NUCLEAR POWER NEED NOT LEAD TO THE ACQUISITION OF NUCLEAR WEAPONS

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Abstract.

Although nuclear power and nuclear weapons both exploit the physical phenomenon of nuclear fission in uranium or plutonium, a civil nuclear weapon program need not lead to or even be close to a nuclear weapons program. And a nuclear weapon program need not be accompanied by a program for the exploitation of nuclear power. The world already possesses a useful framework under the Non-Proliferation Treaty and the International Atomic Energy Agency for providing assurance that a civil program is not involved with a counterpart nuclear weapon program, and these should be strengthened and expanded. A new approach gaining wide support is the "secure," "multilateral," or "internationalized" fuel cycle, in which fresh fuel for nuclear power plants is leased and relatively soon after discharge the spent fuel from the reactor is taken back or otherwise removed from the using country under international supervision and regulation. The Nonproliferation Treaty needs to be strengthened by additional agreements on the misuse of nuclear energy materials and facilities acquired for peaceful purposes.

Introduction

The United States exploded the three first nuclear weapons in 1945 and immediately began a program to explore the further military uses and to amass a suitable stockpile. At the same time, many of the scientists, engineers, and industries active in the nuclear weapon program during World War II in the United States turned to nuclear power. This was first applied to the propulsion of naval vessels, including submarines, and soon after that to the demonstration and deployment of civil nuclear power plants.

In order to maximize the probability of success in the acquisition of nuclear weapons and to ensure that such weapons would be created as soon as possible for use in the battle of survival against Nazi Germany, the United States chose several approaches to the acquisition of the nuclear-weapon usable material-- highly enriched uranium or plutonium. On the uranium side, of course the source material is natural uranium containing 0.71% U-235. U-235, the fissile isotope, readily breaks into two lighter nuclei with the addition of a neutron even of zero energy. In contrast, U-238 has a threshold neutron energy of about 1.5 MeV, below which its fission probability is very small. Hence if uranium is to be used in the neutron chain reaction that is at the base of a nuclear weapon, the uranium must be enriched in U-235 and correspondingly reduced in the fraction of U-238 that is present.

The U.S. experimented with various means to separating the isotopes, emphasizing physical approaches that depend only on the difference in mass of the uranium component of some molecule or of the atom itself. Most convenient, though, is the fact that uranium has a stable (although chemically reactive) gaseous compound, UF6, and fluorine is ideal for molecular enrichment processes because it has only a single isotope and so does not blur the mass spectrum of UF6. Still, the U.S. investigated thermal diffusion and gas centrifuge before settling on the electromagnetic ("Calutron") process and then on gaseous diffusion as its production means during the war and ever since. Other countries, more recently, have used the gas centrifuge process for enrichment, and expend only about 2% as much energy in the process as is required for gaseous diffusion.

Most nuclear power plants are now operated with ordinary ("light") water, which is incapable of sustaining a chain reaction with natural uranium, even if the uranium is divided optimally into pellets or rods, so that the fission neutron with an energy of about 2 MeV escapes from the metal or uranium oxide material and slows down in water, in order that it have a high probability of fission when it again encounters a U-235 nucleus. But these light-water reactors (LWR) readily carry on a chain reaction with fuel enriched in the 3-5% range.

Heavy-water reactors are usually operated with natural uranium, and they have advantages and disadvantages-- one advantage being that they do not require costly enrichment. Many HWRs are operating throughout the world-- most of them sold by Canada as the CANDU reactor. And pure graphite has been widely used with natural or very low enriched uranium, as in the case of the Soviet-produced RBMK reactors, notorious from the disaster at Chernobyl but a good performer elsewhere.

Nuclear power is not a necessary prelude to nuclear weapons.

But nuclear power was not in any way necessary and is in no way necessary now for a nuclear weapons program. A state could, of course, buy nuclear weapons from another state or buy highly enriched uranium –HEU-from which to make its nuclear weapons. A nuclear weapon depends upon the assembly of an amount of material that is greater than the "critical mass," a term applied to the minimum mass of material of a given density and composition that will carry on a self-sustaining chain reaction. That critical mass is least for a sphere, and critical masses are usually given as "bare-sphere critical mass" at normal density.

As explained in my books with Georges Charpak[1] and Venance Journé[2] and, of course,

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[1] R.L. Garwin and G. Charpak, *"Megawatts and Megatons: the Future of Nuclear Power and Nuclear Weapons"* The University of Chicago Press, January 2003.

elsewhere!), the critical mass is dependent on density and also on the geometrical form of the material. For instance, 60 kg of pure U-235 in the form of a thin shell 100 cm in diameter is subcritical. But if that shell were gently squeezed so that it became a solid ball at the normal density of metallic uranium-- 19.05 g/cm^3-- it would be just critical and a neutron injected would produce with high probability on the average 2.5 neutrons, about one of which would remain in the ball to cause another generation of fissions.

In just the same fashion, if that ball were now squeezed to double normal density, it would be far more than critical, and most of the fissions would result in more than one neutron that remained in the material. In fact, the critical mass is a factor 4 smaller at double density.

It is important for the existence of a fission weapon that the fission process be "prompt," that is, that it not take a second, a year, or even a millisecond. It did not have to be this way. For instance, if the capture of a neutron in uranium led to another isotope that itself was subject to spontaneous fission with some considerable lifetime, the neutrons could multiply gradually but there would be no explosion. If the core were sufficiently well insulated, it might melt but not explode.

In reality, fission takes place in a time that is not readily measurable-- far below one picosecond, and the time between generations is the time for the neutron to

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[2] G. Charpak, R.L. Garwin, and V. Journé, *"De Tchernobyl en tchernobyls"* (in French), Editions Odile Jacob, September 2005.

travel in the solid material to have another collision-- the distance on the order of 7 cm in uranium. With a neutron velocity of 20,000 km/s corresponding to its energy, of 2 MeV, this is about 3.5 nanoseconds.

If one can somehow achieve a mass that is substantially supercritical, then a few neutrons injected at a given time (from cosmic rays or the results of radioactivity or so-called spontaneous fission) will grow exponentially, doubling every 3.5 nanoseconds, approximately, and so growing to consume essentially the whole mass in a time that is simply the (natural) logarithm of the number of atoms in the fissile mass. This corresponds to about 60 "generations" (factors of *e*) or 87 doublings (factors of 2).

The enormous energy density and pressure lead to the rapid expansion of the fissile mass in the later stages, cutting short the neutron chain reaction before it has consumed the entire mass. Nevertheless, with a total fissile energy yield of 17,000 tons of high explosive equivalent per kilogram of fissile material (17 kt/kg), the Hiroshima bomb that had about 60 kg of U-235 and a yield of 13 kt thus had an efficiency of about 1.3%. With about 6.0 kg of Pu-239, and an explosive yield of 20 kt, the Nagasaki bomb (and the test at Alamogordo, New Mexico in July 1945) had efficiency of the order of 20%.

Beyond the acquisition of the fissile material and its transformation into metal, there is the question of the assembly of the nuclear weapon, keeping it safe before it is supposed to go off, and detonating it reliably when it is to be used. The gun-type assembly consists typically of dividing the fissile mass into two sub-critical pieces, and projecting one down a gun barrel with the aid of normal smokeless power propellant so that it "assembles" with the other. That is what was done with the

Hiroshima bomb. It is quite simple in principle and can be practiced with inert material such as natural uranium metal.

The implosion weapon that can be built with 6 kg of Pu or about 20 kg of U-235 is much more complicated and involves large amounts of high explosive, multiple precision detonators, and the like. In any case, a nuclear explosion is impossible without the adequate amount of fissile material-- typically U-235 from enrichment, Pu-239 from reprocessing of fuel that has been in a reactor, or some other isotopes such as neptunium, that are lesser components of the spent nuclear fuel.

In contrast, a nuclear power reactor is much more complicated in principle and in design than is a gun-type nuclear weapon. That is because a major problem in nuclear reactors (especially for the production of commercial electric power) is the safe operation at a constant power level and the removal of heat to be used to drive a steam turbine or other "heat engine" in turn to drive generators or alternators to produce the electrical power. A bit more heat is available per fission in a nuclear reactor than in the explosion of a nuclear weapon because the short-term radioactive decays that contribute only to the radioactive fallout or immediate radiation from a nuclear explosion cloud contribute also their heat to the heat transfer fluid ("coolant") in a nuclear reactor. Furthermore, the sub-picosecond time for fission and the few nanosecond time between generations in a metal chain reacting system are no friends to the reactor designer. In fact, of crucial importance in almost all reactor designs is the fact that with U-235 about 0.6% of the neutrons from fission are "delayed" by an average of ten seconds (ranging from one second to about 100 seconds) because the neutrons are not emitted in the fission process itself, but from the very highly excited fission products. Most of the neutrons are emitted from fission products in the fraction of a nanosecond before they come to rest, but the

0.6% that are much longer delayed are crucial to the ease of control of the chain reaction in producing useful heat and electrical power.

Furthermore, although one can have a chain reaction with as little as 0.5 kg of U-235 dissolved in water and surrounded by a reflector of graphite or beryllium, not much power can be extracted from such a small reactor. And the fuel would not last very long, since a typical reactor of 1000 megawatts electric (1000 MWe) operating at an efficiency of 1/3 has a thermal power of 3000 MWt. Each MWt-day corresponds to the fission of about one gram of U-235 or other fissile material, so a typical power reactor destroys 3 kg of U-235 per day converting into just about that much fission products. Hence the power reactor has to have a lot of fuel and typically contains on the order of 100,000 kg of fuel, at an enrichment of approximately 4%.

If the fuel remains in the core on the average for four years, with 25% of the fuel replaced each year, this means that the typical reactor is fed 25 tons of low-enriched uranium—LEU-- per year containing about one ton of U-235.

The spent fuel as it is removed from the reactor (25 t per year) would glow red hot and even melt if it were not immersed in water, and refueling of the reactor is typically done without exposing the fuel to the atmosphere. The background of radiation from the continuing gamma and beta radioactivity of the fission products is fierce, and so refueling is done remotely behind heavy reactor shields and with the use of transfer casks and other appropriate shielding.

The spent fuel is typically transferred to so-called pool storage ("swimming pool") at the reactor site, where the fuel elements, themselves 500 cm long, are stored vertically in a grid pattern, with another 500 cm of water covering them to provide a "biological shield" so that people can work near the storage facility. After some months or years or decades in pool storage, the spent fuel is normally shipped in shipping casks for entombment in a mined geologic repository or to be reprocessed and to have the fission products and so-called minor actinides (the heavy metals other than uranium and plutonium) sent to such a repository.

Proliferation hazard from reprocessing, enrichment, or spent fuel

The routine civil reprocessing operation either separates plutonium or separates plutonium accompanied by a modest amount of other material) so that the product could readily be processed chemically to obtain pure plutonium usable in nuclear weapons.

Spent fuel itself is a potential source of plutonium for nuclear weapons, but it contains only about 1% plutonium, and is much more radioactive than is the product of reprocessing that contains plutonium.

Hence both the front end of the nuclear fuel cycle (enrichment) and the back end of the nuclear fuel cycle (spent fuel and reprocessing) can be sources of fissile material for nuclear weaponry, and since the 1950s there has been an intense effort among nations to prevent the non-state and to discourage the state acquisition of nuclear weapons. Chief among the tools are the 1970 Non-Proliferation Treaty and the U.N. agency, the International Atomic Energy Agency.

The Nonproliferation Treaty –NPT– initially admitted five states as Nuclear Weapon States (NWS) that had detonated a nuclear explosion before 1964, and was open to adherence by other states as Non-Nuclear Weapons States (NNWS) that committed themselves not to obtain nuclear weaponry and were thereby granted, in principle, favored treatment with the provision of information training for the peaceful uses of nuclear energy.

The NPT allows a state operating as an NNWS to acquire and operate reactors and to ensure that they are used for peaceful purposes, but three months after giving notice, those same facilities (if unrestricted in their acquisition) could, without legal hindrance, be turned to the production and extraction of Pu-239 for weapons. Similarly, an enrichment plant of gas centrifuge or other design could after three months be turned to making HEU instead of LEU. Since these enrichment techniques for the most part produce only a tiny increase in concentration of U-235 in the material, many stages are required. The simple gaseous diffusion plant operating with a mass ratio different from unity by only 0.86% can have at most an enrichment per stage half of that, or 0.43%-- i.e., a stage concentration ratio 1.0043.

The situation is more complicated in a gas centrifuge that is usually operated in a regenerative mode, and in which the heavier molecules equilibrate toward the outside of the rapidly spinning cylindrical shell. A production centrifuge such as that used in Pakistan can have a stage concentration ratio 1.2-1.4. To be definite, we take 1.2, for which about 90 successive stages are required to go from the 0.7% U-235 of natural uranium to the 90% U-235 in highly enriched uranium-- HEU-- used for nuclear weapons. For LEU of 4% Ul-235 content, about 30 successive stages are required.

Of course, the "cascade" of centrifuges is tapered, so that there are many more at the feed point of 0.7% U-235, where UF6 is introduced, and far fewer at the takeoff point for the enriched product. An intermediate number is present at the lower end of the cascade, where the "tails" are removed, typically at a U-235 content of 0.2-0.3%.

Terrorists might acquire either HEU or weapon-usable Pu from the military stocks of the former Soviet Union-- FSU. It would be much easier for them to fashion the HEU into a nuclear weapon by gun assembly. Implosion assembly as is required for Pu is much more difficult. Terrorists or non-state actors might also acquire HEU from Pakistan and Pu from the vast stores of so-called civil Pu that has been separated from spent fuel in France or Great Britain and has been returned to Japan or other countries and not yet incorporated into fresh mixed-oxide-- MOX-- fuel for LWRs.

Nevertheless, the subject of this paper is state actors that wish to have a nuclear power sector and wish not to have nuclear weapon programs. A clandestine nuclear weapon program is always a possibility, and that could employ enrichment-- probably centrifuge enrichment-- starting either from natural uranium or from LEU as supplied for their nuclear plants. There could also be clandestine "production reactors" or diversion of spent fuel from the civil reactors, and a clandestine reprocessing plant.

Neither enrichment nor reprocessing is at the cutting edge of technology, and although it is the "inalienable right" of nations to practice such technology-- even under the NPT as an NNWS-- there is no reason for them to do so on balance.

Thus our interest is in devising a system of supply of fuel or fuel materials so that nations could have assured access to nuclear power while clearly not having a nuclear weapon program.

The secure fuel cycle as a basis for non-proliferative use of nuclear power

In principle this can be simply stated. States could be supplied either with ready-to-use fuel elements for their reactors (fabricated into fuel rods and assembled into "bundles" ready for installation in the reactor) or they could be provided with the fuel pellets and could, if they wished, package them into fuel rods and elements themselves. The question for the using nation is assured supply from multiple sources, in view of the fact that the United States, for instance, has placed impediments to the acquisition of nuclear technology that some argue are unacceptable under the NPT.

Multiple sources of supply of fresh fuel would help, as would the ability to buy fuel several years in advance-- sufficiently far in advance so that a nation, if the fuel supply were cut off, would have time to build the native capacity for enrichment and fabrication to continue to operate its nuclear power sector.

It is instructive to estimate the cost of an enrichment facility, and what it might do for either producing nuclear weapons material or for feeding a civil nuclear power sector. Take for example the 50,000 centrifuges that are planned for installation at Natanz, Iran. If these are P1-type centrifuges as used in Pakistan, the estimated enrichment capacity of each centrifuge operating for a year is 2 separative work units (2 SWU/yr). It takes a bit of arithmetic to determine the number of SWUs necessary in an optimal enrichment capacity (approached by a proper array of centrifuges) to produce 1 kg of U-235 contained in HEU or, alternatively, contained in 4% LEU[3].(3)

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[3] *“Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options (1995)”* CISAC, pp.288-289), National Academies Press, available at http://darwin.nap.edu/books/0309051452/html/289.html

Suffice it to say that to go from 0.7% NU to 95% HEU requires 232 SWU/kg of U-235 contained in the product, whereas to go from 0.7% to 4.4% requires 151 SWU/kg U-235 contained in the product. The following table provides some useful SWU-content values, which depend on the U-235 content of “feed” and “tails” (waste).

SWU per kg for various enrichment parameters.

R.L. Garwin, 04/25/05 SWU_Calculations (version 2).xls

	Xp (product)	Xw (waste_	Xf (feed)	P kg of product	W/P	F/P	Vp	Vw	Vf	ΔSWU/kg P	ΔSWU/kg of U-235 in product
1	0.95	0.0025	0.00711	1	204.53	205.53	2.65	5.96	4.87	220.75	232.37
2	0.95	0.0025	0.044	1	21.83	22.83	2.65	5.96	2.81	68.64	72.25
3	0.95	0.0025	0.199	1	3.82	4.82	2.65	5.96	0.84	21.38	22.51
4	0.95	0.04	0.044	1	226.50	227.50	2.65	2.92	2.81	26.15	27.53
5	0.95	0.04	0.199	1	4.72	5.72	2.65	2.92	0.84	11.66	12.28
6	0.95	0.15	0.199	1	15.33	16.33	2.65	1.21	0.84	7.57	7.97
7	0.95	0.18	0.199	1	39.53	40.53	2.65	0.97	0.84	7.03	7.41
8	0.044	0.0025	0.00711	1	8.00	9.00	2.81	5.96	4.87	6.66	151.41
9	0.95	0.005	0.00711	1	446.87	447.87	2.65	5.24	4.87	163.79	172.41
10	0.95	0.044	0.199	1	4.85	5.85	2.65	2.81	0.84	11.35	11.95
11	0.199	0.00711	0.044	1	4.20	5.20	0.84	4.87	2.81	6.69	33.62

Table 1. Separative work content per kg of contained U-235 at various enrichments

We already know that a nominal 1 GWe civil power plant consumes about 1000 kg/yr of U-235 as LEU, so that the SWU requirements for feeding that reactor are about 151,000 SWU/yr.

Natanz would provide only about 2/3 of the continuing fuel needs of a single reactor such as that almost ready for operation at Bushehr. But that plant could readily be reconfigured by changes in the small-diameter tubing into a cascade optimal for producing HEU, and for that it could produce 50,000 x 2/232 = 430 kg of 95% HEU per year. At 20 kg of HEU per implosion bomb, this would be on the order of 22 bombs per year. At 60 kg of HEU per Hiroshima-type bomb, this would be on the order of seven bombs per year.

The point is that even such a large facility as Natanz would be only marginally useful in the civil nuclear power sector, but it would provide a very substantial bomb-making capacity.

If instead of feeding 0.7% U-235, the cascade were fed from a stock of 4.4% LEU, only 72 SWU need be added per kg of U-235 in the HEU product. Natanz would therefore be able to produce on the order of 100,000/70 = 1384 kg of HEU per year or about 70 implosion-type nuclear weapons. Hence the need to account for and to have international intervention to prevent diversion of the stockpile of LEU that might be supplied under an internationalized secure fuel cycle.

The protection of the spent fuel from the reactor is less critical, especially in the absence of a reprocessing plant in the using nation. Furthermore, the using nation would be less concerned about the international community’s promptly fulfilling its obligations under a secure fuel cycle arrangement to transfer the spent fuel from the using nation. So far as the continued operation of the nuclear power plants is concerned, the using nation could inexpensively provide additional spent-fuel storage, as needed.

A comment about the Global Nuclear Energy Partnership—GNEP[4]

Launched in February 2006 with a statement by President George W. Bush, GNEP has the stated goals of reducing proliferation hazards and encouraging the growth of safe nuclear power worldwide. The secure fuel cycle aspects of GNEP—leasing of LEU fuel and its take-back for disposition—deserves priority support and would be helpful for non-proliferation, but the enormous initiative to reprocess spent fuel from the fleet of 103 US power reactors surely is not helpful in nonproliferation efforts. Whether through ignorance or deception, the argument that a reprocessing technique such as COEX, proposed by AREVA, is significantly less vulnerable to diversion or theft of the plutonium-containing material is wrong. The proposed mixture of 1 kg of Pu with 2 kg of U provides no further radiation barrier than does Pu itself, and the Pu and U are readily separated in a glove box, on the way to the conversion to Pu metal, which is needed for the bomb. And a recent report[5] by

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[4] R.L. Garwin, Testimony of April 6, 2006 to the Energy Subcommittee of the House Science Committee, available at www.fas.org/RLG/

[5] *“Economic Assessment of Used Nuclear Fuel Management in the United States,”* Boston Consulting Group, July 25, 2006. http://www.bcg.com/publications/files/2116202EconomicAssessmentReport24Jul0SR.pdf

the Boston Consulting Group, supported by AREVA, ignores a May, 2006, report by the industry-sponsored organization, EPRI[6], that concludes that the technical capacity of the US spent fuel repository at Yucca Mountain, Nevada, is at least 4 times larger than the limit now mandated, and probably 9 times larger.

Action required by the international community

In order to implement rapidly the secure fuel cycle in a confident fashion, there must be an initiative to allow competitive, commercial, mined geologic repositories and to establish international regulation of those repositories to ensure security and environmental acceptability. Similar regulations are needed to define and enforce acceptable forms and packages of spent fuel and reprocessed high level waste so that commercial deals can be made on a level playing field. Similarly, regulations are needed to provide the basis for international intervention to prevent or respond to the misuse of materials provided in the secure fuel cycle.

Outside the secure fuel cycle, states should be strongly urged to adopt a further Additional Protocol to the NPT that would commit them to returning to

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[6] *"Program on Technology Innovation: Room at the Mountain – Analysis of the Maximum Disposal Capacity for Commercial Spent Nuclear Fuel in a Yucca Mountain Repository,"* EPRI, Palo Alto, CA, 2006. 1013523 (at www.epri.com).

the supplier any material or facilities obtained by the state as a NNWS member of the NPT. Thus it would no longer be possible for a state such as North Korea to reject its NPT membership and to continue to use facilities or materials supplied or built while a NNWS member of the NPT. Naturally, to encourage NNWS states to adopt such an additional protocol, the NWS, particularly the United States, must take more seriously their obligations under the NPT and the commitments they have made at the various 5-year NPT review conferences.

Although this paper has not addressed non-state acquisition of nuclear weapons, I hope that it has made the point that even a large nuclear power sector such need not lead to the acquisition of nuclear weapons.

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