used American heavy water in the reactor that produced the plutonium. The heavy water had been sold under a 1956 contract that restricted its use to "peaceful uses." India claimed its explosion was "peaceful."

[9] This is still a common view in nuclear bureaucracies, not least in the US Department of Energy, where it underlies advanced plutonium-fueled reactor and spent fuel reprocess research and development.

The United States revealed extensive information on reprocessing at the 1955 Geneva Atoms for Peace Conference. Under the Atoms for Peace program the United States trained many foreigners in reprocessing technology at the US national laboratories such as the Oak Ridge National Laboratory and the Argonne National Laboratory that did pioneering work in reprocessing. That is where the Indian and Pakistani reprocessing experts got their start.[10] The US Atomic Energy Commission, and later the Department of Energy, published encyclopedic technical volumes on the subject as well as detailed engineering reports that explicated reprocessing "know how."[11]

None of this was in any way prohibited by the Nuclear Nonproliferation Treaty *as it was then universally interpreted* even though it was at odds with the purpose of the Treaty. According to the prevailing interpretation of the Treaty nuclear technology that was labeled by its owner as "peaceful," had some possible civilian application, and was subject to inspection by the International Atomic Energy Agency (IAEA) was deemed to be legitimate. This was so even if the technology—say, reprocessing or enrichment—brought the owner to the threshold of nuclear weapons. At that time the real role of the IAEA inspectors was to legitimize trade rather than to find wrong-doing. The view was that international nuclear gentlemen did not inquire too deeply into the affairs of other nuclear gentlemen, and in any case kept what they learned to themselves.[12]

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[10] To cite one important example, Munir Khan, who as head of the Pakistani Atomic Energy Commission in the 1970s launched the weapons program and associated fuel cycle activities, studied in the United States on a Fullbright Grant and received an MSc in nuclear engineering from Argonne National Laboratories as part of the Atoms for Peace Program. (http://www.hipakistan.com/en/detail.php?newsId=en62190&F_catID=17&f_type=source&day=)

[11] See Justin T. Long, *Engineering for Nuclear Fuel Reprocessing*, American Nuclear Society, 1978. This volume of over 1000 pages was published by the Atomic Energy Commission in 1967 and republished in 1978 for the Department of Energy. The 1967 Forward by Floyd Culler, Assistant Director of the Oak Ridge National Laboratory, and one of the foremost experts on reprocessing, states: "This book presents the engineering aspects of the reprocessing of power-reactor fuels. From many diverse sources of information, an attempt has been made to summarize the basic approaches to the engineering of a chemical separation plant. The book does not offer engineering information only; it also reviews the processes most widely used and most of those under development. Particular attention has been given to describing the equipment used in reprocessing fuel. Shielding, criticality control, liquid and gaseous waste disposal, safety, ventilation, fuel-element storage and handling, materials accountability, and maintenance are covered in summary form, and the information given is supplemented by extensive and selected references to reports that are available fro the rather specific domain of atomic energy literature. The information is presented in such a way that the book, either as a whole or in part, can be used as a text for instruction in a course on radiochemical course design. The process data and the underlying engineering principles make the book useful either as a textbook or a handbook. . . . We hope, too, that it will serve as a reasonably accurate introduction to reprocessing technology for those who are now entering the field."

[12] The IAEA continued in this mode for many years. After the embarrassment of the discoveries after the first Gulf War that Iraq had run a weapons program under the noses of the IAEA inspectors the Agency carried out important improvements in its mode of operation. In recent years the IAEA has become a first-rate international inspection agency limited principally by what its Board of Governors will permit.

In its public pronouncements the US government more or less stuck to the position that the NPT legitimized all "peaceful" nuclear activities. At the same time the government could not ignore the dire security implications—post-1974 Indian nuclear explosion—of unrestricted commerce in nuclear technology, even if it was subject to IAEA inspection. France was then negotiating with Pakistan for the export of a reprocessing plant and Germany was pursuing a package deal with Brazil that involved both reprocessing and enrichment technology.[13] A complication at the time was that France was not yet an NPT member. To help introduce a common set of export guidelines that included "restraint" in the export of "sensitive" technology, the United States organized the Nuclear Suppliers Group of nuclear exporting countries, initially 15 of them. This Group operated, and continues to operate, as a kind of extra-treaty backstop for the NPT. The main concern at the time of its founding was technology that provided access to plutonium as uranium enrichment technology was still tightly held.[14] There were some important US successes, among them stopping the French sale of a reprocessing plant to Pakistan, which France finally abandoned in 1978.[15]

What the United States should do about reprocessing and plutonium use, both domestically and internationally, became an election year issue in 1976. President Gerald Ford issued a nuclear policy statement that plutonium was at the root of the security problem associated with nuclear energy. Once separated from the radioactive waste contained in spent fuel, the material could rapidly be put to military use. President Ford stated that reprocessing, that is chemical separation of plutonium, "should not proceed unless there is a sound reason to conclude that the world community can effectively overcome the associated risks of proliferation." In perhaps his boldest step, he announced that the United States would act domestically in a way that was consistent with what we asked of others. The United States would no longer in its energy planning assume future reliance on plutonium fuel. He said that he believed that we could make use of nuclear energy, and even increase reliance on it, with this security restriction. "We must be sure," he said, "that all nations recognize that the U.S. believes that nonproliferation objectives must take precedence over economic and energy benefits if a choice must be made." To this day, US policy on spent fuel assumes that it will be disposed in a repository on a "once through" basis, that is, without reprocessing, although the current reason for this probably has more to do with economics than with security.

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[13] The Germans sought to sell the Brazilians a type of enrichment technology that did not offer much promise. The Brazilians later got involved in centrifuge technology and are now constructing a centrifuge enrichment plant that would supply more or less the fuel needs of one of their two reactors. They have been reluctant, however, to allow the IAEA inspectors to see the centrifuges, presumably because the inspectors would then know the source of the technology. The US government has so far not reacted to this very suspicious and worrisome state of affairs.

[14] Perhaps it would be more accurate to say, "was *thought* to be tightly held," as the industrial spy A.Q. Khan was already delivering to Pakistan centrifuge plans and contractor lists that he had stolen from Urenco while he worked there.

[15] Although it now appears that Pakistan may be trying to revive the plant, possibly with Chinese help.

Gerald Ford lost the 1976 election to Jimmy Carter and as a consequence it is Carter's name that usually attaches to the origin of a restrictive US nonproliferation policy with respect to plutonium. Unfortunately, President Carter's erratic style and his administration's tendency to equate saying something with doing it left US nonproliferation policy in a confused state that did not engender respect either at home or abroad.[16] At first Carter took a rigid anti-proliferation stance on a number of key issues but abandoned these positions one after another when they met with domestic and international criticism, most particularly with respect to reprocessing and future use of plutonium.[17] Subsequent presidents watered down further US policy on disapproval of foreign reprocessing so that it is now barely perceptible except as regards countries of direct and near-term proliferation concern and which the United States considers hostile.

What has remained, however, is the view—agreed to over the entire spectrum of nuclear opinion—that if commercial reprocessing is not present in a country then the reactors themselves do not pose a proliferation danger. Gerald Ford drew a sensible distinction between what is too dangerous for the arteries of commerce (that is, separated plutonium) and what in the circumstances was a reasonably acceptable alternative (a once-through uranium fuel cycle). Over time, the reasonably acceptable came to be described as entirely satisfactory. This view, however, ignores some stubborn technical facts that have been know for decades but unfortunately forgotten, about the ease and rapidity with which a country could reprocess LWR spent fuel and about the usability of such plutonium for bombs. That is the reason for a fresh look at this subject.

1976-1977 Ford-Carter restrictive policy on commercial reprocessing leads to debate over clandestine reprocessing

Generally speaking, the nuclear industry and the nuclear bureaucracies in the Department of Energy and elsewhere did not support the once-through nuclear fuel

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[16] Just before the Shah was overthrown in 1979, as part of a reactor sale agreement, Jimmy Carter had agreed to grant Iran "most favored nation" status for reprocessing so that Iran would not be discriminated against when seeking permission to reprocess US-origin fuel. That meant Iran would now have the same right as Japan to reprocess US-enriched power reactor fuel. The Shah left Iran before the negotiations were concluded. —*Nucleonics Week*, 12 January 1978, pp. 2-3; in Daniel Poneman, *Nuclear Power in the Developing World*, (George Allen & Unwin: London), 1982, p. 88. (http://www.nti.org/e_research/profiles/Iran/1825.html)

[17] Carter rapidly reversed himself on the issue of Japanese reprocessing of US-supplied fuel (over which the United States had reprocessing control) after his proliferation policy advisor, Gerard Smith reminded him that World War II started after the United States cut off Japan's oil supply. In the case of Pakistan's nuclear weapons program, then in its early stages, the United States looked the other way after the Soviet invasion of Afghanistan so as to promote Pakistani help in opposing the Soviets.

cycle that avoided reprocessing. Ironically, industry saved a lot of money over the last nearly thirty years by adopting this approach, however reluctantly, because commercial reprocessing and recycle of plutonium as fuel is highly uneconomic.[18] Mostly the defense of commercial reprocessing was based on the arguments that Ford and Carter had exaggerated the dangers—that so long as the commercial activities were subject to IAEA inspection (which went by, and continues to go by, the misleading name of "safeguards") there was nothing to worry about. And, it was said in further defense of reprocessing, that the plutonium from LWRs was unsuitable for bombs and was therefore not a source of worry.[19] Both of these points are wrong and we will devote special attention in this report to the latter one.

For the present, however, we are more interested in a different line of argument against the Ford-Carter policy supporting a once-through fuel cycle. These critics argued that banning commercial reprocessing wouldn't provide any additional security because it was anyhow easy to extract the plutonium from spent fuel using small jerry-built plants that most countries could build quickly and secretly. Although they didn't put it that way, they argued, in effect, that if a country had nuclear power reactors things were much *worse* than the new Carter administration thought. [20] This line of argument was based on an informal technical report written in 1977 by reprocessing experts at the Oak Ridge National Laboratory that presented a design for a small, quickly-built, simple reprocessing plant that the designers thought could easily be hidden. [21] The argument based on this report didn't gain much traction because the nuclear industry was reluctant to support an argument that, if taken seriously, could lead to the conclusion that nuclear reactors were themselves too dangerous to operate on a commercial basis. And supporters of the once-through approach tended to write off the significance of the Oak Ridge report in the context of the arguments over allowing large-scale commercial reprocessing. The report may have overstated to an extent the ease with which LWR spent fuel could be reprocessed quickly and secretly, but it and a number of other subsequent studies on small-scale and clandestine reprocessing made an important point. It is that LWRs operating on a commercial once-through fuel cycle—with no commercial reprocessing—are not as safe a proposition from the point of view of proliferation as they were made out to be.

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[18] In spite of the unfavorable economics support for plutonium recycle continues, including in high places in the current administration, as witnessed by comments on this issue in the president's National Energy Plan of May 2000. Such support is based in part on ideology (on the part of nuclear true believers) but mainly on commercial opportunism (on the part of nuclear fuel firms looking for subsidies). Nuclear fuel firms providing reprocessing and plutonium services have discovered that a process does not have to be economical in order to be profitable.

[19] That is what Sigvard Eklund, the IAEA Director General, told one of the authors in conversation in 1976. To correct this view the US government offered Mr. Eklund a briefing on the subject. At that briefing his jaw literally dropped when presented with a slide that refuted his earlier view. The new facts had far-reaching implications for the IAEA inspection system.

[20] One needs to reemphasize, because it is so frequently forgotten, that the initial rejection of US reprocessing was done by President Ford. But he lost the election a few days after announcing his policy and so the focus turned to Jimmy Carter.

[21] D.E. Ferguson to F.L Culler, Intra-Laboratory Correspondence, Oak Ridge National Laboratory, "Simple, Quick Processing Plant," August 30, 1977, 22 pages. This is the same Mr. Culler whose Forward to a USAEC volume on reprocessing was cited earlier.

A number of studies on "quick and dirty" clandestine reprocessing for bombs suggest this is a feasible option

There have been a number of studies on small-scale reprocessing but perhaps none that received comparable attention and none that involved persons as prominent in the field. The godfather of the 1977 study was Floyd Culler, than Oak Ridge assistant director, and a leading developer of PUREX technology. He assembled a team to prove that a country with a minimal industrial base could quickly and secretly build a small reprocessing plant capable of extracting about a bomb's worth of plutonium per day.

The response came in the previously cited 1977 Oak Ridge memorandum that presented a design for such a plant together with a flow sheet and equipment list, with dimensions and specifications. The main technical references were from standard textbooks and handbooks.

The equipment is chosen with a several-month campaign in mind rather than long-term operation so, for example, plastic pipe can serve in places where steel pipe would be used in a commercial plant. A plant diagram attached to the memorandum and keyed to the equipment list shows the plant equipment layout from the receiving pool for radioactive spent fuel to the metal reduction furnaces for producing plutonium metal "buttons."[22] The structure housing the entire operation would be about 130 feet long and much less wide. Although they describe the plant as a "quick and dirty" one, the designers went to some pains to contain the radioactive wastes and to filter the effluents both for reasons of safety and to avoid detection.

The study concluded the plant could be in operation four to six months from the start of construction, with the first 10 kilograms of plutonium metal (about two bombs' worth) produced about one week after the start of operation. Once in operation the small plant could process about one PWR assembly per day, which translates into production of about 5 kilograms of plutonium per day.

If one accepts this conclusion about the possible performance of such a "quick and dirty plant," or something close to it, the implications are very far-reaching

[22] The diagram appears in the Washington *Post* of August 4, 2002, to illustrate an article, "Those N. Korean Reactors Light Up Danger Signals," by Victor Gilinsky and Henry Sokolski. The Oak Ridge report does not see the initial mechanical disassembly of the LWR spent fuel as a particularly difficult step. This issue came up in arguments over the risks posed by the two LWRs that the United States had promised North Korea as part of the 1994 Agreed Framework. The State Department insisted that while North Korea had experience with reprocessing it would not be able to reprocess LWR fuel because of the difficulty of cutting up the fuel rods, a part of the process with which a high-capacity French commercial plant had difficulty. The Oak Ridge design proposed abrasive saw cutting underwater and it refers for the details to the 1967 Long volume which has a section on the subject.

concerning the risks posed by LWRs in countries interested in obtaining nuclear weapons. There would be little chance of detecting such a plant until it was in operation and spent fuel to be processed was missing from a power reactor storage pool. Given the short process time—a few days from delivery of spent fuel to plutonium metal—IAEA inspectors would have little chance of detecting a diversion and start of reprocessing under the current approach. From metal plutonium to weapon components is a matter of days. The IAEA guidelines for LWR inspections assume that from LWR spent fuel to metal weapon components takes about 1-3 months,[23] but the Agency's resource limitations and the resistance of member countries keep the actual inspection frequency of LWR inspections lower than once every three months. Therefore if the Oak Ridge design or something similar would work as planned—start up quickly and then produce about a bomb's worth of plutonium a day—the operator could produce dozens of bombs before the IAEA could count on detecting it, at least using the current inspection approach.

This conclusion assumes of course that the reactor operator cooperates with the would-be bomb-makers. It also assumes that weapon design and readiness for fabrication would be prepared in advance. Both of the latter are difficult to detect and when detected are often clouded in ambiguity. In any case such detection has not led in the past to drastic international action to halt nuclear activity in the country. The history of nuclear activities in Iraq, North Korea, and Iran, suggests that the more time-scale for international enforcement actions is more typically on the order of years. The George W. Bush administration's tougher approach on "weapons of mass destruction" and the preventive invasion of Iraq point in a different direction. But what the lesson from that experience will be, and what policy will emerge toward countries suspected of nuclear weapon ambitions, is yet unclear. The difficulties of coping with post-invasion Iraq suggest that the United States is likely to be slower on the trigger in the future.

In view of the potentially far-reaching implications of the Oak Ridge report, the General Accounting Office prepared an evaluation for Congress.[24] The GAO examined reviews of the Oak Ridge memorandum by five Federal agencies and a number of individuals.[25]

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[23] IAEA 2001 Safeguards Glossary, p. 22. Available on the IAEA web site, www.iaea.org.

[24] Report by the Comptroller General of the United States "Quick and Secret Construction of Plutonium Reprocessing Plants: A Way To Nuclear Weapons Proliferation?, EMD-78-104, October 6, 1978. Senator John Glenn, then Chairman of the Subcommittee on Energy, Nuclear Proliferation and Federal Services, Committee on Government Affairs, and very active on nuclear proliferation issues, made the request. (Throughout, we do not distinguish between Oak Ridge report and Oak Ridge memorandum.)

[25] The Arms Control and Disarmament Agency (ACDA), the Department of Energy (DOE), the Nuclear Regulatory Commission (NRC), and the Congressional Research Service (CRS). In terms of his knowledge of reprocessing, the most imposing of the 11individuals consulted was Manson Benedict, Institute Professor Emeritus, Massachusetts Institute of Technology. The CRS review in its entirety was published separately several days later. Warren Donnelly, A *Preliminary Analysis of the ORNL Memorandum on a Crude Nuclear Fuel Reprocessing Plant*, November 4, 1977

The GAO raised questions about quickly the plant could be built and to what extent it could be hidden, but concluded it was a credible possibility for an experienced group of reprocessing engineers and operators. In other words, one cannot assume that a country interested in nuclear weapons will be barred from extracting militarily significant amounts of plutonium from its LWRs simply because it lacks a commercial reprocessing capability.

On the question of detectability, since 1977 we have greatly improved intelligence—for example, in the case of overhead photography and chemical analysis of environmental samples. Yet intelligence on Iraq's nuclear program was caught flat-footed in 1991 (and, of course, the IAEA completely missed the weapons program) and then was wildly off the mark in 2003. North Korea's uranium enrichment facilities have not been found. And Iran's enrichment plant was located after a dissident Iranian group specified the coordinates.[26] There are probably more people around today skilled in the arts of reprocessing and they have more information to work with. Additionally, we have learned that NPT membership does not guarantee performance—Iraq and North Korea violated the Treaty, and very likely Iran did, as well.

Since the publication of the Oak Ridge report other studies have been published that also consider the issue of the credibility of clandestine small-scale LWR reprocessing.

The subject of clandestine plutonium extraction was addressed in a 1995 Livermore report.[27] The report states that "plutonium can be separated from spent nuclear fuel with modest facilities and equipment," which tracks fairly closely with the conclusions of the Oak Ridge study.

In 1996 a Sandia National Laboratories team produced a design for a small plant for reprocessing LWR spent fuel quickly and secretly.[28] They characterized it as "…a relatively simple process that might be operated by an adversarial group in makeshift or temporary facilities such as a remotely located warehouse or a small industrial plant." The estimated preparation lead-time for producing the first kilograms of plutonium employing a staff of 6 technicians was about 8 months, which is even more optimistic than that of the Oak Ridge team about 20 years earlier.

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[26] According to rumor they served as a conduit for Israeli intelligence.

[27] W.G. Sutcliffe and T.J. Trapp, Eds., *Extraction and Utility of Reactor-Grade Plutonium for Weapons (U)*, Lawrence Livermore National Laboratory, April 27, 1995. The report is based on briefings given to the National Academy of Sciences' Committee on International Security and Arms Control during its study of the management and disposition of excess weapons plutonium. The full report is classified. The material used here is taken from an unclassified summary.

[28] J. P. Hinton et al., *Proliferation Resistance of Fissile Material Disposition Program (FMDP) Plutonium Disposition Alternatives: Report of the Proliferation Vulnerability Red Team,* Sandia National Laboratories, Report no. SAND97-8201, October 1996, Section 4.1.1.3 Recovery Process for LWR or MOX Spent Fuel, pp. 4-3 – 4-9. The work was done in the context of assessing the proliferation resistance of various alternatives for the disposition of stocks of weapons-grade plutonium that have been declared excess to national security needs by the US and Russia.

The Oak Ridge and Sandia proposals are both bare bones paper designs about which some reservation is appropriate. Both processes differ in some important respects from the standard PUREX process flow sheet. Also, no information is provided on crucial matters such as control instrumentation. This is not a process that inexperienced, even if competent, persons could handle easily. Spent fuel reprocessing is among the most sophisticated chemical engineering processes and making it work takes a good deal of know-how. But even the critics of the practicality of the Oak Ridge design all thought that the highly skilled and experienced Oak Ridge team could have made it work.

In this context it is also worth mentioning a much earlier commercial design that does not cut corners. In the late 1950s the Phillips Petroleum Company made a very detailed feasibility study of a small PUREX plant designed to reprocess per day about one-third ton of LWR spent fuel. It was designed to handle spent fuel whose burnup is roughly that of current LWR fuel after one refueling cycle (as opposed to the normal three).[29] The plant's head end used an underwater saw to free the fuel pins from the fuel assembly and a mechanical shear to chop individual fuel pins into small pieces. One of the striking features of the plant is its small size, about 65 feet square.[30]

It is credible for states with an industrial base and nuclear infrastructure needed to operate LWRs to construct and operate such reprocessing plants "without cutting corners" to produce significant quantities of plutonium as quickly as possible without detection.[31] Whether or not a country might opt for a "quick and dirty designs," it would have the possibility to of building one with a lower probability of malfunction and with smaller telltale releases. Details in support of these conclusions are provided in Appendix 2.

Before we consider the policy implications of the possibility of quick and dirty reprocessing for the use of LWRs let us pursue this question of the suitability of LWR plutonium for weapons.

Contrary to conventional wisdom, LWRs can be a copious source of near-weapon grade plutonium suitable for bombs

Since the beginning of the nuclear age it has been difficult to rationalize the widespread use of uranium-fueled reactors that—inescapably—produce plutonium, which is one of the two key nuclear explosives. The 1946 Acheson-Lilienthal plan, that required "dangerous" nuclear activities to be used only under international

[29] The Phillips design was for spent fuel with an average burnup of 10,000 MWd/t.

[30] H. Schneider et al., *A Study of the Feasibility of a Small Scale Reprocessing Plant for the Dresden Nuclear Power Station,* Report IDO-14521, Phillips Petroleum Company, April 28, 1961. Available from the National Technical Information Service (NTIS), Washington, DC.

[31] In our judgment, it is not credible that a sub-national group with the type of skills enumerated in the Sandia report could construct and operate even the simplified plants outlined in the Oak Ridge and Sandia reports.

auspices, did contemplate that uranium-fueled reactors would be in national hands. The authors' rationale was that the plutonium produced by these reactors could be "denatured" to make it unusable for military application. They didn't spell out the scientific basis for the denaturing they had in mind but it appears to have been the idea that the isotopic composition of plutonium formed in reactor fuel that had been irradiated for an extended time would be unusable for bombs. The notion is wrong but it is understandable that it would appear plausible at that early point.

During the World War II Manhattan Project it was discovered that just as a uranium-238 nucleus can absorb a neutron to form plutonium-239, so the plutonium-239 can absorb a neutron to form plutonium-240.[32] The longer the uranium fuel is irradiated in a reactor to form plutonium-239, the more of the plutonium-239 will convert into plutonium-240. This isotope fissions spontaneously and releases neutrons which tend to "pre-initiate" nuclear explosions as soon as the mass of nuclear explosive is in a "critical" configuration. It is this effect that made it impossible to use plutonium in a gun-type nuclear device (as it is possible to do with uranium-235 and was in fact the design used in the Hiroshima bomb). It was not possible to use a gun to bring two pieces of plutonium together fast enough. As soon as they got close enough to form a critical mass the spontaneous neutrons from plutonium-240 would set off a chain reaction whose heat would blow the pieces apart before the nuclear yield was significant.

It was this stumbling block that led to a focus on the implosion design—using high explosives to drive the nuclear explosive rapidly inward to form a dense super-critical mass. The speed of the process reduces the chance of pre-initiation. Even so, an unwanted that appears early in the compression can set off a premature chain reaction and limit the yield to a "fizzle yield." To reduce the chance of this the plutonium used in the first US warheads was produced in uranium fuel that had been lightly irradiated to keep the fraction of plutonium-240 at about 1 percent. In an implosion design, however, the fizzle yield, while not optimal, is still large—in the case of the first Trinity explosion it was about 1 kiloton, which it is useful to recall is one thousand *tons* of high explosives. In short, the trouble with the idea that higher plutonium-240 content would only produce a fizzle is that the fizzle yield is still pretty large.

Since the time of the Acheson-Lilienthal report, weapons designers have learned to work around the pre-initiation problem to achieve high yields with the lower quality plutonium. In time, as advanced weapon designs made the pre-initiation problem more or less irrelevant, the US weapons complex settled on plutonium with a plutonium-240 content of about 7 percent (and thus a plutonium-239 content of about 93 percent) as a reasonable compromise between quality and production rate. Plutonium of this isotopic content, or something close to it, say in the range of 90 percent, is termed weapons-grade.

[32] In turn the plutonium-240 absorbs neutrons to form plutonium-241. Plutonium-240 is not fissionable by neutrons in an LWR core but plutonium-241 is.

That the denaturing argument was not valid in technical terms did not dissuade those who found it convenient for rationalizing commercial plutonium activities from using it. The idea permeated the technological permissiveness of the 1950s Atoms for Peace program when it came to plutonium extraction and application. One could say that the false security of denaturing plutonium underlay the whole Atoms for Peace program.[33]

After the Indian nuclear explosion in 1974 that used high isotopic purity plutonium extracted from the spent fuel of a Canadian-supplied research reactor, the United States woke up to fact that misinformation in the international nuclear community downplaying the dangers of commercial plutonium was standing in the way of effective security measures. By this time commercial LWR fuels were fairly highly irradiated during commercial operation and the notion gained currency that the plutonium in such fuel, "reactor-grade" plutonium was not usable at all for bombs. The Ford administration felt compelled to brief foreign nuclear leaders to correct this view and arranged for Dr. Robert Selden of the Livermore laboratory to present the material. [34] Selden's summary slide stated: "Reactor grade plutonium is an entirely credible fissile material for nuclear explosives."[35]

But despite numerous reports and analyses that addressed the issue and arrived at the same result, the controversy would not die because so much was at stake commercially and bureaucratically in the hundreds of LWRs deployed throughout the world and, in some countries, in the reprocessing and recycle of LWR plutonium. [36]

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[33] In time the Atoms for Peace program permitted the US export of large quantities of HEU to fuel foreign research reactors. There was no question about the dangers of HEU as a bomb explosive. As Albert Wohlstetter once said, "The nuclear bureaucracy knew what they were saying about denaturing plutonium was false so they didn't think it mattered if they exported HEU, too."

[34] The author returned from a 1976 European trip and reported to the National Security Council (NSC) staff that the IAEA Director General and his staff believed plutonium from commercial LWR fuel was not usable for weapons, and that the top German officials, then negotiating a nuclear sale to Brazil that involved reprocessing technology were adamant in this view. They thought that US statements to the contrary were made for commercial, rather than security, reasons. This report to the NSC led to the November 1976 Selden briefings for select top international nuclear figures that included Sir John Hill, head of the UK Atomic Energy Authority, M. Andre Giraud, the head of the French Atomic Energy Commission (CEA), Dr. Eklund, Director General of the IAEA, and Mr. Ryukichi Imai, a senior advisor on nuclear affairs to the Japanese Foreign Ministry.

Shortly before this the author, then a commissioner of the U.S. Nuclear Regulatory Commission, gave a speech at the Massachusetts Institute of Technology in which he said the following: Of course, when reactor-grade plutonium is used there may be a penalty in performance that is considerable or insignificant, depending on the weapon design. But whatever we once might have thought, we now know that even simple designs, albeit with some uncertainty in yield, can serve as effective, highly powerful weapons—reliably in the kiloton range.

Victor Gilinsky, "Plutonium, Proliferation, and Policy," Remarks given at MIT, November 1, 1976 (NRC Press Release No. S-14-76)

Robert W. Selden, "Reactor Plutonium and Nuclear Explosives," Lawrence L Livermore Laboratory, undated slides.

See, for example, *Management and Disposition of Excess Weapons Plutonium*, National Academy of Sciences, National Academy Press, Washington, 1994. The Executive Summary, p. 4, states:

Rather than pursue this argument, which seems to have reached a stalemate, the approach we take here is to circumvent it by pointing out that LWR can also be copious producers of near-*weapons-grade* plutonium and even of weapons-grade plutonium itself. To explain the difference between our point of view and the conventional one as regards LWR plutonium we have to say a few words about the way an LWR is fueled.

A PWR core, to use a specific example, may contain about 75 tons of uranium.[37] The operators refuel the reactor about every 18 months. The fuel elements normally stay in the reactor for three fuel cycles, or about sixty months. But the refueling schedule is staggered so that at each refueling the operators take out one-third of the fuel assemblies—the ones that have been in the core for three cycles—and replace them with fresh fuel.

The conventional characterization of the isotopic composition of the plutonium contained in LWR spent fuel—so-called reactor grade plutonium—is of fuel that has been in the reactor for a full three fuel cycles. This is the LWR plutonium over which arguments have raged concerning its usability for weapons. Such fuel indeed has a high content of isotopes other than the most desirable plutonium-239. There is a certain logic in this characterization in that most of the LWR spent fuel in storage pools at LWRs contains this type of plutonium, and the LWR-bred plutonium that has been separated in reprocessing plants is more-or-less of this composition, too.[38]

But an LWR operator seeking better plutonium for weapons is not constrained to using the plutonium from irradiated fuel assemblies. For example, if the operator of a newly operating LWR unloaded the entire core after 8 months or so the contained

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"Plutonium of virtually any isotopic composition, however, can be used to make nuclear weapons. Using reactor-grade rather than weapon-grade plutonium would present some complications. But even with relatively simple designs such as that used in the Nagasaki weapon—which are within the capabilities of many nations and possibly some subnational groups—nuclear explosives could be constructed that would be assured of having yields of at least 1 or 2 kilotons. Using more sophisticated designs, reactor-grade plutonium could be used for weapons having considerably higher yields.

A report of a US-Japanese arms control study group arrived at the following statement:

The participants agreed that as a technical matter, with some additional efforts, a country can produce nuclear weapons using any kind of plutonium, using well-known technologies.

The members of the working group on reactor-grade plutonium included Hiroyoshi Kurihara, former Executive Director of the Japanese Power Reactor and Nuclear Fuel Development Corporation, Atsuyuki Suzuki, Professor of Nuclear Engineering at the University of Tokyo, and Victor Gilinsky. The overall report was published as *Next Steps in Arms Control and Non-Proliferation,* Carnegie Endowment for International Peace, 1996. See also Richard L. Garwin, "Reactor-Grade Plutonium Can be Used to Make Powerful and Reliable Nuclear Weapons: separated plutonium in the fuel-cycle must be protected as if it were nuclear weapons", August 26, 1998, available on www.fas.org.

[37] In nearly 200 fuel assemblies containing over 40,000 fuel rods.

[38] There is an exception worth noting. Some fuel is removed early from a reactor, generally because it is not performing properly, possibly because it is leaking radioactive material. The plutonium is such fuel will have a composition higher in plutonium-239 than the fuel that remains in the reactor longer.

plutonium would be weapons-grade—with a plutonium-239 content of about 90 percent. The amount of plutonium produced would be about 2 kilograms per ton of uranium, or about 150 kilograms per 8 month cycle.[39] This comes to about 30 bombs' worth. Does a would-be nuclear weapon state need more? If the short refueling cycles were continued the annual output of weapons-grade plutonium would be about 200 kilograms (allowing for refueling time), but this would require a large amount of fresh fuel. Such a progression involves a considerable departure from commercial operation and for an NPT member would signal Treaty violation. Still, it illustrates what a standard LWR can do when viewed as a plutonium production reactor.

The small Oak Ridge-designed reprocessing plant described earlier would have difficulty keeping up with this kind of reactor operation for long because it wasn't designed for reliable long-term operation. But suppose we just consider one run of 8 months. The small reprocessing plant was designed to handle about one assembly per day. To reprocess the entire core of 177 fuel assemblies in our example would take about six months of operating time plus some realistic amount of down time. In less than a year the would-be nuclear weapons country would have about 30 bombs' worth. That is quite an arsenal.

Consider a mode of operation closer to commercial operation. Because of the staggering of the refueling, at any refueling once the reactor has been operating for a time, one-third of the core (about 25 tons in our example) will have been in the reactor for three cycles, on-third will have been in the reactor for two cycles, and one-third will have been in the reactor for one cycle. The plutonium in the one-cycle fuel would have a much higher content of the most desirable plutonium-239 isotope than the three-cycle fuel—over 80 percent as opposed to about 55 percent. This plutonium is often called "fuel-grade" to distinguish it from the better weapons-grade stuff and the less desirable reactor-grade.[40] At each normal refueling the operator has available 25

[39] The details come from a chart, "Trends in LWR Pu Production", in a set of briefing slides, Light-Water Reactor Fueling Handling and Spent Fuel Characteristics, J.A. Hassberger, Lawrence Livermore National Laboratory, dated February 26, 1999. The briefing was presented to a Stanford University/Livermore Laboratory group preparing a report on the problems of safeguarding the LWRs to be supplied to North Korea under the 1994 US-DPRK Agreed Framework, Verifying the Agreed Framework, Michael May, General Editor, UCRL-ID-142936/CGSR-2001-001, April 2001

[40] The distinction is made in a useful paper by Bruno Pellaud, a former deputy director general of the IAEA and head of the IAEA Department of Safeguards. Bruno Pellaud, "Proliferation Aspects of Plutonium Recycling," Journal of Nuclear Materials Management, Fall 2002, Volume XXXI, No. 1, p. 30. He provides the following table of "plutonium mixtures for explosive purposes:"

tons of uranium containing about 5 kilograms plutonium per ton, or about 125 kilograms of plutonium with about 80 percent plutonium-239, not bad material for bombs. (There is more plutonium per ton than in the earlier example because the irradiation time is longer.) In fact, this characterization understates the usefulness of the one-cycle material for weapons because what really counts is the amount fissile fraction—the sum of plutonium-239 and plutonium-241—which in the case of spent fuel removed after one refueling cycle is nearly 85 percent.

Even more interesting is an example we will consider in detail—the situation at the start of operation. We shall examine the weapons characteristics of the plutonium produced in the first core after the start of operation and will compare that with the characteristics of weapons-grade plutonium. At the end of the first refueling cycle *all* the fuel will have been irradiated for only one cycle. The first cycle is also normally a bit shorter than the later ones so the plutonium is even higher in plutonium-239 content—about 84 percent plutonium-239. At the end of the first cycle the 75-ton core will contain about 330 kilograms of plutonium, or more than 60 weapons' worth. According to its designers it would take the Oak Ridge plant about 150 days of operation to reprocess the entire core.

One might say that this kind of operation in violation of the NPT would not be allowed, that the international community, or perhaps some country, would step in to prevent it. Yet North Korea is believed to have reprocessed the missing 8,000 fuel rods from its small reactor and there has been no world response. Suppose they had by now had in operation the LWRs that the United States promised them under the 1994 US-DPRK Agreed Framework and had operated them in the way outlined above. Can we be confident that there would be international action to enforce the NPT rules?

How good would the first core plutonium be for weapons? The usual standard of comparison is US weapons-grade plutonium, which is nominally taken to contain about 93 percent plutonium-239. How different then are the weapons characteristics of the plutonium in the fuel after the first cycle as compared with weapons-grade plutonium?

Grades	Pu-240	Usability
Super grade (SG)	<3 percent	Best quality
Weapon grade (WG)	3-7 percent	Standard material
Fuel grade (FG)	7-18 percent	Practically usable
Reactor grade (RG)	18-30 percent	Conceivably usable
MOX grade	>30 percent	Practically unusable

The categories are to some extent arbitrary, but they make for useful peg points. Pellaud's aim is obviously to vindicate the use of MOX grade fuel. Still, he makes helpful points along the way.

NPEC asked Dr. Harmon W. Hubbard, an experienced physicist who had worked on nuclear weapons at the Livermore Laboratory, and served for several years on the panel that evaluated foreign nuclear explosions for the U S government, to examine the issue relying on publicly available information. His paper, "Plutonium from Light Water Reactors as Nuclear Weapon Material," May 2003, is appended to this report. All of the data and theory used in his paper have been in the public domain for many years.

The subject of illegal construction of nuclear explosives was earlier reviewed in technical detail by J. Carson Mark, late T-Division head at Los Alamos National Laboratory (LANL), in a 1990 report.[41] He concluded that the difficulties encountered in using reactor-grade plutonium for explosive fabrication differ only in degree, but not in kind, from the problems in using weapon grade plutonium. In his 2003 paper, Hubbard develops the calculations for the better grade of plutonium available in spent fuel after irradiation for the first fuel cycle to see how this plutonium compares in weapons use with weapons-grade plutonium.

Hubbard assumes the simplest design for a first effort explosive, one consisting of a solid plutonium spherical core. This core is very nearly a critical mass when surrounded by a high density tamping (that is, neutron reflecting) material which is taken here to be uranium. This larger sphere is then encased in the high explosive system which is designed to provide a converging spherical shock wave that would compress the assembly for a few microseconds before it flies apart from the force of the nuclear explosion.

Then, based on the published Trinity data, Hubbard calculates probabilities of yields to be expected from reactor grade plutonium. He then extends these probabilistic yield estimates to improved implosion technology by adjusting a parameter in the model. One might think of these steps as increases in the speed with which the core is compressed, although some other aspects of design are involved, as well. He carries out the yield calculations for first-cycle LWR plutonium and for weapons-grade plutonium.

Although the weapons-grade plutonium has less of it, both materials have some plutonium-240 that spontaneously emits neutrons. These spontaneous neutrons can start the chain reaction prematurely and cause the nuclear explosion to blow the bomb apart before the plutonium core reaches maximum compression. Hubbard takes weapons-grade material that contains 6 percent plutonium-240 (and thus 93.5 percent plutonium-239 and 0.5 percent plutonium-241, which is more-or-less equivalent for explosive purposes) and first cycle LWR plutonium contains 14 percent plutonium-240 (and 84 percent plutonium-239 and 2 percent plutonium-241). In both cases there is some spread in resultant yields—more in the case of first cycle LWR plutonium because it contains more plutonium-240, but not dramatically so.

[41] J. Carson Mark, "Reactor Grade Plutonium's Explosive Properties, Nuclear Control Institute, 1990.

The following Table sums up the results of the calculations. The entries in the first three columns give the probabilities that the design will achieve an explosive yield in the ranges: 1 to 5 kilotons, 5 to 20 kilotons, and greater than 20 kilotons (the nominal yield of the 1945 Trinity shot in the New Mexico desert). The first row gives the probabilities for the Trinity design using the type of plutonium that was actually used at the time. This might be termed "super-grade" as the plutonium-240 content was only about 1 percent. The following three rows provide the same estimates for three levels of bomb technology: the 1945 Trinity technology, a two-fold (100 percent) improvement in that technology, and a three-fold improvement (200 percent). In each case the results are presented for weapons-grade plutonium and for first-cycle LWR plutonium (bold). So, for example, the probability that a bomb using 1945 Trinity technology and first-cycle LWR plutonium would exceed 20 kilotons in yield is 12 percent. If we drop to the next row—that provides the probabilities for a two-fold improvement in the 1945 technology—we find that the probability of exceeding 20 kilotons becomes 34 percent, or about one-third. And if we drop to the last row—that assumes a three-fold technology improvement—the probability of exceeding 20 kilotons with first cycle LWR plutonium is 49 percent, or almost one-half.

TABLE:

Probability of Achieving Various Explosive Yields and the Expected Yield
for 1945 US Technology and for Two Improved Levels
Using 1st Cycle LWR Plutonium and Weapon Grade Plutonium (WGPu)

	Probability that yield is between 1 and 5 kilotons %	Probability that yield is between 5 and 20 kilotons %	Probability that yield is not less than 20 kilotons %	Estimated *average* yield kilotons
1945 Trinity shot 1% plutonium-240 (**actual**)	*4*	*6*	*88*	*19*
Calculated:				
Trinity technology WGPu 1st cycle LWR	21 **36**	23 **23**	44 **12**	13 **5**
Trinity technology x 2 WGPu 1st cycle LWR	12 **25**	14 **25**	66 **34**	15 **10**
Trinity technology x 3 WGPu 1st cycle LWR	8 **18**	12 **22**	76 **49**	16 **12**

The last column is especially interesting. It lists rough estimates of the average yield of the specific weapon design and plutonium quality combinations listed on the left. Even though there is some uncertainty in yield, the average yields are quire substantial, and the differences between weapons-grade and first-cycle LWR plutonium becomes very much less as technology is improved (that is, moving down in the Table).

A country attempting to build nuclear weapons today could take advantage of the wide availability of declassified nuclear weapon information and the enormous increases in computing and other technological aids since the 1945 Trinity shot. It seems reasonable to attribute to a new group at least a doubling of the efficacy of the Trinity implosion system through the use of advances in implosion technology, initiators, and better core design.[42] At this level of design a would-be nuclear state

[42] An initiator is a contrivance that injects neutrons into the device at the proper moment—when the nuclear explosive has been compressed to a super-critical state—to start the explosive chain

could use first-cycle LWR plutonium to produce fission weapons with a modestly reliable yield around an average of about 10 kilotons. A weapon of this design would have about a 70 percent chance of exceeding 5 kilotons. It should be remembered that the minimum, or fizzle, yields will likely be at least as large as that of Trinity—around 1 kiloton—and that this guaranteed yield is already quite destructive. Considering that the destructive radius of the explosions varies roughly as the third root of the yield, the differences between the performance of weapons with first-cycle plutonium and those with weapons-grade plutonium are not very great.

LWRs are less proliferation-resistant than usually assumed in policy discussions and are dangerous in the wrong hands

What emerges from this discussion is that LWRs are not the proliferation-resistant technology they have been made out to be. Forgotten from the earlier days of nuclear energy is that LWRs can produce large quantities of near-weapons-grade plutonium, and that a country bent on making bombs would not have much trouble extracting it quickly in a small reprocessing operation, and possibly even keep the operation secret until it had an arsenal.

The possibility of clandestine centrifuge enrichment exists even in the absence of a nuclear power program. Pakistan pursued enrichment before it had any reactors that used enriched uranium fuel. But a nuclear power program provides resources and makes it easier to mask a clandestine enrichment program. There is however one respect in which the presence of an LWR offers added opportunities for clandestine enrichment. Fresh LWR fuel, which typically has an enrichment level (uranium-235 concentration) of 4 percent can, after crushing and fluorination, itself be used as feed for a clandestine gas centrifuge enrichment operation. Use of such low enriched feed, as opposed to natural uranium with a uranium-235 concentration of less than one percent can reduce the enrichment effort by a factor of five.

In other words, LWRs themselves pose a large security issue if they are in the wrong hands. It would be useful for informing U.S. policy to gain a clearer understanding of the extent to which near-weapons grade plutonium is readily available from these reactors. Two specific examples stand out of nuclear policy inadequately informed by an understanding of the technical possibilities.

The first is the confused and inconsistent policy toward North Korea which included promising, as part of a 1994 US-DPRK nuclear deal, two large LWRs whose plutonium production capacity turned out to larger than that of all the indigenous North Korean reactors they were supposed to replace. When this came to light the State Department insisted that the North Koreans would not have the technology to extract the LWR plutonium.

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reaction. If the neutrons arrive too early, we get a reduction in yield, at worst a fizzle. If the neutrons come too late, there may be no nuclear explosion at all.

The second example involves Iran. The United States opposes Russian supply of LWRs at Bushehr, but does so on the grounds that the nuclear project can serve as a cover for clandestine nuclear activities. There does not seem to be recognition yet that the LWRs could themselves be a copious source of plutonium for weapons, or their possible link with enrichment.

Altogether, underestimating the production capacity of LWRs for weapons-grade and near weapons-grade plutonium and overestimating the difficulty of "quick and dirty" reprocessing have contributed to poor decisions.

There are several broad policy implications of the weapons-grade production capability of LWRs:

1. *We need to reassess the role of LWRs in international programs.* They are not for everyone and we should be cautious about promoting their construction in worrisome countries. This is not a benign technology. At a minimum we should not support such technology where it is not clearly economic.
2. *Clandestine enrichment and reprocessing*. The IAEA and national intelligence has constantly to be on the lookout for clandestine plants because they can rapidly change the security equation. There needs to be much closer accounting of LEU fuel in view of its significance as possible feed for clandestine enrichment.
3. *IAEA inspection of LWRs*. IAEA inspection frequencies for LWRs to check on fuel inventories and refueling need adjustment upward in countries of concern from the point of view of potential bomb-making to take account of possible undiscovered clandestine reprocessing. Because of inevitable IAEA resource limitations it is necessary for the agency to concentrate the inspection where they are most important. It would help to gain support for such a system if it were possible to develop some objective way of defining "countries of concern." The IAEA should take greater account of the presence of weapons-grade plutonium or near weapons-grade plutonium in spent fuel pools and storage in devising its inspections.
4. *Enforcement*. The NPT members must enforce the IAEA inspection system. An important purpose of IAEA safeguards is to deter nuclear weapons activities—by would-be nuclear weapon countries—by the threat of early detection. This assumes there will be a strong reaction to such an early detection of illicit activity. If would-be bomb-makers conclude they have nothing to fear because the international community is not likely to react to their violations, the whole system of control falls apart.

APPENDIX 1

The Gas Centrifuge and Nuclear Proliferation

By Marvin Miller

Current concern stems from revelations about Pakistani spread of gas centrifuge technology

The current concern about the use of gas centrifuges to produce highly-enriched uranium (HEU) for nuclear weapons is due to the activities of the Pakistani metallurgist, A. Q. Khan, who acquired knowledge about centrifuge technology while employed in a URENCO centrifuge plant in the Netherlands in the 1970s.[1] Upon his return to Pakistan, Khan and his associates implemented the stolen process in the Kahuta plant to produce HEU for weapons. Pakistan subsequently transferred the technology to Iran, North Korea, Libya and perhaps other countries.

In the following, we first summarize some technical facts about centrifuges that are relevant to its use to produce HEU for weapons, and then discuss the proliferation connection in more detail.[2]

Gas centrifuge technology basics

The gas centrifuge for uranium enrichment consists of a thin-walled cylinder (the "rotor") with a large length-radius ratio, which is spun vertically at very high speeds inside a stationary vacuum casing. The rotor is made of high strength–to-density materials in order to withstand the stress due to the very large centrifugal force. It is suspended at the top and bottom by two special bearings which provide for almost frictionless rotation.

The gas that is used is uranium hexafluoride (UF_6) which has desirable properties for enrichment. In particular, fluorine has only one isotope, so the variation in molecular

[1] The development of the gas centrifuge as a practical device for enriching uranium after World War II is largely due to the work of the German engineer, Gernot Zippe, which led directly to the commercialization of the centrifuge process for the production of low-enriched uranium (LEU) for power reactors by the URENCO consortium, consisting of the UK, Germany, and the Netherlands.

[2] The best single technical reference for uranium enrichment in general and centrifuges in particular is the text by Manson Benedict, Thomas Pigford, and Hans Levi, *Nuclear Chemical Engineering,* 2nd Edition, McGraw-Hill, 1981, hereafter referred to as NCI. The discussion of the gas centrifuge is on pp. 847-875. A good popular account of how centrifuges work with a profile of Zippe can be found in an article in the *New York Times* by William Broad, "Slender and Elegant, It Fuels the Bomb", March 23, 2004.

masses depends only on the difference between the masses of uranium isotopes. A hexafluoride plant is thus a necessary part of any enrichment enterprise.

In a centrifuge the gas to be enriched is introduced near the middle of the rotor and then rotates with it. The rapid rotation confines the gas molecules to the region adjacent to the wall with the heavier U-238 isotope being slightly more abundant than the lighter U-238 isotope closer to the wall. This radial separation of the isotopes which provides the basis for centrifuge enrichment is significantly enhanced by an axial flow of enriched (light) and depleted (heavy) fractions of UF_6 gas in opposite directions between the bottom and the top of the rotor. The enriched product and the depleted waste ("tails") streams are withdrawn at the ends of rotor.

Since each centrifuge performs a limited amount of enrichment, in practical application many units are couple together to produce the desired enrichment. The product is about 4 % U-235 for LWR fuel, and about 90% U-235 for bomb explosives. The number of units in series, or "stages," depends on the individual characteristics of the centrifuges. Typically, about 10-30 would be needed to enrich to LEU levels, compared to more than 1,000 for the gaseous diffusion process. . The number of units in parallel depends, for a given centrifuge design, on the desired throughput—more units in parallel means more product. The stages form a "cascade," which could consist of thousands of centrifuges, or even many more in large plants.

There exists a standard technical measure—"separative work"—of the amount of enrichment required for a particular application. The capacity to perform separative work, or separative capacity, can be calculated for each individual separating element, such as a centrifuge, or an entire enrichment plant containing many such elements.[3] On this basis we can calculate how many units we need to perform a certain job *in a given time* or, conversely, what a given plant can accomplish.

As an example of the use of these concepts, consider using centrifuges with an individual nominal separative capacity of 5 kg separative work units per year (SWU/yr). This is roughly characteristic of the P2 design now used in Pakistan. How many of these would be needed to produce 100 kg/yr of 90% enriched uranium, about four bombs' worth, starting with natural uranium as feed and rejecting waste or tails at a concentration of 0.3%?[4] The calculation is facilitated by using the separative work calculator available on the web.[5] We find that about 20,000 kg SWU/yr are required to produce 100 kg of 90% enriched uranium/yr with the feed and tails as specified. Since each centrifuge can perform 5 kg SWU/yr at full capacity, 4000 such centrifuges would be required.

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[3] The units of separative work and capacity are the units of flow, i.e., kilograms or tons/yr. This can be confusing because we are not talking about amounts of material. For a definition and discussion of these terms as well as the theory of enrichment cascades, see NCI, op. cit., pp. 644 – 677.

[4] The concentration of the waste (tails) stream has an important influence on the amount of separative work needed. If we reject material at a relatively high concentration of desired product—if we just skim the cream—we need less separative work but more feed material. If we do more separative work by scraping the barrel, so to speak—throwing away less of the desired component, we need less feed material.

[5] At www.urenco.de/trennarbeit/swucal_e.html

Obviously, the larger the separative capacity of an individual centrifuge, the smaller the number required for a given enrichment task. While this by itself wouldn't justify developing larger SWU centrifuges, it turns out that larger SWU machines also have smaller specific investment costs ($/SWU/yr), and hence are economically advantageous. The separative capacity of a centrifuge scales as V^2L, where V is the peripheral speed and L the rotor length. Getting higher unit separative capacity is difficult because the peripheral speed is limited by the centrifugal stress the rotor material can withstand. And the length is limited by the increased flexion of long rotors. The long thin rotor has certain characteristic vibrations, just like a violin string, and flexion at "resonant" speeds can wreck the rotor or its bearings.

The strength problem can be overcome by using higher strength–to-density materials. Special "maraging" steels (MS) allow rotation at peripheral speeds of 500 m/sec; carbon fiber-resin composites (CFRC) allow speeds in the range of 700 – 800 m/sec. The aluminum (Al) alloys used in early centrifuges permit maximum speeds of about 350 m/sec. A low-tech solution to the problem of flexural vibrations with long rotors is to break up the length of the rotor with short, thin flexible joints located so as to take up the energy of the vibrations at the resonant speeds. While this method is still used in relatively short Al and MS centrifuges, longer, faster CFRC machines instead use special drives that can accelerate the rotor rapidly through the resonances before the amplitude of the vibrations grows sufficiently to damage the machine. The technology is quite sophisticated.

Table 1 provides a comparison of some of the important characteristics of current centrifuge designs based on unclassified sources (and educated guesses). The two major suppliers of LEU produced by centrifuges on the international enrichment market are URENCO and Russia. They both use CFRC as the rotor material, as does the US R&D program and Japan in its centrifuge plant that partially supplies its own LEU needs. A centrifuge plant has never been built in the US, although there are now plans to do so.

Centrifuges using Al and MS rotors such as the P1 and P2 designs are not commercially competitive. However, P2 centrifuges operate in Pakistan, and in India and Brazil. And PI centrifuges—the original URENCO design and the one first implemented in Pakistan by A. Q. Khan—is still the logical "starter" technology for countries such as Iran that might have trouble making rotors of more advanced materials. Maraging steel is much more difficult to work than aluminum. For now, manufacturing CRRC machines is beyond the technical capability of states of current proliferation concern such as North Korea and Iran.[6] But P1 and P2 centrifuges have been used to make HEU for weapons. More machines are needed than with more advanced designs, but once the technology is mastered, they can be mass-produced.

[6] But not necessarily for countries with a stronger industrial base, e.g., Brazil, India, and Pakistan.

Table 1
Basic Parameters of Contemporary Centrifuges

Type	P1	P2	Russia	URENCO	US
Rotor Material	**Al**	**MS**	**CFRC**	**CFRC**	**CFRC**
Speed (m/sec)	**350**	**500**	**700**	**700**	**> 700**
Length (m)	**1-2**	**1**	**< 1**	**3-4**	**12**
kg SWU/yr	**1-3**	**5**	**10**	**40**	**300**

Proliferation risks associated with gas centrifuge technology

There are three major risks associated with the operation of centrifuge plants: (1) secret use of a declared, safeguarded LEU plant to produce HEU or excess LEU covertly; (2) construction and operation of a clandestine plant to produce HEU; and (3) conversion of a declared, safeguarded LEU plant to HEU production following breakout. We discuss each in turn briefly in the following.

1) The basic "Hexapartite" safeguards approach for centrifuge plants was developed during the early 1980s by a group of six countries—Germany, the UK, and the Netherlands (the URENCO states), and the US, Japan and Australia. It consists of two sets of activities:
   (a) verifying the uranium material balance by measuring the amount of uranium as UF_6 introduced into the plant as feed material and withdrawn as enriched product and tails; and
   (b) verifying that no material beyond the declared enrichment level, in particular, no HEU is being produced.

   While (a) doesn't require inspector access to the cascade halls where the centrifuges are installed, (b) does, and the inspection procedures were designed to provide an element of surprise in order to deter production of HEU between routinely scheduled inspections, while also accounting for the plant operator's concern about the inspector's gaining knowledge of proprietary information relating to the construction and operation of the centrifuges. Various technical difficulties have been encountered over the years in applying (b) at specific plants. But confidence in the IAEA's ability to detect illicit production of HEU has improved dramatically since 1995 with the introduction of sampling and subsequent analysis of particles deposited on surfaces in the cascade area as a standard safeguards tool. Since release of particles to the plant environment is difficult to avoid, and the analysis is highly precise, environmental sampling has emerged as a significant deterrent to clandestine HEU production in a declared LEU plant. On the other hand, current safeguards procedures cannot detect the production of LEU in excess of what the plant operator declares to be the normal

production rate,[7] and this can significantly increase the difficulty of detecting a clandestine plant as we discuss next.

2) The much smaller energy consumption and process area characteristic of centrifuges plants compared to gaseous diffusion plants of the same separative capacity make the former much more difficult to detect. For example, a centrifuge plant with a separative capacity of 5,000 SWU/yr—sufficient to produce 25 kg/yr of 90 % enriched uranium—would likely require less than 100 kw of power and have a "footprint" of about 500 m^2 .[8] Moreover, detection by wide area environmental monitoring is also difficult because emissions from a centrifuge plant normally are very small. The plant operates under high-vacuum conditions so that leaks primarily lead to an inflow of air into the centrifuge equipment, not to a significant release of UF_6 from the system into the environment. Finally, as noted above, and illustrated in Table 2 below, if excess LEU is used as feed for the clandestine plant instead of natural uranium, the size of plant required to produce a given amount of HEU product is reduced significantly, especially if the tails concentration is also increased.

3) There is the possibility of breakout, i.e., takeover by a state of a declared, safeguarded LEU centrifuge plant, and reconfiguration of the plant to produce weapons grade uranium.[9] Because of its high separation factor compared to the gaseous diffusion process, the inventory of a centrifuge plant is much smaller than a diffusion plant, and so is the equilibrium time, i.e., the time required to achieve full production after plant startup or subsequent modification, e.g., from production of LEU to production of HEU by recycling the product material back as feed. Typically, the equilibrium time for LEU centrifuge and diffusion plants are on the order of hours and months, respectively.

[7] That is, the IAEA currently cannot verify the separative capacity of a centrifuge plant as stated by the operator. Thus, the operator could understate the plant's true separative capacity, and feed undeclared uranium to the cascades, producing excess, undeclared LEU after the inspectors have left the plant following their monthly visits which normally last several days.

[8] This is based on the use of 5 kg SWU/yr P2 centrifuges which each occupy an area of about 0.25 m2 and have an energy consumption of about 150 kw/kg SWU.

[9] Such reconfiguration can be accomplished in various ways depending on the plant design. For example, in Urenco plants, which consist of many parallel independent cascades each producing LEU product, the LEU product of one cascade can be used as feed material for another cascade, and so on, until the desired HEU product concentration is achieved. By contrast, centrifuge plants of Russian design are configured as one large cascade whose product and tails concentrations can be changed remotely from the plant control room by changing the valve connections on the centrifuges.

Table 2
Separative Work Requirements for Producing 90% Enriched Uranium as a Function of Feed and Tails Assays

Feed (%U-235)	**0.7% (Natural U)**	**4% (Reactor-grade U)**	**4%**
Product	**90% (Bomb-grade U)**	**90%**	**90%**
Waste or "Tails"	**0.3%**	**0.3%**	**2%**
Approx # of Centrifuges Required to produce 100 kg/yr of 90% enriched U	**4,000**	**1,200**	**700**

Notes

1. The % U-235 in the waste or tails stream is normally chosen by the enrichment plant operator on the basis of the relative cost of separative work and the cost of the uranium feed. The higher the relative cost of the former, the greater the % U-235 discharged as waste, and vice versa. The value in the first two columns is typical for commercial enrichment plants given the current relative costs of separative work and natural uranium.
2. The number of centrifuges depends on the amount of product required per year and the individual separative capacity of the centrifuges. For the former, we have chosen 100 kg or 4 significant quantities" (SQ), where one SQ is the approximate amount needed to make a bomb according to the IAEA. For the latter, we have assumed the centrifuges used have a capacity equivalent to those reportedly now used in Pakistan about 5 SWU/yr. However, the ratio of the numbers in the columns would be the same irrespective of the amount of product and the capacity of the individual centrifuges. That is, only about 30% of the separative capacity or the number of centrifuges is required if the feed is reactor-grade U instead of natural U and the tails U-235 is the same, while less than 20% of the separative capacity is required if the tails U-235 is also increased, in this example to 2%.
   In sum, centrifuge enrichment is a major proliferation vulnerability, especially if declared LEU plants are allowed to proliferate. Even if such a plant is not reconfigured to quickly produce HEU after breakout, it can facilitate the construction and operation of a small clandestine HEU plant by providing a rationale for the legitimate acquisition of both centrifuge and associated technology, in particular that required to produce UF_6, as well as being a potential source of LEU feed as discussed above. With regard to the former, UF_6 production technology as well as centrifuge technology is covered in the so-called "Trigger List" contained in the Nuclear Suppliers Group (NSG) Guidelines for the Export of Nuclear Material, Equipment and Technology, issued by the IAEA as INFCIRC/254/Part 1, (latest version, October 1997). However, while transfers of centrifuge technology by the NSG states could trigger safeguards since, as noted,

there is an existing safeguards approach for centrifuge plants; no such approach currently exists for UF_6 production plants.[10]

Finally, we note that while a "reactors only" fuel cycle is not "proliferation proof" since the reactor spent fuel could be used as feed for a clandestine reprocessing plant, a similar consideration also holds at the front end. That is, the pellets of UO_2 in LWR fresh fuel could be crushed in a ball mill, and, without any further chemical processing, the resultant UO_2 powder could be fluorinated to produce UF_6, e.g., via the direct process:[11]

$$UO_2 + 3F_2 \rightarrow UF_6 + O_2.$$

By starting with low enriched UO_2 rather than with uranium ore, one avoids five of the eight basic processes that are required or getting from uranium ore to UF_6.[12]

[10] Although the IAEA has asked the US to investigate the feasibility of developing safeguards for UF_6 production facilities. Private communication from James Lemley, Brookhaven National Laboratory, September 2004.

[11] Private communication from Ron Ballinger, Nuclear Engineering Department, MIT, September 2004.

[12] See, for example, Samuel Glasstone, *Principles of Nuclear Reactor Engineering*, Van Nostrand, 1955, section 8.27.

APPENDIX 2

The Feasibility of Clandestine Reprocessing of LWR Spent Fuel

By Marvin Miller

Some nuclear fuel basics

Fresh LWR fuel is uranium enriched to about 4 percent uranium-235, the rest being uranium-238. The uranium is in the form of cylindrical uranium oxide pellets, less than a half inch in diameter, contained in 12 foot long, thin, and thin-walled, zirconium tubes (called cladding).[1] About 250 such tubes are bundled in a long square PWR fuel assembly containing about 500 kilograms of uranium.[2] During its stay in an operating reactor core some of the uranium-235 fissions—splits and releases energy (which of course is the point of the whole thing). The residual fragments of the split uranium-235 nucleus are generally radioactive—they continue to emit energetic particles as they change to more stable forms. This is the radioactive nuclear waste. The amount of uranium-235 so transformed would depend on the length of time the fuel was irradiated in the reactor core. After the normal fuel irradiation of several years spent LWR fuel contains about 3 percent radioactive waste, with about 1 percent uranium-235 still remaining (of the original 4 percent).

Most of the neutrons in an LWR core cannot fission the uranium-238 that constitutes the bulk of the uranium, but some of them are absorbed by the uranium-238 and transform it into plutonium-239, which does fission and plays a role more-or-less equivalent to that of uranium-235. Again, the amount of plutonium-239 created depends on the length of time the fuel spends in the reactor core. After several years of commercial use about 1 percent of spent LWR would be plutonium. Thus a fully irradiated LWR spent fuel assembly might contain about 5 kilograms of plutonium. The object of reprocessing is to extract this plutonium, either for use in nuclear weapons or for recycle into LWRs or possibly plutonium breeder reactors in the future.[3]

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[1] Uranium oxide (UO2) is a ceramic. Zirconium is chosen for cladding because of its low absorption of neutrons.

[2] BWR assemblies are smaller, having about 60 fuel rods per assembly containing about 200 kilograms of uranium.

[3] During the operation of the LWR some of the plutonium created is later fissioned, contributing to the energy production of the reactor. For normal commercial LWR operation, about a third of the total energy output comes from fissioning plutonium. The object of commercial reprocessing is to extract the remaining plutonium and reuse it as fuel in the form of MOX—mixed oxide fuel (that is mixed plutonium and uranium oxide). Such a fuel rod might contain about 4 percent plutonium—the rest being natural uranium. Since the spent fuel contains about 1 percent plutonium, one has to reprocess at least 4 spent fuel rods to obtain enough plutonium for a fresh

Table 1
Plutonium Composition of Spent Fuel at Discharge (%)

Isotope	CANDU 7,500 MWD/MT	BWR 27,500 MWD/MT	PWR 33,000 MWD/MT
Pu-238	**0.1**	**1.0**	**1.5**
Pu-239	**68.4**	**57.2**	**55.7**
Pu-240	**25.6**	**25.7**	**24.5**
Pu-241	**4.6**	**11.5**	**13.4**
Pu-242	**1.4**	**4.5**	**4.9**
Pu-238 + 240 + 242	**27.1**	**31.2**	**30.9**
Spontaneous Fission Rate (Neutrons/sec/gm)	**287**	**363**	**371**

Standard PUREX reprocessing technology has been publicly available for decades

The standard technology for reprocessing spent fuel from nuclear reactors, the PUREX process, was developed at the Oak Ridge National Laboratory (ORNL) around 1950 and used at the huge military reprocessing plants at Savannah River and Hanford to extract plutonium for nuclear weapons from spent fuel discharged from special plutonium production reactors.[4] The PUREX process was subsequently implemented for the same purpose in other countries and also adapted for reprocessing spent LWR fuel.

The first step in the process is to dissolve the spent fuel in nitric acid. In preparation for dissolution, the fuel is exposed by either chemically removing the

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MOX fuel rod. Because of greater health hazards, plutonium fuel fabrication is much more expensive than uranium fabrication. The result is that MOX fuel is *several times* more expensive than fresh low enriched uranium fuel.

[4] PUREX, for plutonium/uranium extraction. A different process was used earlier during the WWII Manhattan Project. An Oak Ridge Laboratory history states that " some Laboratory executives believe the PUREX process may constitute the Laboratory's greatest contribution to nuclear energy." http://www.ornl.gov/info/ornlreview/rev25-34/chapter4.shtml

aluminum or magnesium cladding from the natural uranium metal fuel used in plutonium production reactors, or by mechanically shearing or sawing the individual fuel tubes into short pieces. The next step is to allow the stream of acid solution containing the dissolved spent fuel to flow past another solvent stream that has an affinity for and so extracts the plutonium and uranium, leaving the radioactive fission products behind in the nitric acid stream. This step is called primary decontamination; in the PUREX process the solvent is an organic mixture of tributyl phosphate (TBP) and kerosene. The plutonium and uranium are subsequently separated and then purified using ion exchange. In a commercial LWR reprocessing plant, the purified plutonium solution is converted to plutonium oxide (PuO_2), while the purified uranium solution is either converted to uranium oxide and stored or converted to UF_6 for subsequent re-enrichment. In a plant dedicated to weapons production, the purified plutonium would be converted to metallic form, while uranium purification can be eliminated. About 5 kilograms of plutonium are required per warhead, or roughly the same amount as is present in a fully irradiated (spent) PWR fuel assembly.

Since the spent fuel is highly radioactive, it must be handled and processed remotely until after the uranium and plutonium are separated in the primary decontamination step. The highly radioactive fission product waste is first concentrated and then either stored as liquid in tanks or converted to solid form for permanent disposal.

Although details about how PUREX technology is implemented in specific plants is sometimes closely held because of proprietary and/or national security concerns, the basic reprocessing technology was declassified at the First Atoms for Peace Conference in Geneva in 1955. Since then it has been described in great detail in numerous reports and books[5], and also disseminated via training programs, often under the sponsorship of government agencies such as the former US Atomic Energy Commission (AEC). This policy was rationalized on the grounds that the isotopic quality of so-called reactor-grade plutonium from LWRs makes it unsuitable for nuclear weapons use. As discussed in Appendix 3, there is much less to this argument than appears—LWRs can be the source of large quantities of near-weapons grade plutonium.

Countries that can support LWRs would generally be capable of building small scale clandestine reprocessing plants

The consensus US view, since the Ford and Carter administrations, has been that the once-through cycle is both cheaper and safer in terms of proliferation to one involving the reprocessing and recycle of plutonium.[6] That remains a sound position. A commercial

[5] See, for example, the previously cited texts by Justin T. Long and Manson Benedict *et al*.

[6] For example, according to a comprehensive study of civilian nuclear power systems by the US Department of Energy during the Carter administration: "No nuclear fuel cycle which can be commercially deployed in the next few decades would offer more proliferation resistance than that associated with realization of the LWR once-through cycle, in which spent fuel is safeguarded in interim storage facilities and enrichment services are provided by the existing suppliers". *Nuclear Proliferation and Civilian*

reprocessing plant provides ready access to weapons-useable plutonium, and can also provide convenient cover for acquiring the technology and masking the emissions of a smaller clandestine plant.

But the consensus view has taken the argument further to say that LWRs by themselves, in the absence of commercial reprocessing and recycle, are a pretty safe proposition for siting just about anywhere. It is this extended proposition that we question here on the basis of a reexamination of the possibilities of small, difficult-to-detect, clandestine fuel facilities to extract near-weapons grade plutonium from spent LWR fuel. If such a plant could be built and hidden, and operated to obtain significant bomb quantities of plutonium before the international inspection system had time to react, it would reduce the proliferation safety margin between the once-through fuel cycle and the one involving plutonium recycle. In these circumstances the stand-alone LWR would not be nearly so safe a proposition as it has been made out to be.

Thus, the fundamental question that needs to be addressed is whether a country with a modest industrial base and a nuclear infrastructure sufficient to operate an LWR can build and operate a clandestine plant to reprocess diverted LWR fuel using the PUREX process. Since all non-nuclear weapons states are now parties to the NPT, we assume that all their declared nuclear facilities, in particular, the LWR and spent fuel storage, are safeguarded, and that the state has also agreed to implement the Additional Protocol, INFCIRC/540.

The most credible evidence that such a country could build a small clandestine reprocessing plant is:

- First, the record of such states on building and operating PUREX-type reprocessing plants;
- Second, the existence of detailed commercial designs of small PUREX plants, that although not built and operated, were engineered to commercial specifications using conventional technology to reprocess LWR fuel;
- Third, the simplified designs of small "quick and dirty" PUREX plants that utilize unconventional technology and were designed to support particular points of view with regard to nonproliferation policy

Plants that reprocess low burnup spent fuel to extract plutonium for weapons have been built and operated by many countries, e.g., North Korea; plants that reprocess LWR spent fuel for the same purpose differ in several respects from the former, but could also be built and operated successfully by, e.g., North Korea and Iran

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Nuclear Power: Report of the Nonproliferation Alternative Systems Assessment Program (NASAP). Volume II: Proliferation Resistance, US Department of Energy, Report No. DOE/NE-0001/2, June 1980, pp. 1-21 – 1.22. For a recent reaffirmation of this view, see: *The Future of Nuclear Power: An Interdisciplinary MIT Study*, MIT, 2003. In particular, the basic study finding with regard to the proliferation challenges to a large expansion of nuclear power is that "*…over at least the next 50 years, the best choice to meet these challenges is the open, once-through fuel cycle*". [Emphasis in text.] (Executive Summary, p. x)

All of the P-5 weapons states as well as Israel, India, and North Korea have operated PUREX reprocessing plants for weapons production. As noted, the feed for these plants is aluminum or magnesium clad natural uranium metal fuel discharged from special non-electricity producing reactors after a short period of irradiation (months). The plutonium extracted from this low burnup spent fuel is ideally suited for weapons, and, although sometimes denied, this is the purpose of building such reactors and reprocessing plants. The US, Russia, the UK, France, India and Japan have also operated PUREX-type commercial reprocessing plants whose feed is zircalloy-clad enriched uranium oxide fuel discharged from LWRs (and zircalloy clad natural uranium oxide fuel from CANDU reactors in the case of India) after an irradiation period of several years.[7]

There are several significant differences between the weapons and commercial PUREX plants which bear on the issue of the credibility of building and operating a clandestine reprocessing plant to extract plutonium from LWR spent fuel for use in weapons. Chemical decladding works for the lower burnup metal weapons fuel; mechanical decladding, a more difficult process, is needed for the higher burnup LWR fuel. High burnup also increases requirements for shielding and remote maintenance. On the other hand, the much lower concentration of plutonium in the low burnup fuel implies a much larger spent fuel throughput for the same rate of plutonium production, and therefore a much larger physical plant than a plant designed to process LWR fuel with an equal plutonium production capacity.

The closest plant to the type we are talking about that is in operation is the Radiochemical Laboratory at Yongbyon in North Korea.[8] It uses standard PUREX technology supplied by the Soviet Union that was later supplemented by detailed information about spent fuel decladding and waste treatment developed by Eurochemic, the European Company for the Chemical Processing of Irradiated Fuels, which operated a reprocessing plant in Mol, Belgium from 166 to 1974.

The average concentration of plutonium in the spent uranium metal fuel (average burnup about 600 MWD/t) which the Yongbyon facility in North Korea is designed to reprocess is 0.06%, while the concentration of plutonium in the spent LWR fuel would be at least 10 times larger. Thus, an LWR reprocessing plant with the same plutonium production capacity could be much smaller, hence less detectable than the Yongbyon plant which is designed to reprocess about 250 tons of spent fuel/year and hence is quite large: 192 m long and 27 m wide. The smaller Israeli reprocessing plant at Dimona which was also designed to reprocess low burnup uranium metal fuel has an annual

[7] The US plant at West Valley as well as the small, experimental Eurochemic plant in Belgium has been shut down. The other commercial plants continue to operate. For a listing, see David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996,* Oxford, 1996, Table 6.2, p. 156.

[8] Details of how the PUREX process has been implemented at the Yongbyon Laboratory are provided in *Solving the North Korean Nuclear Puzzle,* Edited by David Albright and Kevin O'Neil, The Institute for Science and International Security, Washington, DC, 2000, pp. 154–156. The commercial LWR reprocessing plants at La Hague in France, Sellafield in the UK, and Tokai Mura in Japan are at the other extreme of complexity.

capacity of about 100 tons of spent fuel, and is hidden underground in a building 60 m long and 24 m wide. A plant of comparable capacity reprocessing spent LWR fuel could produce about 600 kg/yr of plutonium, or about 75 kg/month, assuming the plant operates 8 months a year, as at Dimona.[9]

Although the Yongbyon and Dimona plants use chemical decladding while a plant to reprocess LWR fuel would require mechanical decladding, the latter is not as formidable an obstacle as is sometimes claimed. While large commercial LWR reprocessing plants such as the two 800 ton/yr plants at La Hague in France and the 700 ton/yr plant at Sellafield in the UK use sophisticated mechanical shearing devices to chop high burnup spent fuel assemblies, simpler devices can be utilized in smaller weapons plants that process LWR fuel which has a lower burnup and has also been cooled for a longer period before reprocessing. For example, a simple mechanical shear that was developed at Oak Ridge and Hanford in the early 1960s. Its first production use, at the West Valley reprocessing plant of Nuclear Fuel Services from 1966-1972, was very satisfactory, with necessary maintenance carried out by remote means. [Ref. to M. Benedict et al., op. cit., p. 475.] A even simpler two-step procedure would be to first free the fuel tubes from the PWR or BWR assembly using a saw operating underwater, and then chop up the tubes individually in a shielded cell that doesn't require an inert atmosphere to mitigate the risk of fires due to spontaneous ignition of the zirconium cuttings if the fuel has been cooled for more than a year. [Ref. private communication from Lee Thomas, LLNL, September 2004].

On the basis of the experience in Israel and North Korea, we judge that countries like North Korea and Iran could also build clandestine plants to reprocess LWR fuel using mechanical means for cutting the fuel rods based on published or transferred design information. Compared to the Israeli and North Korea plants, the LWR plant could be substantially smaller for the same plutonium production rate because of the higher plutonium concentration in the fuel; compared to commercial LWR plants, the weapons LWR plant would require less shielding and no uranium purification.

There are commercial designs for small reprocessing plants that don't cut corners

In the late 1950s the Phillips Petroleum Company made a feasibility study of a small plant designed to reprocess about 100–300 kg per day of BWR spent fuel with an average burnup of 10,000 MWd/t. The study report contains detailed process information and drawings, including of the plant's "headend," where the individual fuel pins are chopped into small pieces in a mechanical shear after having been freed from the assembly hardware using an underwater saw. One of the striking features of the plant is

[9] For details of reprocessing at Yongbyon and Dimona, see *Solving the North Korean Nuclear Puzzle,* Edited by David Albright and Kevin O'Neill, The Institute for Science and International Security, Washington, DC, Chapter VIII, pp. 139-165, and Frank Barnaby, *The Invisible Bomb,* I. B. Tauris & Co, Ltd., London, 1989, pp. 29-38, respectively.

its small size. With the exception of storage areas for raw materials and radioactive wastes, the whole plant is enclosed by a 65 ft square building of standard construction.[10]

There are designs for "quick and dirty" small clandestine reprocessing plants specifically to separate plutonium for bombs

There are two interesting designs for "quick and simple" reprocessing plants—one carried out at Oak Ridge in 1977 and another at the Sandia National Laboratory in 1996.

1977: Oak Ridge National Laboratory Design

In 1977 Floyd Culler, than Oak Ridge assistant director, and one of the leaders in the development of PUREX technology, set out to prove that a country with a minimal industrial base could quickly and secretly build a small reprocessing plant capable of extracting plutonium for bombs. The purpose of the exercise was to undermine the rationale for the Carter administration rejection of commercial reprocessing in the United States and its attempts, at least at the start of the administration, to convince other countries to do the same.[11]

Culler asked D.E. Ferguson, one of the Oak Ridge reprocessing experts, to assemble a team to see what it takes to build a minimal LWR spent fuel reprocessing plant, one that could quickly begin to separate about 5 kilograms of plutonium per day, or about one bomb's worth per day. The response came in a 1977 Oak Ridge memorandum from Ferguson to Culler that presented a design for such a plant together with a flow sheet and equipment list. The main reference for Ferguson's memorandum was the previously-cited 1967 AEC volume by J.T. Long, *Engineering for Nuclear Fuel Reprocessing*. The additional references were two papers presented at the 1958 Geneva Atoms for Peace Conference[12] and a standard plutonium handbook.[13]

The equipment list included dimensions and material specifications. The equipment is chosen with a several-month campaign in mind rather than long-term operation so, for example, plastic pipe can serve in places where steel pipe would be

[10] H. Schneider et al., *A Study of the Feasibility of a Small Scale Reprocessing Plant for the Dresden Nuclear Power Station,* Report IDO-14521, Phillips Petroleum Company, April 28, 1961. Available from the National Technical Information Service (NTIS), Washington, DC. See also the report by John Lamarsh, "On the Extraction of Plutonium from Reactor Fuel by Small and/or Developing Nations", in *Nuclear Proliferation Factbook,* Congressional Research Service, Library of Congress, September 28, 1977, pp. 563-585, where the author discusses how the Phillips design can be simplified if the feed is low burnup uranium metal instead of LWR spent fuel.

[11] One needs to reemphasize, because it is so frequently forgotten, that the initial rejection of US reprocessing was done by President Ford. But he lost the election a few days after announcing his policy and so the focus turned to Jimmy Carter.

[12] Second UN Conference on Peaceful Uses of Atomic Energy, 1958.

[13] *Plutonium handbook, Vol II*, Gordon and Breach, Science Publishers, Inc., 1967.

used in a commercial plant. A plant diagram attached to the memorandum and keyed to the equipment list shows the plant equipment layout from the receiving pool for radioactive spent fuel to the metal reduction furnaces for producing plutonium metal "buttons."[14] The structure housing the entire operation would be about 130 feet long and much less wide. Although they describe the plant as a "quick and dirty" one, the designers went to some pains to contain the radioactive wastes and to filter the effluents both for reasons of safety and to avoid detection.

Ferguson concluded that such a plant could be in operation four to six months from the start of construction. He thought the first 10 kilograms of plutonium metal (about two bombs' worth) could be produced about one week after the start of operation. Once in operation the small plant could process about one PWR assembly per day which translates into production of about 5 kilograms of plutonium per day.

This conclusion assumes of course that the reactor operator cooperates with the would-be bomb-makers. It also assumes that weapon design and readiness for fabrication would be prepared in advance. Both of the latter are difficult to detect and when detected are often clouded in ambiguity.

Acting on a November 1977 request from Senator John Glenn[15] the General Accounting Office (GAO) prepared an evaluation of the Oak Ridge report.[16] The GAO examined reviews of the Oak Ridge memorandum by five Federal agencies—the Arms Control and Disarmament Agency (ACDA), the Department of Energy (DOE), the Nuclear Regulatory Commission (NRC), and the Congressional Research Service (CRS). It also discussed the memorandum with knowledgeable individuals in industry, government, research laboratories, and universities who had reviewed, or whose staffs had reviewed, the memorandum.[17]

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[14] The diagram appears in the Washington *Post* of August 4, 2002, to illustrate an article, "Those N. Korean Reactors Light Up Danger Signals," by Victor Gilinsky and Henry Sokolski. The Oak Ridge report does not see the initial mechanical disassembly of the LWR spent fuel as a particularly difficult step. This issue came up in arguments over the risks posed by the two LWRs that the United States had promised North Korea as part of the 1994 Agreed Framework. The State Department insisted that while North Korea had experience with reprocessing it would not be able to reprocess LWR fuel because of the difficulty of cutting up the fuel rods, a part of the process with which a high-capacity French commercial plant had difficulty. The Oak Ridge design proposed abrasive saw cutting underwater and it refers for the details to the 1967 Long volume which has a section on the subject.

[15] Senator John Glenn was then Chairman of the Subcommittee on Energy, Nuclear Proliferation and Federal Services, Committee on Government Affairs, and very active on nuclear proliferation issues. (Throughout, we do not distinguish between Oak Ridge report and Oak Ridge memorandum.)

[16] Report by the Comptroller General of the United States "Quick and Secret Construction of Plutonium Reprocessing Plants: A Way To Nuclear Weapons Proliferation?, EMD-78-104, October 6, 1978.

[17] In terms of his knowledge of reprocessing, the most imposing of these was Manson Benedict, Institute Professor Emeritus, Massachusetts Institute of Technology. One of the authors of this report, Victor Gilinsky, then an NRC commissioner, was also among the 11 persons interviewed by GAO.

GAO found that none of the reviews it examined doubted the technical feasibility of the construction and operation of the Oak Ridge-designed plant, at least if it was done by persons as skilled and experienced as the Oak Ridge team. There was wide divergence on how quickly such a plant could be built. GAO stated, "GAO believes the Oak Ridge memorandum's estimate of 4-6 months, although not highly probable, should be considered credible in some circumstances."[18]

In short, the GAO concluded that the Oak Ridge design was a credible possibility for an experienced group. In other words, one could not assume that a country interested in nuclear weapons will be barred from extracting militarily significant amounts of plutonium from its LWRs simply because it lacks a commercial reprocessing capability.

1996: Sandia National Laboratory design for a minimal reprocessing plant

In 1996 a report by a team organized by the Sandia National Laboratories assessed the proliferation resistance of various alternatives for the disposition of stocks of weapons-grade plutonium that have been declared excess to national security needs by the US and Russia.[19] In particular, a simplified flow diagram for a process to recover plutonium from LWR or MOX fuel is provided, and the process steps are characterized as representing "…*a relatively simple process that might be operated by an adversarial group in makeshift or temporary facilities such as a remotely located warehouse or a small industrial plant*. [Emphasis added.] The Sandia team also estimated the number and skills of personnel and the types of skills required to build and operate a facility to extract plutonium from LWR spent fuel using the suggested process as well as the length of time required to build and test the facility and operate it to produce a one significant quantity SQ (8 kg) of plutonium. It was judged that 6 skilled people would be required, that an appropriate mix of skills would include in the group one BS chemist or chemical engineer, one mechanical engineer and one electrical engineer, or persons with equivalent experience, and that it is likely that experienced people could be obtained from nuclear weapons states or from states with nuclear power plants.. The estimated preparation lead time would be about 6 months, and about 8 weeks would be needed after that to produce the first SQ of plutonium.

Non-standard design issue associated with Oak Ridge and Sandia designs

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In a January 25, 1978 letter to Senator John Glenn, the author argued that the results of the Oak Ridge report—that it was easy to build quickly a small reprocessing plant and easy to hide—did not negate the value of limiting large commercial reprocessing plants, and expressed some skepticism about whether others could meet the Oak Ridge design objectives. He added, however, that "if it is as easy as the memorandum contends to build and operate a reprocessing plant in secret, then the danger point would come at the power reactor itself." Since then, lots more technical people around the world have obtained experience in reprocessing and more process equipment is available off-the-shelf.

[18] GAO Report, p. iii.

[19] J. P. Hinton et al., *Proliferation Resistance of Fissile Material Disposition Program (FMDP) Plutonium Disposition Alternatives: Report of the Proliferation Vulnerability Red Team,* Sandia National Laboratories, Report no. SAND97-8201, October 1996, Section 4.1.1.3 Recovery Process for LWR or MOX Spent Fuel, pp. 4-3 – 4-9.

The Oak Ridge and Sandia proposals both differ in some important respects from the standard PUREX process flow sheet, e.g., with respect to the method used for primary decontamination, and in the case of the Oak Ridge report, for chopping the fuel. [The chopping process in the Sandia design is not specified.]As the designs were never implemented there is some question about the practicality of operation that need to be answered. Also, no information is provided on such crucial issues as the control instrumentation required and how equipment malfunctions would be corrected, especially in the first stages of the process where intensely radioactive materials are handled.[20]

The CRS critique of the Oak Ridge proposal notes the absence of any discussion of instrumentation and maintenance procedures in the report, and also questions the estimated 4-6 month time period for completion of the proposed plant from the breaking of ground to the beginning of routine reprocessing on the basis that the overall enterprise requires additional, time-consuming steps both before the breaking of ground and before the start of routine operations that are not considered in the report.

Since the publication of the 1977 Oak Ridge report, obtaining and using a mechanical shear for fuel cutting is now much less of a technical challenge for a state with the industrial base and nuclear infrastructure needed to operate a nuclear power plant. On the whole, mechanical chopping using a shear would be preferred to sawing under water.

Despite these reservations, the Oak Ridge and Sandia studies add to our understanding of the possibilities of small-scale clandestine reprocessing and they remain a possibility. At the same time, we would judge it more likely that, nearly thirty years after the publication of the Oak Ridge design, states with an industrial base and LWR infrastructure could and, if they chose to do so, would construct and operate reprocessing plants "without cutting corners." The interest of producing significant quantities of plutonium as quickly as possible without detection and therefore without serious glitches would point in this direction.[21] Indeed, given the resources of such a state, plants can be designed, built and operated that have a lower probability of experiencing interruptions in operation due to process upsets, criticality-related and

[20] The evaluation of the Oak Ridge report prepared by the General Accounting Office (GAO) summarized reviews of the report by five Federal agencies – The Arms Control and Disarmament Agency (ACDA), the Department of Energy (DOE), the Nuclear Regulatory Commission (NRC), and the Congressional Research Service (CRS). It also consulted with and quoted the reviews of 11 well-known individuals with varying degrees of knowledge of reprocessing. Report by the Comptroller General of the United States, *Quick and Secret Construction of Plutonium Processing Plants: A Way to Nuclear Weapons Proliferation?,* EMD-78-104, October 6, 1978. The CRS review in its entirety was published separately several days later. Warren Donnelly, *A Preliminary Analysis of the ORNL Memorandum on a Crude Nuclear Fuel Reprocessing Plant,* November 4, 1977.

[21] In our judgment, it is not credible that a sub-national group with the type of skills enumerated in the Sandia report could construct and operate even the simplified plants outlined in the Oak Ridge and Sandia reports.

other accidents, and equipment failures, and also release smaller quantities of tell-tale solid, liquid, and gaseous effluents than "quick and dirty designs."

Clandestine diversion of spent fuel and its reprocessing may be difficult to detect before the start of reprocessing operations

The detectability of clandestine diversion of spent LWR spent fuel and subsequent reprocessing is an important consideration in evaluating various scenarios. States like North Korea could divert spent fuel from at-reactor storage pools both covertly and overtly between IAEA inspections. They could also limit the emission of tell-tale effluents during operation. Of course, there are no such emissions from a reprocessing plant until it operates.

Spent fuel safeguards must beat the time to produce first significant quantities of plutonium in order to be effective

The major inspection effort at spent fuel storage pools at reactors is focused on the verification of the contained fuel. The IAEA uses surveillance cameras primarily to monitor the movement of spent fuel transport casks from the pool area, and the surveillance record is checked by inspectors at three month intervals during inspection visits. In addition, the inspectors count the assemblies in the pool and also use a "Cerenkov" light detector to verify that they have been irradiated. However, the resolution of the Cerenkov device is not good enough to detect the replacement of a significant number of the irradiated rods in an assembly with non-radioactive dummies. Moreover, the surveillance cameras have only a limited view of the pool area. This makes the covert diversion of spent fuel possible.

Alternatively, given confidence that the reprocessing plant would operate long enough to extract significant quantities of plutonium before inspectors returned to the pool, assemblies could be diverted between inspections with no attempt made to conceal this fact if and when the inspectors return. The location of the reprocessing plant would represent a compromise between minimizing detection during transport which would favor building it close to the reactor, and the possibility that its presence would be detected by environmental sampling around the reactor.

Reprocessing plant emissions signal operation but could be reduced

The potential for detecting clandestine uranium enrichment and spent fuel reprocessing plants by wide area environmental sampling is a subject of increasing attention and several unclassified overviews have been published.[23] Regarding emissions to the

[23] See, e.g., US Congress, Office of Technology Assessment, *Environmental Monitoring for Nuclear Safeguards*, OTA-BP-ISS-168, Washington, DC, US Government Printing Office, September 1995; and *IAEA Use of Wide Area Environmental Sampling for the Detection of Undeclared Nuclear Activities,*

atmosphere from reprocessing plants during normal operation, it is well-known that the most useful signature is the noble fission product gas krypton-85 since it is difficult to contain and is produced in reactor fuel in relatively large quantities. It is conceivable that the operator of a clandestine facility would attempt to contain the krypton and prevent its release into the atmosphere. Several methods, including adsorption on activated charcoal and cryogenic distillation, have been developed and described in the technical literature. They are, however, expensive and haven't been implemented in existing plants. Nevertheless, one cannot rule out the possibility if there is a sufficient premium for a state on avoiding detection of its clandestine reprocessing.

Conclusion: small-scale clandestine reprocessing is a credible possibility in countries seeking nuclear weapons

It is credible that states that operate nuclear reactors could also build and operate small PUREX reprocessing plants to extract militarily significant quantities of plutonium from LWR spent fuel. It is also credible that they could extract such quantities before detection by the IAEA or by national intelligence. The clandestine reprocessing of old spent fuel—that has been in storage for many years—is particularly worrisome because its lower radiation level makes it easier to divert, transport, and reprocess, and more difficult to detect. Krypton-85, the most detectable signature for reprocessing plant operation decays with a ten year half-life.

These considerations underline the fact that the once-through fuel cycle is not a panacea for preventing proliferation, and cast doubt on current proposals to lessen the IAEA inspection effort at LWRs, at least without further assessment. Such reductions have been suggested for spent fuel pools in states which have negotiated both a Comprehensive Safeguards Agreement (CSA) and an Additional Protocol (AP) with the IAEA, on the following grounds:

> If the IAEA can draw a conclusion regarding the absence of any undeclared reprocessing plant in a state with both a CSA and an AP in force, it follows, *prima facie*, that it needs to spend less effort to verify that there has been no diversion or irradiated nuclear fuel in that state. [24]

But what if the IAEA cannot draw such a conclusion? Until there is more experience with the application of the AP, it would not be prudent to increase the interval of inspections at spent fuel pools from three months to a year as has been proposed. Indeed, current safeguards should be strengthened by placing adding cameras around the pool to detect the possible substitution of dummies in spent fuel assemblies. And the IAEA

Member State Support Programmes to the IAEA, STR-321, August 1999. Unfortunately, the comprehensive IAEA report has not been published by the Agency, and is only available from the six member states which contributed to the study.

[24] Jill Cooley, "Integrated nuclear safeguards: genesis and evolution", in *Verification Yearbook 2003,* Edited by Trevor Findlay, The Verification Research, Training and Information Centre (VERTIC), London, 2003, pp. 29-44. Cooley is Director of the Division of Concepts and Planning in the Department of Safeguards at the IAEA,

should also press for the use of remote monitoring of cameras which could detect possible diversions on a near real time basis of spent fuel.

Additional comment on alternatives to PUREX under current development: potential benefits have been exaggerated

There has been some discussion of alternatives to PUREX in the context of easing nonproliferation restraints on reprocessing. While this is implausible in terms of our principal focus—small clandestine reprocessing—it does merit some discussion. Supporters of plutonium recycle have promoted variants of the basic PUREX process such as "co-processing" of uranium and plutonium as well as other reprocessing techniques such as pyroprocessing. In normal operation of these processes there would be only a partial separation of fission products and other radioactive elements from the spent fuel. The separated plutonium, it is argued, would be surrounded by a radiation barrier that would make it more difficult to handle and steal. On this basis, these alternative processes have been advertised as being more "proliferation resistant" than the PUREX process. However, here again the potential benefits have been highly exaggerated. For example, the radiation barrier surrounding the partially decontaminated pyro-processed fuel is much smaller, and the plutonium content of the fuel is much greater, than is the case for plutonium still locked in radioactive LWR spent fuel.

In any case, pyroprocessing of spent fuel is still in the R&D phase, so the practical choice for civilian nuclear power today is between the once-through nuclear fuel cycle with no reprocessing, as is the practice in the United States, and plutonium recycle in LWRs utilizing the PUREX process.

APPENDIX 3

Plutonium from Light Water Reactors as Nuclear Weapon Material

By Harmon W. Hubbard

The feasibility of using "reactor grade" plutonium (Pu) for nuclear explosives was established some years ago. The Department of Energy, in 1977, declassified the fact that an underground test had been conducted (in 1962) in which weapon grade Pu had been replaced with reactor grade Pu with successful results. They re-emphasized the test in 1997 for the arms control community[1]. The subject of illegal construction of nuclear explosives was reviewed by J Carson Mark, late T-Division head at Los Alamos National Laboratory (LANL), in a 1990 report.[2] The focus of his report was terrorist organizations with access to spent reactor fuel, and he concluded that the difficulties encountered by a terrorist group in using reactor grade Pu for explosive fabrication differ only in degree, but not in kind, from the problems they would find using weapon grade Pu. In this note, however, we are more interested in a "rogue" state with access to Pu from a light water reactor (LWR), and having perhaps more technical expertise than the putative terrorist group. Our approach is qualitative with quantification of key items necessary for estimates. All of the data and theory used in this note have been in the public domain for many years[3].

The model assumes the simplest design for a first effort explosion

We assume the simplest design for a first effort explosive, consisting of a solid Pu spherical core, very nearly a critical mass when surrounded by a high density tamping material, taken to be uranium. This larger sphere is then encased in the high explosive system which is designed to provide a converging spherical shock wave that would compress the assembly for a few microseconds before it flies apart. If the Pu core is nearly critical before the implosion, any compression will achieve supercriticality because a critical mass of fissile material depends inversely on the square of the density of the compressed material. For example, a compression of a factor 1.4 cuts the critical mass almost in half, so the core in this condition would contain about 2 critical masses.

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[1] US Department of Energy, "Non-Proliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives" (Washington, D.C.: U.S. Department of Energy, 1997) pp. 37-39 and The National Academy of Sciences, *Management and Disposition of Excess Weapon Plutonium* (Washington, D.C.: The National Academy of Sciences, 1994) pp. 32-33.

[2] J. Carson Mark(Washington, D.C. Nuclear Control Institute, 1990).

[3] The National Academy of Sciences, "The Nuclear Weapons Complex: Management for Health, Safety, and the Environment" (Washington, D.C.: The National Academy of Sciences,1989, Appendix E "Physics of Nuclear Weapon Design".

Introduction of neutrons into the core while it is in this supercritical state may start a chain reaction culminating in an explosion. On the other hand, introduction of neutrons before maximum compression will result in less energy being released, which is a problem for those who want to use reactor grade Pu for explosives. The Pu obtained from uranium reactor fuel, will contain several Pu isotopes made by neutron capture or ejection because of the inescapable exposure of the created Pu-239 to the neutron flux in the reactor. The amounts of capture products, Pu-240, 241, etc. are dominated by the 1st capture, Pu240; the next most abundant product, Pu-241, is so similar to Pu-239 that the two can be lumped together and considered to be a single fissile material for this purpose. Higher capture products will be ignored because significant production depends on long exposure, and we are interested in only moderately irradiated, "1st cycle", LWR fuel. The real problem is, of course, the Pu-240, for the simple reason that this nucleus has a small but finite probability of spontaneously breaking apart and releasing two or more neutrons as part of this process. The rate of this spontaneous fission is large enough to produce a sizeable neutron source in the amounts of fissile material we will consider.

Calculating the chain reaction in an assembly of fissionable material

If a neutron is introduced into an assembly of fissionable material, it will end with one of several possible fates: 1) it can leak outside the material before it collides with a nucleus, or after making scattering collisions, 2) it may be captured by a nucleus with the emission of a gamma ray, 3) if it has enough energy it may knock another neutron out of a nucleus or 4) it may be captured by a nucleus which subsequently fissions and releases more neutrons. Taking all of these options into account, suppose that the average number of neutrons remaining after the first neutron disappears is k. Then each of these k will produce k more, or k^2, and so on. The total number is then $1+ k + k^2 + k^3 + \text{etc} = (1-k)^{-1}$ for $k<1$. As k approaches 1 the total number becomes infinite, i.e. the chain continues indefinitely and the assembly is critical for the condition k=1. Of the four possible fates of each neutron listed above, the first two produce no new neutrons, and the third has such a small probability for neutrons of fission energy (too low) that it can be ignored, so the value of k is determined solely by the probability that a neutron causes a fission. If we denote the average number of neutrons per fission by ν and the probability that a neutron causes a fission by p_f, then, just at critical we can write $k=1=\nu p_f$, and $p_f = 1/\nu$. For Pu-239, the average number of neutrons emitted per fission is about 3, so that the probability that a neutron causes a fission at criticality, is just1/3; 2/3 leak out or are captured without causing a fission.

Just at critical, all the neutrons are required to maintain that state, including the very small fraction of delayed neutrons--those which appear seconds after fission rather just at the time of fission. The existence of these delayed neutrons allows the number of neutrons to be controlled by moving absorbing materials in reasonable times (seconds), and nuclear reactors are possible when operated at critical. Just above critical, (k>1), the neutron chain is maintained by prompt neutrons, and cannot be easily controlled. The time behavior of such a prompt chain is an exponential

increase, the rate being determined by a quantity, α, which contains all the physics—the composition of the material, the change of the configuration with time, etc. The neutron population increases as $e^{\int \alpha dt}$, where $\int \alpha dt$ is called the number of generations—which tells us the number of neutrons and the amount of energy released by the fission chain after it has been initiated.

The value of α increases as the plutonium ball is compressed and then drops as it flies apart. If a chain does start, then when the number of generations reaches 43-45 or so, the pressure in the plutonium due to vaporization of the metal by the energy of fissions is equivalent to several kilograms of high explosive and will stop the implosion and begin the disassembly. If initiation occurs at nearly peak α, then more generations can occur during the time the device disassembles than if initiation occurs earlier at a lower value of α, because, of course, the generation time is just 1/α. If the chain produces about 56 generations,(i.e. another 11 to13 generations after the 43 to 45), approximately 20 kilotons of energy will have been generated.

Plutonium in LWR fuel irradiated for one fuel cycle

As pointed out, the spontaneous fissions of the Pu-240 present in reactor irradiated uranium fuel provide a troublesome neutron source in the separated plutonium. Each gram of Pu-240 produces about 1000 neutrons per second from this source[3], so that a ball of reactor grade plutonium weighing m kilograms and containing a fraction x of Pu-240 will produce about 10^6mx neutrons/second. Many of these neutrons would not cause fissions or start a chain reaction—only 1/3 would at critical, as we have seen—they leak out or suffer non-fission capture. In fact, even though several neutrons are introduced at the same time, it is possible that none of them starts a chain reaction if the α and therefore the probability of fission is not large enough. At a fission probability of about 1/2, it can be shown[4] that the chance of starting an explosive neutron chain is about 1/3. To raise this probability from 1/3 to a sure fire 99% requires enough neutrons so that the chance of no chain is 1%; or mathematically, $(2/3)^n$=.01, where n is the number of neutrons needed. The solution of this equation is n=11.4 neutrons, and indeed, experience shows that about 10 neutrons are required for a 99% probability of actually starting a chain in plutonium and we will use this number. We can then define a probability per second that a chain will be initiated in reactor grade plutonium as about 10^5mx. But what we are really interested in is the probability; P, that the assembly will survive at least to an initiation time, t=T, that is expected to produce an explosion of energy yield Y. The time sequence of these events is: 1) the high explosive implosion starts to compress the Pu core, which becomes critical at time t=0, 2) at time t=T the neutron population in the now supercritical core becomes high enough to start a neutron chain reaction, either from unwanted spontaneous fissions, or by injection from an initiator, 3) about 45 generations later the device starts to disassemble due to the high pressures developed in the Pu, and 4), the remaining

[4] An approximate formula for the probability of chain initiation is $(\nu p_{f-1)}/\chi p_f$, where χ is the value of k(k-1)/2 averaged over the spectrum of fission neutrons, and k is the number emitted , ranging from 0 to about 5. For Pu, χabout3.

neutrons cause more fissions producing a total yield of Y kilotons as the material flies apart. It is easy to show that the survival probability, P, is related to the time, t, by the equation $P=e^{-st}$.

If we now assume a linear connection between α and t, α=bt, we can write st=sα/b, where b, the rate of change of α, is related to the speed of compression, and can be taken as an indicator of the state of this aspect of the implosion art. Such a linear relationship between α and t is warranted if the compression is not too high, and greatly simplifies our numerical considerations. An important case is when initiation occurs at the earliest possible moment; t=T=0, when the core is just critical, then α=0, and we obtain P=1 for the so-called fizzle yield, which is clearly a lower bound for the yield produced by the device. (P=1 means 100% probability that at least this yield will be attained.) This guaranteed yield was expected to be a little less than a kiloton for Trinity[2], and would be at least as large for the designs we are considering.

If the plutonium is substantially diluted with isotopes other than 239, then the change of reactivity must be taken into account in estimating the critical mass. We are particularly interested in fuel that is removed from a LWR after one cycle, which, on average contains about 83% Pu-239. The 17% that is converted to other isotopes will be assumed to be about 14% Pu-240 and 3% Pu-241. The Pu-241 has, for this purpose, characteristics so close to Pu-239, that they may be lumped together, as mentioned above. LANL has calculated that a bare critical mass of Pu-240 is about 40kg compared to16.28 kg for Pu containing 4.5% Pu-240[5]. A uranium tamped critical mass of Pu-240 can therefore be estimated (using the measured value of 5.91kg for uranium tamped 4.8% material and ignoring the difference from 4.5%) to be about 5.91·40/16.28=14.52kg, Using these numbers, the critical mass of plutonium of any fraction x of Pu-240 , assuming an approximately linear relation, is given by 5.50+9.02x kilograms. Inserting x=.14 in this formula, the critical mass of 1st cycle LWR plutonium, encased in a thick uranium shell, may therefore be estimated to be 6.73kg.

Probability estimates for explosion yields

We will base the calculation of predetonation probability on data from the first actual experiment (the Trinity nuclear test) and the results of calculations provided by Carson Mark. (It is interesting that these predictions were reported by Oppenheimer after the Trinity test, to apply to the Nagasaki bomb. Prior to Trinity, yield estimates by the prominent scientists were all over the map, but not for reasons of preinitiation, but rather from uncertainties about many aspects of the untested design[6]). To proceed, we need the composition and mass of the Trinity device. For this first test apparently very clean plutonium was obtained by frequent chemical processing of the uranium fuel at Hanford, resulting in a Pu-240 content of about 1%, and it is reported that data provided

[5] Plutonium critical masses are taken from H. C. Paxton, "Los Alamos Critical-Mass Data" LAMS-3067, 1964

[6] Richard Rhodes, "The Making of the Atomic Bomb", (NY,NY: 1986).

by Gen. Groves gave the mass as 6.2kg[7]. From the critical mass approximate formula in the previous paragraph, the critical mass of 1% material is just 5.6kg, less than the actual mass used for Trinity. This is because of a central void for an initiator, and somewhat different tamper. The LANL measured critical mass of 1% Pu with a central void for an initiator, presumably a mockup of Trinity, is 6.46kg.

We will take the above indicated changes into account as follows: we simply rely on the mathematical form of the probability, $P=e^{-st}$, where, since s is proportional to mx, a change to m`x` would imply that the new probability is $P`=P^{(m`x`/mx)}$. This assumes, of course, an implosion system of the same quality as that used for Trinity, but this too could be changed by simply reducing the time to the initiation value of α, T=α/b, by increasing b, the rate at which α increases. Then the exponent of P would involve mx/b. The ratio b`/b can be increased without knowing the Trinity value, b, so we can speak of technical improvements in relative terms. These improvements would be in the high explosive system and the design of the core- tamper arrangement to achieve higher compression, faster, and in design of the core itself. To prepare the proper exponent, since only mass ratios are involved, and since Trinity was close to critical, and if we correct for both the central void and backing off from critical by correction factors, they are the same factors for any x, and will cancel out. Hence, for the pre-initiation calculation we can simply use the solid ball critical masses, so that the proper exponent of P is (6.73·.14/5.59·.01)·(b/b')=16.85b/b'. For comparison, we make the same calculations for weapon grade Pu (6% Pu-240), and an intermediate, 4.5% Pu-240 core, for which a measured critical mass was published. The calculated critical mass from our formula is 6.04 kg and the exponent for the comparison with Trinity is 6.483·b/b', for the 6% case, and 4.758b/b' for the 4.5% material, using the measured 5.91kg critical mass. The values of the probability P shown below are given only for yields of 20, 5, and 1 kilotons, because they depend on the only published values of P associated with the Trinity nuclear explosion: P=0.88, 0.94, and 0.98 respectively[2].

The results are presented in the following 3 charts in which the probability of achieving at least a yield Y is plotted against yield for the three Pu-240 fractions considered. The published Trinity data have been added to the first chart since it applies to unimproved Trinity technology.

Conclusions

Taking into account the wide availability of declassified nuclear weapon information and the enormous increases in computing and other technological aids since the Trinity

[7] Carey Sublette, "Nuclear Weapons Frequently Asked Questions" at http://gawain.membrane.com/hew/ This website contains a large amount of information on many aspects of nuclear weaponry in the public domain.

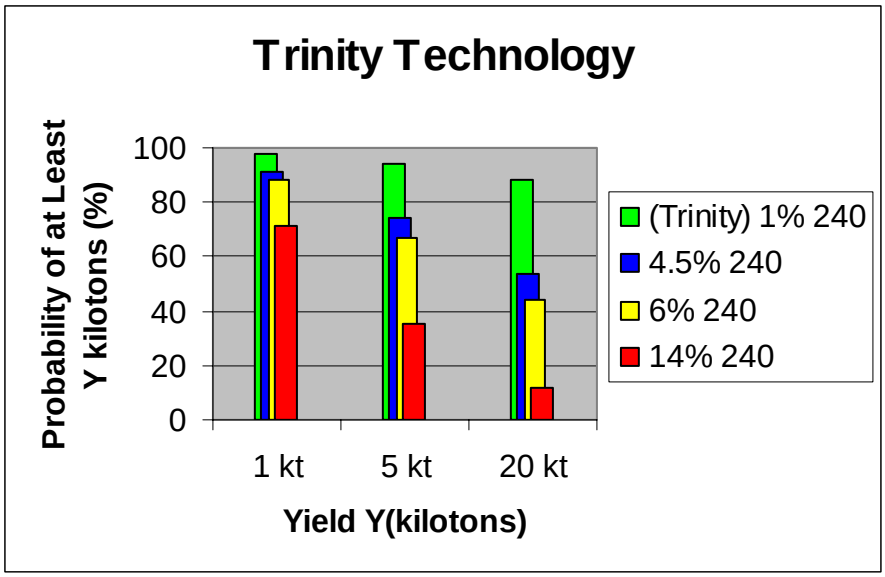
shot in 1945, it seems reasonable to attribute at least a doubling or tripling of the efficacy of the Trinity implosion system through the use of advances in implosion technology, initiators, and core design. If this is the case, then we can expect 1st cycle LWR plutonium to provide a state operated laboratory with the basis for modestly reliable fission weapons of around 5 kilotons or somewhat greater yield using the reactor grade material, according to the following charts. The nominal 20kt yield would be unreliable even with improvements, and from the second chart even weapon grade material does not fare too well at less than a doubling or tripling of technological level. The 4.5% metal provides considerable improvement in reliability, but its production is of course a cost tradeoff. (Critical masses of this grade of plutonium were reported in the 1950's and correspond to a relaxation of the purity requirement post Trinity and pre boosting as implosion technique improved). However, these estimates are based on unspecified extrapolations of the very first fission device design, and major improvements are almost a certainty. To take full advantage of this material, boosting with some kind of fusion capsule would probably be required, but would likely need nuclear testing. Finally, however, it should be remembered that the fizzle yields of the devices considered will be at least as large as that of Trinity[2]; around 1kt, and that this guaranteed yield is already quite destructive.

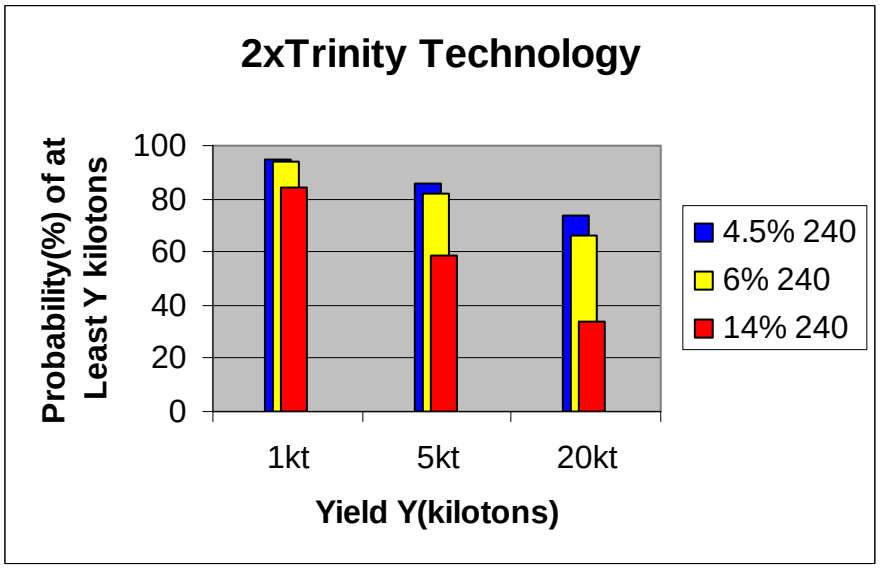
CHARTS

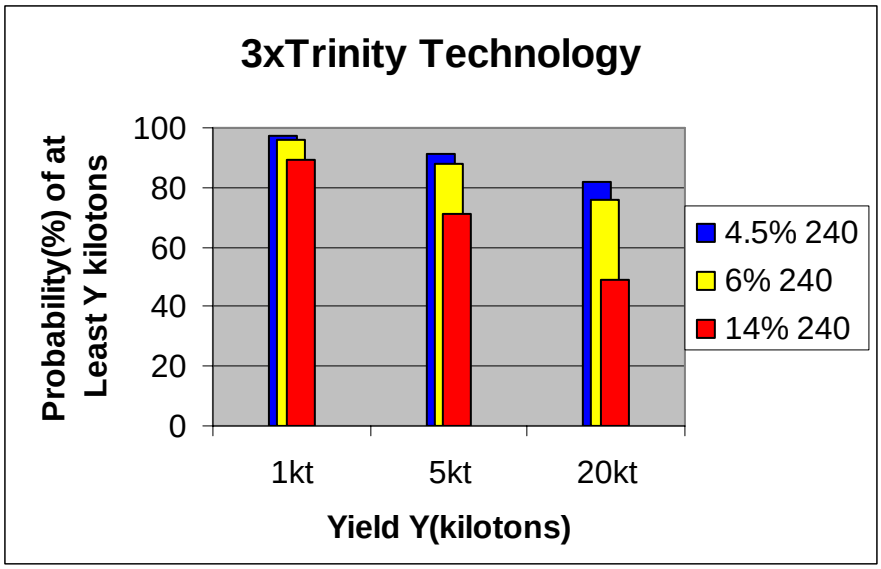
All 3 charts show the probability of achieving at least a yield Y(kt) for several Pu-240 fractions:

- 4.5% corresponds to the Pu used during the years following Trinity before boosting was introduced in the 1950's,
- 6% is a more or less standard "weapon grade" Pu,
- 14% is the expected average 240 content of Pu withdrawn from a LWR after the first fuel cycle.

The first chart applies to unimproved Trinity technology, and includes an addition of the published Trinity data as well as the 3 Pu-240 fractions described above.
The second and third charts correspond, respectively, to 100% and 200% unspecified improvement in implosion technology over Trinity. Given the vast changes in every pertinent aspect of technology and information on previous work since 1945, these assumed improvements are probably justified.


Trinity Technology
Probability of at Least Y kilotons (%)
100
80
60
40
20
0
1 kt
5 kt
20 kt
Yield Y(kilotons)
(Trinity) 1% 240
4.5% 240
6% 240
14% 240


2xTrinity Technology
Probability(%) of at Least Y kilotons
100
80
60
40
20
0
1kt
5kt
20kt
Yield Y(kilotons)
4.5% 240
6% 240
14% 240


3xTrinity Technology
Probability(%) of at Least Y kilotons
100
80
60
40
20
0
1kt
5kt
20kt
Yield Y(kilotons)
4.5% 240
6% 240
14% 240