Living with Nuclear Weapons: Sixty Years and Counting[1]

RICHARD L. GARWIN[2]
IBM Fellow Emeritus, Thomas J. Watson Research Center

IN HIS MEMORABLE PRESENTATION of 16 November 1945, J. Robert Oppenheimer began with the theme of unaccustomed secrecy and then proceeded to his main point, which was that nuclear weapons, during our lifetime, "could be either a great or a small trouble. They cannot be a small hope. They can be a great one."

Oppenheimer judged that if nuclear weapons were used again, it could well be by the thousands or tens of thousands, and that the use of many nuclear weapons could lead to the destruction of civilization. He noted also that "wherever reactors are in operation there is a potential source, not necessarily a convenient one, of materials for weapons."

Oppenheimer also commented that the much-observed $2 billion cost of the Manhattan Project to obtain the two bombs used to destroy Hiroshima and Nagasaki was highly misleading if used to calculate the cost of a bomb at $1 billion, and that any reasonable assessment should lead to a number even a thousand times smaller. He could not say even a few words about the construction of nuclear weapons, because President Truman had formally banned publication of such information beyond the highly informative but qualitative *Smyth Report* of August 1945.[3]

Oppenheimer spoke with the authority associated with his having directed the Los Alamos Scientific Laboratory from its inception in March 1943 through the assembly and delivery of the two nuclear weapons over Hiroshima and Nagasaki and the prior 16 July 1945 detonation of the implosion weapon at Alamogordo, New Mexico.

Los Alamos was created to assemble the weapon-usable material to arrive from Oak Ridge in the form of highly enriched (at least 90% U-235, compared with the 0.711% U-235 in natural uranium), and the artificial fissionable isotope plutonium-239 that would arrive from

---

[1] Read 30 April 2005.

[2] http://www.fas.org/rlg/.

[3] http://nuclearweaponarchive.org/Smyth/Smyth12.html.

the 200-megawatt (thermal) reactor at Hanford, at the rate of about 0.2 kg per day.

Oppenheimer led the Los Alamos effort with inspiration and excellence. His choice for that role was itself an inspired one by the managing genius of the Manhattan Project, Brigadier General Leslie R. Groves.

By all reports, Oppenheimer had a deep understanding of everything that passed at Los Alamos, both theoretical and experimental, and guided with a sure hand both substance and process.

Oppenheimer was thus seized with the problem of the proliferation of nuclear weapons—one that is currently at the top of the talk, but not of the action, in the United States and in other leading countries. Where do we stand now on the beneficial uses of nuclear energy, on the number of nuclear weapons and the readiness to use them, and on the effort to obtain security by limiting proliferation?

First I present the facts and then my own views.

The "Peaceful Use" of Nuclear Energy

More than a million intense radioactive sources are in use worldwide[4] for industrial radiography, cross-linking of plastics, and food sterilization. Powerful sources are also used in radiation therapy for cancer, and weak sources in the ever-present nuclear scans for heart disease, and for other medical diagnostic purposes. By far the greatest investment and perhaps most visible aspect of things nuclear is the more than four hundred nuclear reactors worldwide, equivalent to about three hundred million-kilowatt power generators. A bewildering variety of practical fission reactors for extracting energy from the uranium nucleus is represented in a mere three types:

- Light-water reactors
- Heavy-water reactors
- Graphite-water reactors

Enrico Fermi and his group in Rome clearly saw the products of fission in their experiments with slow neutrons on uranium, beginning in 1934, but it was not established until late 1938 that this was the "fission" or breakup of the uranium nucleus into two very large fragments, despite work in many laboratories in the intervening four years. By 1939, Fermi and others had realized that the 0.7% abundant light isotope of uranium—U-235—was subject to fission by a neutron of any

---

[4] L. M. Branscomb (co-chair) and R. D. Klausner (co-chair), et al., *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism* (Washington, D.C.: National Research Council of the National Academies, National Academies Press, 2002).

energy, and each fission would yield about 2.5 neutrons in turn, on the average. If two of these neutrons caused another fission, then (roughly speaking) a neutron introduced would become 2, 4, 8, et cetera, and would soon lead to fission of much of the mass. In uranium with a high concentration of U-235, this would constitute "an atomic bomb," and all that would be required would be a sufficient mass (more than a critical mass) of U-235 in order that more than one of the fission neutrons would cause fission instead of escaping harmlessly from the assembly. Of course, it is a "nuclear bomb" rather than an "atomic bomb."

Fermi created the first self-sustaining nuclear chain reaction in the graphite "pile" under the west stands of the Stagg Field stadium at the University of Chicago on 2 December 1942, and remained at Chicago to participate in the design of the plutonium production reactors at Hanford, Washington. The scale-up from the two-watt operating level of the Chicago reactor to the 200-megawatt Hanford plant required attention to the high levels of radioactivity produced, and to preventing the reactor from overheating by the use of Columbia River water for cooling. That work laid the basis also for later use of reactors not primarily for the production of the fissile isotope plutonium, but for heat to produce electricity. The direct descendants of those reactors now account for almost 20% of the world's electricity production.

Many experiments had shown Fermi at Columbia University that natural uranium, no matter how pure, would not produce a chain reaction, because of the absorption of neutrons by U-238—the 99.3% abundant isotope. But isotopic enrichment was a thing of the future, in the amounts required to make either a self-sustaining controlled nuclear reaction or a nuclear explosion.

It was clear, however, that even so-called thermal neutrons in pure natural uranium would provoke more fission than absorption under the right conditions, despite the low concentration of U-235.

A neutron in ordinary material does not die a natural death (that takes about twelve minutes and can be observed only in free space). Rather, it is gradually slowed by elastic (billiard-ball) collisions or more rapidly slowed in large leaps by inelastic collisions in U-238 that do not provoke fission but only the emission of a few gamma rays. What is worse, the intermediate energy range for U-238 is fraught with "resonances" that lead to a very big absorption probability for the neutron in its slowing to thermal energies.

More specifically, a fission neutron starts at about 2 million electron volts (2 MeV) or an energy about 0.2% of its rest mass. Its speed correspondingly is some 7% of the speed of light, or about 20,000 km/s. In contrast, a thermal neutron at room temperature has a characteristic energy of the order of 1/40 eV, and a velocity around 2 km/s. The idea of the nuclear reactor fueled with natural uranium depends on "moderating" the neutron (slowing it down) in repeated elastic collisions. A billiard ball will lose all its energy when it collides frontally with another billiard ball. Similarly, hydrogen nuclei would cause the neutron to lose most energy per collision, but hydrogen has an excessive appetite for neutrons. And that is why ordinary water cannot be used with natural uranium to make a nuclear reactor.

Deuterium (hydrogen with mass two) is almost as good at slowing neutrons, although no single collision can lead to a low-energy neutron, and deuterium absorbs only a tiny fraction of the neutrons. Heavy-water moderated reactors contribute about 10% of the world's nuclear-electric power.

In any natural-uranium reactor, the uranium is present either in the form of metal or in the form of pure oxide in lumps or rods arranged in a "lattice" in the moderator. Heavy water or pure carbon makes a good moderator, and the Chicago reactor was made with 6 tons of uranium metal, 40.5 tons of uranium oxide, and 385 tons of graphite. It operated with a power of a paltry 2 watts. Since fission is a linear process, the power in the reactor could have been allowed to rise to 1 kW or even 1 MW, were it not that the fissions and the capture of the neutrons lead to radioactive materials and intense gamma radiation. The reactor had no shielding of those emitted radiations, which would have been harmful to nearby personnel. The high level of fissions would have made the reactor too radioactive for manual disassembly.

The first reactor was not created in the interest of science, for which it was a marvelous tool, but because of the realization—first, probably by Leo Szilard—that fission could be used to make a nuclear weapon. The Nazis were on the march in Europe. By 7 December 1941, the United States was also in the war against Japan and Germany.

The reactor was not necessary to build a fission bomb. But because isotope separation was chancy (although there were several approaches that might be used to separate U-235 for making the core of an "atomic bomb"), another approach was taken, in order to see whether it was possible to use natural uranium in a "pile" to create a nuclear reaction of sufficient duration and intensity that the neutrons absorbed in U-238 would make another easily fissionable isotope, Pu-239. That would be analogous to U-235, in having an even number of protons and an odd number of neutrons, so that the addition of another neutron would give rise to a considerable energy excess in the resultant nucleus, which would then, for the most part, fission rather than decay by the emission of gamma rays. Making 5 or 10 kilograms of this artificial element, plutonium, might be easier than separating the 0.7% of uranium that is U-235 from tons of natural uranium of identical chemical properties.

The U-235 weapon could be built in the form of an ordinary short-barreled gun for rapidly assembling two masses of metallic HEU, and there was such confidence that it didn't need to be tested.

The uranium gun was used on 6 August 1945 to destroy Hiroshima, and the plutonium implosion weapon three days later destroyed Nagasaki. Each of these bombs weighed about four tons, but it was clear that the same devices could be built with less conservatism and more experience in much lighter configurations. It was also clear to the scientists that a nation such as Russia, starting from the simple knowledge that the United States had detonated a nuclear explosive, could build one in about four years. The Soviet Union did detonate its first nuclear explosive on 29 August 1949. It was a carbon copy of the Nagasaki bomb.

After August 1945, most of the scientists involved at Los Alamos had dispersed to their universities, but some remained, with much of the support staff, to continue to develop nuclear weapons and to work on the dream of a hydrogen bomb—a thermonuclear explosive.

With the fission process a reality, others pursued the goal of peaceful applications of nuclear energy, prime among them commercial electric power from nuclear fission. This was greatly aided in the United States by the availability of enriched uranium, so that compact nuclear reactors could be built to produce, for the first time, a true submersible that could cruise deep under water for months at a time. So the nuclear-powered attack submarine—SSN—was born. With the advent of long-range missiles, some of the SSNs were cut and stretched to become ballistic-missile-launching submarines—SSBN—the Polaris and Poseidon missile systems.

With the experience of the large room-temperature reactors at Hanford and the high-temperature steam-producing submarine reactors, American industry was in a good position to build commercial reactors. These did not need to be as compact (nor could they be, because of their much larger power) as the submarine reactors, and so they used only slightly enriched uranium—LEU. A modern light-water moderated reactor contains about 100 tons of uranium as uranium-oxide ceramic in long jackets supplied in bundles of several hundred fuel elements containing initially about 3–4% U-235. Some 25 tons of the core is replaced each year. A typical LWR operates at a thermal power output of 3,000 MW, producing about 1,000 MW of electrical power, enough for a city of almost a million people. It was one of the LWRs in Pennsylvania that became notorious in 1979 as "Three Mile Island" when its core largely melted and the extremely radioactive burden escaped but, fortunately, did not cross the containment dome.

Not having access to enriched uranium, Canada built reactors that are moderated and cooled with heavy water, running steam turbines.

These are the so-called CANDU (Canadian-deuterium-uranium) reactors, of which there are some thirty-one in commercial service around the world. The Soviet Union built plutonium weapons and, although it later obtained an enrichment capability, based its initial power reactors on graphite-moderated natural uranium, very similar to the Hanford production reactors, except that the cooling tubes around the fuel element "slugs" were now strengthened to survive the pressure of superheated water.

In April 1986 one of the reactors at Chernobyl, north of Kiev, suffered a catastrophic malfunction and burst its pressure system, breaking its confinement and freely disseminating much of the accumulated radioactivity. Thousands of sq km were evacuated and remain officially evacuated to this day.

Nevertheless, with growing populations and growing prosperity, the world has an urgent need for large amounts of energy that does not put carbon dioxide into the atmosphere. Nuclear power is one approach. I have suggested reactor populations of as many as 9,000 full-size reactors as compared with the current 300.[5]

Standing in the way of such expansions are the high cost of nuclear plants in comparison with oil and natural gas prices of a few years ago, the lack of a demonstrated and available waste disposal facility for the spent nuclear fuel, and, to my mind most serious, the possibility of additional catastrophic accidents or disasters from terrorist attacks on nuclear reactors.

THE CURRENT PROBLEM OF SECRECY

Nuclear weapon information, unlike all other secrets in the United States, is "born secret." That is, even if it is initially conceived by someone not in the employ of the United States government, it is still subject to classification and to penalties in its transmission. Nevertheless, an official program of declassification has allowed much authoritative information about nuclear weapons and about the production of U-235 and plutonium to be officially released. A compilation of such declassification decisions is available from the Department of Energy on the Web.[6]

Some of the declassification happened quite early, in conjunction with the 1953–55 Eisenhower initiative, "Atoms for Peace." Some of it

---

[5] R. L. Garwin, "Can the World Do Without Nuclear Power? Can the World Live With Nuclear Power?" presented at the Nuclear Control Institute, 9 April 2001 (available, with persistence, at www.nci.org).

[6] "Restricted Data Declassification Decisions 1946 to the Present (RDD-7)," www.fas.org/sgp/othergov/doe/rdd-7.html.

is involved with the 1970 Non-Proliferation Treaty, in making available to non-nuclear weapon States Parties to the NPT the benefits of peaceful nuclear energy.

In the era of the Cold War, the principal task was to keep nuclear weapons information from the Soviet Union, which soon had nuclear weapons of its own. The better to protect the secrets of modern nuclear weapons from being transmitted to the Soviet Union, attention was focused on advanced designs rather than the original, very simple designs. As a result, much has been published on the initial gun-type weapon using metallic highly enriched uranium that destroyed Hiroshima with its yield of some 13,000 tons of high explosive equivalent, and also on the plutonium implosion weapon that destroyed Nagasaki with its yield of 20 kilotons.

Clearly the Soviet Union knew all about such weapons, and there was little benefit in keeping such information from them. Few realized that a major problem would be proliferation to additional states, and even to terrorist groups.

A major concern now is that with the enormous available stocks of weapon-usable material, especially in Russia, but also elsewhere, terrorists might on their own make improvised nuclear devices that in some circumstances would have the full yield of the corresponding weapon, even though they might not be so rugged as in a military configuration. That is a particular concern with the gun-type assembly of uranium metal, which could be configured in a van or in an apartment in a city, to which the U-235 might be smuggled in two or more pieces to ease the task of transportation and concealment.

In any case, plenty of useful information is to be had, and for that reason a major barrier to the acquisition of nuclear weapons by terrorists is a tightened system of control of information and materials by states, and greatly limited access to such materials.

The State of Nuclear Weapons

When Oppenheimer left Los Alamos, Norris Bradbury was appointed director. He served for twenty-five years, until succeeded by Harold M. Agnew. The laboratory continued to develop fission bombs, evolving from the solid-sphere plutonium core to shell-and-ball configurations and eventually to the current hollow plutonium shell. The augmentation of the fission reaction by "boosting" was demonstrated and has become standard in all U.S. nuclear weapons. The design process was aided by the evolution of computation, ranging from the card-programmed-calculator (CPC) punched-card machines to the first all-electronic computation on the IBM SSEC in New York. A copy of the von Neumann

Princeton computer was built at Los Alamos, together with the IBM 701—both vacuum-tube machines.

Although Los Alamos had been working at a very low level on thermonuclear weapons, involving the classical Super—a long cylinder of liquid deuterium somehow ignited by a fission reaction at one end—it wasn't until March 1951 that the thermonuclear weapon became feasible, when Stanislaw Ulam and Edward Teller had their idea of radiation implosion. Teller has indicated that I contributed to the design of the first liquid-deuterium test that yielded 11 megatons as the MIKE shot on 1 November 1952. But the main utility of thermonuclear explosives turned out not to be the energy range far beyond that achievable by fission bombs, but the ability to achieve any yield with the use of a single "primary" that contained no more than 6 kg of Pu. Thus, most of the U.S. nuclear weapons are in the range of 100–500 kilotons, rather than the 20-megaton monsters (for which we had bomber delivery capability) that were put into the U.S. stockpile.

After the Soviet nuclear explosion of 1949 and their later indigenous design, the United Kingdom tested its first nuclear weapon in January 1951, followed by France in February 1960, and China in October 1964. All later developed thermonuclear weapons as well. These five are the P-5 of the U.N. Security Council and (perhaps not coincidentally) the official Nuclear Weapons States under the Non-Proliferation Treaty of 1970.

No nuclear explosive has been used in warfare since the two in August 1945, but the U.S. built its stockpile to some 33,000 in 1967 and the Soviet Union peaked at about 45,000 nuclear weapons in 1982. The U.K., France, and China now have nuclear stockpiles in the range of 100–300 weapons while the United States and Russia each possess some 10–15,000.

As secretary of defense, Robert S. McNamara defined "assured destruction" of the Soviet Union, in the context of nuclear deterrence, to be caused by the delivery of 400 1-MT weapons, which would kill 20%–25% of the population and destroy 50% of the industry. As aptly put by a later defense secretary, Les Aspin, in the context of nuclear deterrence, the United States is now the deterree.

On the strategic military front, the United States in the late 1940s and early 1950s strove mightily to obtain a defense against Soviet nuclear weapons delivered by bombers, deploying the SAGE (semi-automatic ground environment) system of radars, communication links, manned interceptor aircraft, and unmanned missiles. Many of these carried nuclear warheads. But I was told that we were never able, in tests, to destroy more than 15% of an incoming Soviet bomber fleet. I worked for about a year on extending the bomber defenses to the sea lines of approach toward the United States and Canada, while pointing out that by the time anything could be deployed from our efforts, the threat would be Soviet nuclear-armed missiles and not primarily bombers.

Statesmanship proved inadequate to the task set by Oppenheimer, that of eliminating war or at least the potential for nuclear weapons to be used in warfare. The Baruch Plan would have required the Soviet Union not to acquire nuclear weapons at all, in return for the internationalization of the nuclear weapon force. The Soviet Union had insufficient faith in the United States and the nascent United Nations to take this seriously, and moved aggressively to develop and deploy its own nuclear weaponry.

The five nuclear weapon states and the great majority of non-nuclear weapon states then supported the negotiation of, and signed and ratified, the Non-Proliferation Treaty (now lacking as signatories only Israel, India, and Pakistan). North Korea was a member of the NPT as a non-NWS but has resigned its membership to pursue nuclear weapons. Some states have taken advantage of the relationship of nuclear power to nuclear weapons to build facilities and even stocks that could rather rapidly be turned to use in nuclear weaponry. Although not an NPT member, India did so in 1974, testing a nuclear explosive underground as a "peaceful nuclear explosion," which deceived no one. More recently, Pakistan and India in 1998 tested nuclear weapons. South Africa in the early 1990s covertly produced six uranium gun-type weapons and voluntarily gave them up just before the transfer of power to the new government. South Africa now is a member in good standing of the NPT.

Even during the depths of the Cold War, the United States and the Soviet Union could agree that additional nuclear-armed states would not be to their advantage, so they collaborated on the Non-Proliferation Treaty. Key elements of the NPT guarantee non-nuclear weapon states (NNWS) the benefits of peaceful use of nuclear energy, even to the extent of "peaceful nuclear explosions"—PNE.

Long before the NPT, there were efforts to negotiate a Comprehensive Test Ban Treaty, CTBT, culminating in the Limited Test Ban Treaty—LTBT—of 1963, which bans nuclear testing in the oceans, atmosphere, and space. The signatories of that treaty, which did not initially include France or China, were thus limited to underground testing. Ultimately France and China committed themselves to behavior consistent with the LTBT, and eventually became full-fledged members.

A CTBT would have greatly limited the arms race between the United States and the Soviet Union, by restricting nuclear weapon production and deployment to those that had already been tested. However, with an LTBT, which was indeed a good public health and environmental measure, weapon testing (i.e., nuclear explosions) moved underground.

The LTBT was later converted to a Threshold Test Ban Treaty, banning explosive yields underground in excess of 150 kt. That eventually evolved into the 1996 CTBT, which France and the United States were the first to sign. However, the United States has not ratified the CTBT, and the half-hearted submission by the Clinton administration to the U.S. Senate in 1997 failed to gain approval.

The NPT bargain for NNWS to remain without nuclear weapons involves nuclear disarmament on the part of the NWS. Although U.S. and Russian weapon numbers are perhaps one-third what they were at their peak, since there was a vast excess of nuclear weapons that is not taken as disarmament. Furthermore, although France closed its underground Pacific test site, active work continues at the nuclear test sites in China and in Russia (Novaya Zemlya), and at the Nevada Test Site.

Since about 1992 the United States has been committed to a program of Science-Based Stockpile Stewardship: verification of performance previously obtained in some part by underground tests is to be achieved by a better understanding of the fundamentals of nuclear weapons, and by greatly increased capability to compute these behaviors.

No U.S. nuclear weapon in the stockpile was designed with computing power exceeding that of my desktop PC, bought for less than $1,000. Yet some in the U.S. nuclear weapon laboratories deem the tens of teraflops of computing capacity now available to them to be insufficient for a full understanding, because nuclear weapon design involves at most two-dimensional calculations, since nuclear weapons are in principle symmetrical about an axis of rotation, whereas nuclear weapons with an assumed crack or fault have an inherently 3-D character.

My Own Observations

I have long participated for the U.S. government and for non-governmental organizations (NGOs) such as the Pugwash movement and the National Academy of Sciences Committee on International Security and Arms Control (CISAC) in informal technical and policy discussions with scientists and political scientists of other states. I chaired for seven years the Arms Control and Nonproliferation Advisory Board of the State Department in the Clinton administration. Few statesmen really understood, or placed the necessary priority on eliminating, the nuclear threat to our survival that was so clearly recognized by Robert Oppenheimer and President Dwight D. Eisenhower. With few exceptions, the first priority is to be reelected, and detailing the disaster that must be avoided is deemed unattractive to the voters. Jimmy Carter put his administration's priority on nonproliferation, banning reprocessing of power-reactor spent fuel, with its attendant commerce in separated plutonium. The recognition that implosion bombs could be made with plutonium from reactors lent urgency to Carter's unsuccessful effort to eliminate commercial reprocessing worldwide.

I judge that luck played a very major role in the avoidance of nuclear war in the 1960s and 1970s and that an all-out nuclear war could still take place by accident.

Furthermore, there are new hazards in the form of terrorist possession of nuclear weapons or construction of improvised nuclear devices that could very well have a full nuclear yield. Even a reduced yield of 1 kt in Manhattan at the busiest time could kill two hundred thousand people—in this case, many of them by immediate radioactive fallout from the ground-level explosion, which did not occur in Hiroshima or Nagasaki. There is now also a strong incentive on the part of some to provoke so-called catalytic war, to get rid of Russia and the United States at one time.

Furthermore, terrorist attacks on nuclear reactors could cause Chernobyl-like results, and we are not doing enough to counter them.

The nuclear weapons acquisition efforts of North Korea and Iran have been much in the news in recent months. Their situations are quite different. North Korea has probably had two plutonium nuclear weapons for ten years or more, and in recent months has probably separated enough plutonium from spent fuel from its one operating 30-MW (thermal) reactor to build another three or four nuclear weapons, in addition to the five nuclear weapons it could have made from the fuel monitored by the IAEA inspectors until their expulsion in December 2002. North Korea has apparently been exploring the centrifuge method of enrichment, using technology provided by A. Q. Khan of Pakistan.

Iran has recently admitted that A. Q. Khan sold Iran centrifuges as well as technology, and Iran is insisting on its "inherent right" to enrich uranium, codified by the NPT provided that Iran affords transparency to the International Atomic Energy Agency (IAEA).

As we speak, Iran is negotiating with "the EU-3" (Britain, France, and Germany), and with the IAEA regarding the nature of the "limited enrichment capability" that would satisfy its need for status while not contributing to the acquisition of nuclear weapons, which Iran's leader says his country neither needs nor desires. The problem is complicated by the Bushehr LWR in Iran, begun by Germany but completed by Russia. Bushehr needs a ton of U-235 per year (in 25 tons of LEU fuel), whereas the IAEA defines a Significant Quantity ("SQ") of HEU as 25 kg. A gas centrifuge plant to supply Bushehr would need 50,000 centrifuges operating for a year to supply a year's worth of fuel. Those same centrifuges could alternatively produce about 650 kg U-235 as 95% HEU—enough for more than ten Hiroshima-type bombs or twenty-five HEU implosion weapons such as constituted the early Chinese and more recently the Pakistani arsenal.

It is unlikely that nuclear armament could have been prevented by an all-out effort by the United States just following World War II. Perhaps the Soviet Union was too suspicious, and Stalin's brutal tactics within the country presaged an equally ruthless world domination that could be resisted only by force. But there is no excuse in 2005 for allowing nuclear weapon material that could produce tens of thousands of nuclear weapons to continue to exist under poor security and no international supervision within the former Soviet Union. Furthermore, it is likely not to be a good bargain to continue sanctions against Iran, if that will impel it to a full-scale enrichment program that is in no way warranted by Iran's new power reactor and the promise of more.

Many of us over the years have tried our best to persuade Japan, with its 54 large power reactors, that its energy security does not depend upon its possession of enrichment and, in particular, reprocessing facilities, but to no avail. France has made similar arguments for its "closed fuel cycle," which includes reprocessing, unrelated to its nuclear weapons program, but a matter of technological imperative. Japan's motives are not so clear.

The United States, however, has been tone-deaf in not recognizing that its continued emphasis on nuclear weapons and on new nuclear weapon development even as a signatory (without ratification) of the CTBT imperils the adherence of others to the NPT as well as our ability to muster the support of the other NNWS against proliferation by Iran and North Korea.

The world's exploitation of nuclear power is affordable for the production of electricity, but for corporate leaders to decide to build nuclear plants, the public needs to have confidence in the solution of three problems:

- Waste disposal
- Reactor safety against accidents
- Adequate supply of fuel

The first will be solved by mined geologic repositories in a competitive, commercial mode. But that will work only if the International Atomic Energy Authority certifies repositories and their operation, and also the waste forms (spent fuel in storage casks and vitrified high-level waste) so that the competition can take place in the public interest.

Safety against accidents can be achieved by design and especially by discipline in operation. But that at present is impaired by the drive for ever-lower costs, and cutting corners on safety and training. The solution is design for automated operation, and for nuclear plants that are more nearly intrinsically safe and eventually all underground. It is a vexing problem to protect against terrorist attacks aimed at large-scale reactor accidents and ensuing contamination.

Fuel supply requires more public investment to demonstrate the cost of recovering uranium from what is surely an unattractive commercial option now—the uranium-from-seawater resources a thousand times as large in the ocean as are present economically exploitable terrestrial reserves. But it is of the first importance for the choice of nuclear power as a mainstay of future energy to determine whether uranium from seawater can be obtained at a cost of $100/kg or even $1,000/kg, in comparison with the current terrestrial price of $30/kg.

For nuclear weapons, paradoxically, we may be closer to a solution in that the avidity of states for nuclear weapons seems to be reduced. Yes, North Korea blatantly asserts that it has nuclear weapons and that it needs them to protect against U.S. attempts at regime change. Iran denies that it has a program to acquire nuclear weapons, and the supreme leader declares that nuclear weapons not only are forbidden by the Qur'ān, but would also not be in the interests of Iranian security. Nevertheless, India made similar protestations against the acquisition of nuclear weapons, until it rather forthrightly tested its own in 1998 and proceeded to induct the weapons into its armed forces.

The NPT has a major flaw in its construction, in that non-nuclear weapon states can obtain facilities and materials nominally for peaceful uses—even weapon-usable material if they declare the location and magnitudes, and the IAEA has no authority for physical control. The NPT permits a state by invoking its supreme national interest to leave the NPT within three months, and there is no provision to bar its future use of weapon-usable materials or facilities that it acquired as an NNWS. I believe that this must be changed, but for the United States to lead such a change, it will need to improve its position of morality and consistency in the eyes of the great majority of NNWS that are parties to the NPT and that have no interest in acquiring nuclear weapons themselves. Unless the United States cuts its current almost 10,000 nuclear warheads (on track to "1700–2200 operationally deployed strategic warheads" by the year 2012)[7] and thus brings its actions into alignment with its commitment to the NPT to engage in nuclear disarmament, it will have no

---

[7] The Moscow Treaty of 24 May 2002 signed by President George W. Bush and Vladimir V. Putin puts that limit on strategic forces of the two states on a single day, 31 December 2012, and then expires.

authority to gain the political and even military support of these states to act or to support coalition action that would divest a nascent nuclear weapon state of its capabilities. Of course, no state has a greater inherent right to nuclear weapons than any other state. And the only legitimacy of nuclear weapons would be to guard against the destruction of civilization. To this end, they must be seen less as a national status symbol, and more as a mechanism to be used in support of broadly shared goals.