CHAPTER 5

A FRESH EXAMINATION OF THE PROLIFERATION DANGERS OF LIGHT WATER REACTORS

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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, by U.S. interest in limiting the possibilities for diversion of civilian facilities to military purposes. U.S. 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 worldwide 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 chapter involves one of these technological policy initiatives, the consequences of which we are living with today—encouraging the spread, starting in the 1960s, of U.S. light water reactor (LWR) technology as the basic nuclear power workhorse throughout the world.[1]

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 U.S. 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.

The LWR could only operate on enriched uranium, that is, uranium more concentrated in the active uranium-235 isotope than natural uranium.[2] 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 U.S. 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.[3]

From the point of view of proliferation, the advantages of the LWR were considerable as compared with natural uranium-fueled reactors. U.S. policymakers 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 (IAEA) 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 of spent fuel from heavy water reactors such as the CANDU, even though the LWR burn-up 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.[4]

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.[5] A standard size LWR with an electrical generating capacity of about 1,000 megawatts produces about 250 kilograms of plutonium per year. (That has to be compared with the nominal five 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 U.S. control, so the spread of LWRs and the consequent market for enrichment encouraged the reinvention by others of the gaseous diffusion enrichment process—originally developed by the United States during World War II—as well as the development of the gas centrifuge enrichment process. Together, these developments broke the U.S. monopoly on the supply of enrichment for LWRs.

In particular, France built a large gaseous diffusion plant, and the United Kingdom (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 United States 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—also have built gas centrifuge plants, although at present they do not supply enrichment services to the international market.

Global attention has been focused recently on the proliferation implications of centrifuge enrichment 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 also has been driven by improvements in centrifuge performance. The newer models are much more reliable and have a larger unit enrichment capacity. Gas centrifuge plants also are inherently much more flexible than gaseous diffusion plants to accommodate different 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 low enriched uranium (LEU) plant would modify it to also produce heavy enriched uranium (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 LEU, a much smaller gas centrifuge plant would suffice to raise the enrichment to bomb levels than would be the case if the starting point was 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 bombmaker would crush the pellets and react the powder with fluorine gas. Suitably processed, the LEU pellets could provide feed for clandestine enrichment.

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 chapter.

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 30 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 could react effectively. To place these issues in context, we first summarize the evolution of U.S. 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 U.S. policies on LWRs. Until 2001, the State Department defended putting LWRs in North Korea as part of the 1994 U.S.-Democratic People's Republic of Korea (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 U.S.-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 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 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.[6] It also alerted those concerned with the spread of nuclear weapons of 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.[7]

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 U.S. 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.[8] The U.S. 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."[9]

None of this was in any way prohibited by the Nuclear Nonproliferation Treaty (NPT) *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 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.[10]

In its public pronouncements the U.S. 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.[11] 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 that technology providing access to plutonium as uranium enrichment technology was still tightly held.[12] There were some important U.S. successes, among them stopping the French sale of a reprocessing plant to Pakistan, which France finally abandoned in 1978.[13]

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, in its energy planning, would no longer 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, U.S. policy on spent fuel assumes that it will be disposed of 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.

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 U.S. 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 U.S. nonproliferation policy in a confused state that did not engender respect either at home or abroad.[14] At first, Carter took a rigid antiproliferation 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.[15] Subsequent presidents watered down further U.S. 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 cycle that avoided reprocessing. Ironically, industry saved a lot of money over the last nearly 30 years by adopting this approach, however reluctantly, because commercial reprocessing and recycle of plutonium as fuel is highly uneconomical.[16] 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.[17] 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 would not provide any additional security because, anyhow, it was easy to extract the plutonium from spent fuel using small jerry-built plants that most countries could build quickly and secretly. Although they did not 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.[18] 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 be hidden easily.[19] The argument based on this report did not 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.

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 as the 1977 Oak Ridge study. The godfather of the study was Floyd Culler, then 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."[20] 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 4 to 6 months from the start of construction, with the first 10 kilograms of plutonium metal (about two bombs' worth) produced about 1 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 five 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 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 weapons components takes about 1-3 months,[21] but the Agency's resource limitations and the resistance of member countries keep the actual inspection frequency of LWR inspections lower than once every 3 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 bombmakers. 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 in the past has not led 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 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 (GAO) prepared an evaluation for Congress.[22] The GAO examined reviews of the Oak Ridge memorandum by five Federal agencies and a number of individuals.[23] It raised questions about how 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 only after a dissident Iranian group specified the coordinates.[24] 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 which states that "plutonium can be separated from spent nuclear fuel with modest facilities and equipment."[25] This 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.[26] 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 six technicians was about 8 months, which is even more optimistic than that of the Oak Ridge team about 20 years earlier.

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).[27] 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.[28]

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.[29] Whether or not a country might opt for a "quick and dirty design facility," it would have the possibility of building one with a lower probability of malfunction and with smaller tell-tale releases.

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

Contrary to Conventional Wisdom, LWRs Can Be a Copious Source of Near-Weapons 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 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 did not 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 have appeared 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.[30] 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 pre-initiation 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 U.S. 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 U.S. 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.

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.[31]

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.[32] Selden's summary slide stated: "Reactor grade plutonium is an entirely credible fissile material for nuclear explosives."[33]

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.[34]

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 LWRs 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 regarding 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.[35] The operators refuel the reactor about every 18 months. The fuel elements normally stay in the reactor for three fuel cycles, or about 60 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.[36]

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 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.[37] This comes to about 30 bombs' worth. Does a would-be nuclear weapons 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 an 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 was not 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 6 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, one-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.[38] At each normal refueling, the operator has available 25 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 U.S.-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 U.S. 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? The Nonproliferation Policy Education Center (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.

The subject of illegal construction of nuclear explosives also was earlier reviewed in technical detail by J. Carson Mark, late T-Division head at Los Alamos National Laboratory (LANL), in a 1990 report.[39] 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 weapons 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 that 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.

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.

	% Probability that Yield is Between 1 and 5 Kilotons: Percent	**% Probability that Yield is Between 5 and 20 Kilotons: Percent**	**% Probability that Yield is Not Less Than 20 Kilotons: Percent**	**Estimated Average Yield in Kilotons: Percent**
1945 Trinity shot 1% plutonium-240 **(actual)**	4	6	88	19
Calculated:				
Trinity technology				
WGPu	21	23	44	13
1st cycle LWR	**36**	**23**	**12**	**5**
Trinity technology x 2				
WGPu	12	14	66	15
1st cycle LWR	**25**	**25**	**34**	**10**
Trinity technology x 3				
WGPu	8	12	76	16
1st cycle LWR	**18**	**22**	**49**	**12**

Table 1. Probability of Achieving Various Explosive Yields and the Expected Yield for 1945 U.S. Technology and for Two Improved Levels Using Weapons Grade Plutonium (WGPu) and 1st Cycle LWR Plutonium.

The last column is especially interesting. It provides 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 quite 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 Table 1).

A country attempting to build nuclear weapons today could take advantage of the wide availability of declassified nuclear weapons 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.[40] At this level of design, a would-be nuclear state 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 five kilotons. It should be remembered that the minimum, or fizzle, yields will likely be at least as large as that of Trinity—around one kiloton—and that this guaranteed yield already is 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 keeping 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 1 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 U.S.-DPRK nuclear deal, two large LWRs whose plutonium production capacity turned out to be 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.

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.

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

1. *Role of LWRs*. The 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 constantly has 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*. Increase IAEA inspection frequencies for LWRs to check on fuel inventories and whether refueling needs adjustment upward in countries of concern from the point of view of potential bombmaking and to take account of possible undiscovered clandestine reprocessing. Because of inevitable IAEA resource limitations, it is necessary for the agency to concentrate inspections 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 bombmakers 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.

ENDNOTES - CHAPTER 5

1. 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.

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

3. 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 United States.

4. The relevant figures for the percentage composition of plutonium in spent LWR and HWR fuels are given in the chart below:

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

5. For example, the two LWRs promised North Korea in a 1994 U.S.-DPRK agreement were nearly 10 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.

6. 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."

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

8. 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. See www.hipakistan.com/en/detail.php?newsId=en62190&F_catID=17&f_type=source&day=.

9. See Justin T. Long, Engineering for Nuclear Fuel Reprocessing, American Nuclear Society, 1978. This volume of over 1,000 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 from 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.

10. 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.

11. 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 U.S. Government has so far not reacted to this very suspicious and worrisome state of affairs.

12. 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.

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

14. 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 U.S.-origin fuel. That meant Iran would now have the same right as Japan to reprocess U.S.-enriched power reactor fuel. The Shah left Iran before the negotiations were concluded. See *Nucleonics Week*, January 12, 1978, pp. 2-3; in Daniel Poneman, *Nuclear Power in the Developing World*, George Allen & Unwin: London, 1982, p. 88, at www.nti.org/e_research/profiles/Iran/1825.html.

15. Carter rapidly reversed himself on the issue of Japanese reprocessing of U.S.-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.

16. 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.

17. That is what Sigvard Eklund, the IAEA Director General, told one of the authors in conversation in 1976. To correct this view, the U.S. 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.

18. One needs to reemphasize, because it is so frequently forgotten, that the initial rejection of U.S. 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.

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

20. The diagram appears in the Washington Post, 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.

21. IAEA 2001 Safeguards Glossary, p. 22, available on the IAEA web site, www.iaea.org.

22. 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 the Oak Ridge report and the Oak Ridge memorandum.)

23. 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 11 individuals 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.

24. According to rumor, they served as a conduit for Israeli intelligence.

25. 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.

26. 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 United States and Russia.

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

28. 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.

29. 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.

30. 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.

31. In time, the Atoms for Peace program permitted the U.S. 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."

32. 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 U.S. 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).

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

34. 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:

> 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 U.S.-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.

35. In nearly 200 fuel assemblies containing over 40,000 fuel rods.

36. 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 a fuel and will have a composition higher in plutonium-239 than the fuel that remains in the reactor longer.

37. 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, 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 U.S.-DPRK Agreed Framework, "Verifying the Agreed Framework," Michael May, General Editor, UCRL-ID-142936/CGSR-2001-001, April 2001.

38. 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:

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

Table. Plutonium Mixtures for Explosive Purposes.

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.

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

40. An initiator is a contrivance that injects neutrons into the device at the proper moment—when the nuclear explosive has been compressed to a supercritical state—to start the explosive chain 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.