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In Memoriam—Ted Taylor

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Ted Taylor died of a stroke on October 28, 2004. He was 79 years old. As many of you know, Ted, for over five decades was one of the most remarkable and original scientists engaged in (and in Ted's case, more like, obsessed with) issues of science and security. Certainly no scientist in the nuclear age ever made a greater jump than Ted's from possibly America's most creative designer of nuclear weapons at Los Alamos to a passionate and inventive supporter of nuclear disarmament and opponent of nuclear energy. In the midst of this journey, Ted also found time to help design and develop the TRIGA reactor at General Atomic, to invent renewable energy technologies, and to dream up and lead for its six-year life the remarkable Orion Project, whose purpose was to design a space-ship propelled by nuclear explosions!

I first met Ted at the time he was working with John McPhee on McPhee's *New Yorker* profile of Ted, later published in 1974 as a book, *The Curve of Binding Energy*. The book for the first time raised publicly and dramatically the specter of nuclear terrorism, and the urgent need to greatly strengthen nuclear safeguards to prevent the diversion of nuclear explosive materials from the civilian fuel cycle to nuclear weapons. Shortly thereafter, Ted came to the Engineering School at Princeton where he joined Frank von Hippel, Bob Williams, and myself in a study of the U.S. breeder reactor program which we came to believe uneconomic and, above all, dangerous in involving the separation of plutonium. Characteristically, Ted sought in the midst of this work to see if he could invent a nuclear power system as alternative to the plutonium breeder which could be nearly as uranium efficient but far more proliferation resistant. This led Ted to exploration of a thorium cycle involving "denatured uranium," that is, uranium-233 mixed with a sufficient quantity of uranium-238 to make the mixture non-weapons-usable.

Though he was a highly imaginative and gifted teacher, Ted fairly quickly tired of the constrictions placed on a University professor, and soon left Princeton. But we stayed in close touch over the ensuing years. And one of the featured articles in the first issue of this journal, in 1989, was a study by Ted on "The Verified Elimination of Nuclear Warheads," a path-breaking analysis of how to dismantle nuclear warheads and to verify this dismantlement at a time just before the end of the Cold War when such issues did not seem of realistic concern. A key objective was to do the dismantlement in a manner which did not give away design information. Ted was one of the few persons who could think through what this entails.

The day after Ted's death, Freeman Dyson, a long-time friend and colleague of Ted, summed up Ted's life in a way all of Ted's friends can relate to: "Taylor was one of the great men of our time, gifted as a scientist, as an administrator and as a human being. It was his fate to succeed brilliantly as the creator of bombs that he came to despise, and to fail in his efforts either to use the bombs for a good purpose or to kill the monster that he had helped to grow. He felt deeply the tragedy of his destiny, but he never lost his sense of humor and his determination to do whatever he could to make the best of a bad situation."

We include the following article that Ted wrote for the Nuclear Age Peace Foundation in 1996, which addresses many of his concerns about nuclear weapons and nuclear energy.

Nuclear Power and Nuclear Weapons*

Theodore B. Taylor, July 1996

INTRODUCTION

The two nuclear fission bombs that destroyed Hiroshima and Nagasaki each released nearly 4,000 times as much explosive energy as chemical high explosive bombs of the same weight. Together they killed more than 200,000 people. The energy released by the splitting of the atomic nuclei in the cores of these bombs was more than 10 million times the energy released by rearrangements of the outer electrons of atoms, which are responsible for chemical changes. For an instant after detonation of the bomb that destroyed Nagasaki, an amount of explosive energy equivalent to a pile of dynamite as big as the White House was contained in a sphere of plutonium no bigger than a baseball.

This is why, a short time later, Albert Einstein said: "The splitting of the atom has changed everything, save our mode of thinking, and thus we drift

*This article was originally published by the *Nuclear Age Peace Foundation* and can be found on their website, WAGINGPEACE.ORG, http://www.wagingpeace.org/articles/1996/07/00_taylor_nuclear-power.htm toward unparalleled catastrophe." Suddenly the destructive capacity accessible to humans went clear off the human scale of things.

About 10 years later this destructive capacity jumped dramatically again when the United States and the Soviet Union developed hydrogen bombs. By the 1970s, there were five announced members of the nuclear club, and the total number of nuclear warheads in the world had increased to some 60,000.

Since 1964, when China tested its first nuclear explosive, further horizontal proliferation of nuclear weapons has been secret or ambiguous or both. India tested a nuclear explosive in 1974, but claimed that is was strictly for peaceful purposes, and has consistently denied that it has any nuclear weapons. Although its government has never admitted that it has nuclear weapons, there is little doubt that Israel has been accumulating a growing stockpile since the 1960s. South Africa announced that it had made a half-dozen or so nuclear weapons, starting in the 1970s, but that it now has eliminated them. Other countries strongly suspected of having at least one nuclear weapon, and the capacity to make more, include Pakistan, North Korea, and Iraq. Commitments have been made by Belarus, Kazakhstan, and Ukraine to turn over to Russia all nuclear weapons on their territories for dismantling. Ukraine completed this transfer on June 1, 1996.

The immense potential destructive capacity of uranium and plutonium can also be released slowly as energy that can serve the peaceful needs of humans. It took about 10 years after the first nuclear bombs were exploded for nuclear energy for peaceful purposes to begin to be practical. Nuclear power has expanded considerably in the last 30 years or so. The two technologies-for destructive uses and for the peaceful uses of nuclear energy-are closely connected. I'll discuss these connections in some detail in this paper.

Facing the realities of the Nuclear Age as they have become evident these past 50 years has been a difficult and painful process for me, involving many changes of heart in my feelings about nuclear weapons and nuclear power since I first heard of nuclear fission on August 6, 1945. I started with a sense of revulsion towards nuclear weapons and skepticism about nuclear power for nearly five years. Then I worked on and strongly promoted nuclear weapons for some 15 years. In 1966, in the midst of a job in the Pentagon, I did an about-face in my perception of nuclear weaponry, and have pressed for nuclear disarmament ever since. My rejection of nuclear power, because of its connection with nuclear weapons, took longer, and was not complete until about 1980.

Since that time I have been persistent in calling for the prompt global abolition of all nuclear weapons and the key nuclear materials needed for their production. Since all of the more than 400 nuclear power plants now operating in 32 countries produce large quantities of plutonium that, when chemically separated from spent fuel, can be used to make reliable, efficient nuclear weapons of all types, I have also found it necessary to call for phasing out all nuclear power worldwide. To accomplish this while being responsive to the environmental disruption caused by continued large-scale use of fossil fuels, I also find it necessary to call for intense, global response to opportunities for saving energy and producing what is needed from renewable sources directly or indirectly derived from solar radiation. I shall try in the rest of this paper to explain briefly the convictions that have led me to join others in making these calls with great urgency.

LATENT PROLIFERATION OF NUCLEAR WEAPONS

There are many possible degrees of drift or concerted national actions that are short of the actual possession of nuclear weapons, but that can account for much of what has to be done technically to acquire them. Harold Feiveson has called such activity "latent proliferation" of nuclear weapons.[1] A national government that sponsors acquisition of nuclear power plants may have no intention to acquire nuclear weapons; but that government may be replaced by one that does, or may change its collective mind. A country that is actively pursuing nuclear power for peaceful purposes may also secretly develop nuclear explosives to the point where the last stages of assembly and military deployment could be carried out very quickly. The time and resources needed to make the transition from latent to active proliferation can range from very large to very small. Inadequately controlled plutonium or highly enriched uranium, combined with secret design and testing of non-nuclear components of nuclear warheads, can allow a nation or terrorist group to have deliverable nuclear weapons within days, or even hours, after acquiring a few kilograms or more of the key nuclear weapon materials.

Contrary to widespread belief among nuclear engineers who have never worked on nuclear weapons, plutonium made in nuclear power plant fuel can be used to make all types of nuclear weapons. This "reactor grade" plutonium has relatively high concentrations of the isotope Pu-240, which spontaneously releases many more neutrons than Pu-239, the principal plutonium isotope in "weapon-grade" plutonium. In early nuclear weapons, such as the plutonium bomb tested in New Mexico in 1945, and then used in the bombing of Nagasaki, use of reactor grade plutonium would have tended to cause the chain reaction to start prematurely. This would lower the most likely explosive yield, but not below about 1 kiloton, compared with the 20 kiloton yield from these two bombs. Since that time, however, there have been major developments of nuclear weapons technology that make it possible to design all types of nuclear weapons to use reactor grade plutonium without major degradation of the weapons' performance and reliability, compared with those that use weapon grade plutonium.[2] These techniques have been well understood by nuclear weapon designers in the United States since the early 1950s, and probably also for decades in the other four declared nuclear weapon states.

Reactor grade plutonium can also be used for making relatively crude nuclear explosives, such as might be made by terrorists. Although the explosive yields of such bombs would tend to be unpredictable, varying from case to case for the same bomb design, their minimum explosive yields could credibly be the equivalent of several hundred tons or more of high explosive.[3] Such bombs, transportable by automobile, would certainly qualify as weapons of mass destruction, killing many tens of thousands or more people in some locations.

All nuclear weapons require plutonium or highly enriched uranium. Some use both. The required amounts vary considerably, depending on the desired characteristics and on the technical resources and knowhow available to those who design and build the weapons. Estimates of the maximum total number of U.S. nuclear warheads and of the total amount of plutonium produced for those warheads correspond to an average of about 3 kilograms of plutonium per warhead.[4] The minimum amount of plutonium in a nuclear explosive that contains no highly enriched uranium can be significantly smaller than 3 kilograms.

Nuclear power plants typically produce a net of about 200 kilograms of plutonium per year for each 1,000 megawatts of electric power generating capacity. Some 430 nuclear power plants, with combined electrical generating capacity of nearly 340,000 megawatts, are now operating in 32 countries. The plants account for about 7% of total primary energy consumption worldwide, or about 17% of the world's electrical energy. Total net annual production of plutonium by these plants is nearly 70,000 kilograms, enough for making more than 10,000 nuclear warheads per year.[5]

So far about four times as much plutonium has been produced in power reactors than has been used for making nuclear weapons-about 1 million kilograms, most of which is in spent nuclear fuel in storage, compared with about 250,000 kilograms for weapons.[6]

Nearly 200,000 kilograms of plutonium have been chemically separated from spent power reactor fuel in chemical reprocessing facilities in at least 8 countries (Belgium, France, Germany, India, Japan, Russia, United Kingdom, and United States).[7] This is typically stored as plutonium oxide that can relatively easily be converted to plutonium metal for use in nuclear explosives.

Research and test reactors can also produce significant amounts of plutonium that, after chemical separation, can be used for making nuclear weapons. This has apparently been the route to nuclear weapons followed by Israel and started by North Korea.

Although use of highly enriched uranium in nuclear power plants has been sporadic and rare, substantial quantities have been used for R&D purposes-as fuel for research and test reactors, and in connection with development of breeder reactors. Principal suppliers have been and now are the five declared nuclear weapon states. It has been estimated that the world inventory of highly enriched uranium for civil purposes is about 20,000 kilograms.[8]

Although this is dramatically smaller than the more than 1 million kilograms of highly enriched uranium associated with nuclear weapons, it may be extremely important to some countries that are secretly developing the technology for making nuclear weapons.

Facilities for enriching uranium in its concentration of the isotope U-235 to the levels of a few percent needed for light water power reactor fuel can be used for further enrichment to high concentrations used for making nuclear explosives. The technology for doing this is proliferating, both in terms of the numbers of countries that have such facilities, and in the variety of different ways to carry out the enrichment.

The continuing international spread of knowledge of nuclear technology related to nuclear power development is an important contributor to latent nuclear weapon proliferation. Some of the people who have become experts in nuclear technology, whether for military or civil purposes, could be of great help in setting up and carrying out clandestine nuclear weapon design and construction operations that make use of nuclear materials stolen from military supplies or diverted from civil supplies, perhaps having entered a black market.

An example of highly advanced latent nuclear weapon proliferation is the nuclear weapons development program that started in Sweden in the late 1940s. It remained secret until the mid-1980s, when much detail about the project started becoming publicly available. It included hydronuclear tests of implosion systems containing enough fissile material to go critical but not enough to make a damaging nuclear explosion. The objective of the Swedish nuclear bomb program was to determine, in great detail, what Sweden would need to do if the government ever decided to produce and stockpile nuclear weapons.[9] I have no reason to believe that Sweden has ever made that decision. I would not be surprised, however, if many other countries with nuclear reactors or uranium enrichment facilities that could be used to supply needed key nuclear materials have secretly carried out similar programs of lesser or perhaps even greater technical sophistication than Sweden's.

BOMBARDMENT OF NUCLEAR FACILITIES

Another type of latent proliferation that I find especially worrisome is the possible bombardment of nuclear facilities that thereby would be converted, in effect, into nuclear weapons. Military bombardment or sabotage of nuclear facilities, ranging from operating nuclear power plants and their spent fuel storage pools to large accumulations of high level radioactive wastes in temporary or long term storage, could release large quantities of radioactive materials that could seriously endanger huge land areas downwind. Electric power plants and stored petroleum have often been prime targets for tactical and strategic bombing, and sometimes for sabotage. In the case of operating nuclear power plants, core meltdowns and physical rupture of containment structures could be caused by aerial or artillery bombardment, truck bombings, internal sabotage with explosives, or by control manipulations following capture of the facility by terrorists. For orientation to the scale of potential radioactive contamination, consider strontium-90 and cesium-137, two especially troublesome fission products with half-lives of about 30 years. The inventories of these radionuclides in the core of a typical nuclear power plant (1,000 electrical megawatts) are greater than the amounts released by a 20 megaton H-bomb explosion, assuming half the explosion energy is accounted for by fission.

Inventories of dangerous radioactive materials can be considerably greater in a waste or spent fuel storage facility that has served the needs of many nuclear power plants for many years. In some cases it may not be credible that chemical explosives could release large fractions of such materials and cause them to be airborne long enough to contaminate very large areas. In such situations, however, the explosion of a relatively small nuclear explosive in the midst of the storage area could spread the radioactive materials over huge areas.

Perhaps the greatest extent of latent proliferation of nuclear weapons is represented by nuclear power fuel cycle facilities that can become enormously destructive nuclear weapons by being bombed by military forces or terrorists.

CAN THE NUCLEAR POWER-NUCLEAR WEAPON CONNECTIONS BE BROKEN?

Given the rapidly increasing rate of worldwide latent proliferation of nuclear weapons, what can be done to assure that it does not lead to considerable surges in active proliferation of nuclear weapons?

Shifts from latent to active nuclear weapon proliferation may be detected or discouraged by application of the International Atomic Energy Agency's (IAEA) nuclear diversion safeguards. IAEA safeguards are applied to parties of the Non-Proliferation Treaty (NPT) that are not nuclear weapons states. But the IAEA has authority only to inspect designated (or in some cases suspected) nuclear facilities, not to interfere physically to prevent a government from breaking its agreements under the treaty if it so chooses. Furthermore, a major function of the IAEA is also to provide assistance to countries that wish to develop nuclear power and use it. Thus the IAEA simultaneously plays two possibly conflicting roles-one of encouraging latent proliferation and the other of discouraging active proliferation.

As we have seen, a nation's possession of plutonium, whether in spent fuel or chemically separated, or its possession of highly enriched uranium or of facilities capable of producing it, need not depend on a government's decision to acquire nuclear weapons. Such a decision might be made secretly or openly at any time government leaders conclude that threats to their security or ambitions of conquest warrant breaking safeguard agreements; at that point they can quickly extract the key nuclear materials needed for a few or for large numbers of nuclear weapons.

Various proposals have been made for developing nuclear power in forms that are less prone to diversion of nuclear materials for weapons than present nuclear power systems. None of these proposals avoid the production of substantial quantities of neutrons that could be used for making key nuclear materials for nuclear weapons, however. And none avoid the production of high level radioactive wastes, the permanent disposal of which is still awaiting both technical and political resolution. Furthermore, such concepts, once fully developed, would require decades for substitution for the present types of nuclear power systems.

Increasing alarm about global climatic instabilities caused by continued release of "greenhouse gases," particularly carbon dioxide produced by burning fossil fuels, has stimulated many advocates of nuclear energy to propose widescale displacement of fossil fuels by nuclear power. Such proposals would require building thousands of new nuclear power plants to achieve substantial global reduction in combustion of fossil fuels. This would greatly compound the dangers of destructive abuse of nuclear energy.

In short, the connections between nuclear technology for constructive use and for destructive use are so closely tied together that the benefits of the one are not accessible without greatly increasing the hazards of the other.

This leaves us with a key question: If nuclear power technology is too dangerous—by being so closely related to nuclear weapon technology—and fossil fuel combustion must be reduced sharply to avoid global climatic instabilities, what can humans do to meet their demands for energy worldwide?

EFFICIENT USE OF RENEWABLE ENERGY

The economically attractive opportunities for using energy much more efficiently for all end uses in any of the wide variety of human settings are now so widely set forth that they need no further elaboration here. Although such opportunities generally exist for use of all kinds of energy sources, their detailed nature can depend on the specific type of energy provided for end use.[10]

Among the many possibilities for economical renewable energy is hydrogen produced by electrolysis of water, using solar electric cells to provide the needed low voltage, direct current electrical energy. Recent advances in lowering the production costs and increasing the efficiency of photovoltaic cells make it likely that vigorous international pursuit of this option could allow production and distribution of hydrogen for use as a general purpose fuel, at costs competitive with the cost of natural gas.[11]

Solar electric cells can also supply local or regional electric power for general use, using generators or fuel cells fueled with stored hydrogen, or pumped hydrolelectic storage, or windpower to meet electrical demands at night, on cloudy days, or in winter. Using such energy storage or windpower makes it possible to provide and use hydrogen to meet all local demands for energy in any climate.

A common criticism of direct use of solar energy for meeting most human demands for energy results from a belief that the areas required are so large as to be impractical. This criticism is generally not valid. An overall efficiency of 15%, in terms of the chemical energy stored in hydrogen divided by the total solar radiation incident on the ground area used by solar cell arrays, is likely to be routinely achievable with flat, horizontal arrays. At a world annual average insolation rate of 200 watts per square meter, the total area required to meet the entire present world demand for primary energy of all types (equivalent to an annual average of about 10 trillion watts) would be about 0.4 million square kilometers. This is less than 0.4% of the world's land area-much less than the annual fluctuations in the area devoted to agriculture, and comparable to the area used for roads. Even in Belgium, with perhaps the world's highest national energy consumption rates per unit land area and lowest solar radiation availability, present demands could be met by solar hydrogen systems covering less than 5% of the country's land area. Vigorous response to cost-effective opportunities for saving energy could lower considerably the land area requirements for solar energy anywhere.

A GLOBAL SHIFT FROM FOSSIL AND NUCLEAR FUELS TO RENEWABLE ENERGY

Consider the benefits of a rapid worldwide shift from dependence on fossil fuels and nuclear power to vigorous pursuit of opportunities for using energy much more efficiently and providing that energy from renewable sources.

If nuclear power is phased out completely, it will become possible to outlaw internationally the possession of any key nuclear weapon materials, such as plutonium or highly enriched uranium that can sustain a fast neutron chain reaction, along with any facilities that could be used for producing them. This would not require a global ban on basic research in nuclear physics nor the use of selected, internationally controlled accelerators for production of radionuclides for medical and industrial applications.

A global ban on materials capable of sustaining nuclear explosive chain reactions would make it unnecessary to distinguish between alleged peaceful uses of these materials and uses that could be threatening. It would greatly increase the likelihood that violations of a ban on all nuclear weapons would be detected technically and by people who can report violations of the ban, without having to determine the intended uses of the materials and production facilities.

A complete phaseout of nuclear power would help focus the world's attention on safeguarding nuclear materials and safe, permanent disposal of all the nuclear wastes and spent nuclear fuel, separated plutonium, or other stockpiles of nuclear weapon materials that had been produced before nuclear power is completely phased out. All such materials could be internationally secured in a relatively small number of facilities while awaiting ultimate safe disposal. Although the quantities of these materials are already very large, applying the needed safeguards to them would be much easier than in a world in which nuclear power continues to flourish worldwide. The job would be finite, rather than open-ended. The costs of safe, environmentally acceptable, permanent disposal of nuclear weapon materials and nuclear wastes-costs that are now unknown, but are very large-would be bounded.

Concerns about safety and vulnerability of nuclear power plants and their supporting facilities to military action or acts of terrorism would disappear.

In anticipation of a phaseout of nuclear power and sharp curtailment of combustion of fossil fuels, research, development, and commercialization of renewable energy sources could be greatly accelerated by a shift of national and international resources toward them and away from dependence on nuclear power and fossil fuel systems that are inherent threats to human security and our global habitat.

GLOBAL NUCLEAR ABOLITION

It troubles me more deeply than I can express that my country continues to be prepared, under certain conditions, to launch nuclear weapons that would kill millions of innocent bystanders. To me, this is preparation for mass murder that cannot be justified under any conditions. It must therefore be considered as human action that is out-and-out evil. The threat of nuclear retaliation also is a completely ineffectual deterrent to nuclear attack by terrorists or leaders of governments that need not identify themselves or that are physically located in the midst of populations that have no part in the initial attack or threat of attack. In short, we humans must find alternatives to retaliation in kind to acts of massive and indiscriminate violence.

These alternatives must focus on ways to deter use of weapons of mass destruction by determining who is responsible for such attacks or threats of attack, and bringing them to justice.

One hangup that many people have with global nuclear weapon abolition anytime soon is that nuclear technology is already too widely dispersed to allow accurate and complete technical verification of compliance, using currently available verification methods. Another widespread hangup is that malevolent national leaders might threaten to use secretly withheld or produced nuclear weapons to force intolerable demands on other countries if they did not face certain devastating nuclear retaliation to carrying out such threats.

I agree that no conceivable global verification system or international security force for identifying and arresting violators of an internationally negotiated and codified legal framework for globally banning nuclear weapons and nuclear power can be guaranteed to deter violation of the the ban. But this is a property of any law governing human beings. The question is not about achieving perfect global security against nuclear violence. The question is: Which would be preferred by most human beings—a world in which possession and threatened use of nuclear weapons is allowed for some but forbidden for others, or one in which they are completely outlawed, with no exceptions?

I believe the time has come to establish a global popular taboo against nuclear weapons and devices or processes that might be used to make them. The taboo should be directed specifically at any action—by governments, non-government enterprises, or individuals—that is in violation of international laws specifically related to nuclear technology.

I also propose that as the taboo is formulated and articulated vigorously worldwide, both informal and formal negotiations of an international nuclear abolition treaty start immediately in the relevant United Nations organizations. Why not adopt a formal goal of completing the negotiations and the codification of the associated laws and regulations before the start of the next millennium? I would also join others now pressing for actions that would complete the process of actual global nuclear abolition no later than 2010.

As is the case for many examples of bringing violators of popularly supported laws to justice, there should be frequent official and popular encouragement, including various kinds of major rewards, of "whistleblowers" who become aware of violations and report them to a well-known international authority. Such whistleblowers should also be well protected against reprisals by the violators, including even authorities of their own country's government. Such actions may be even more important in filling verification gaps than technical verification procedures implemented by an international authority.

In conclusion, I now have new and strong feelings of hope about the future of humankind. We are collectively facing new choices. We can continue to apply those cosmic forces—which we discovered how to manipulate 50 years ago-to feed the destructive competitive power struggles among humans. Or we can join together to reject those immensely powerful forces-that are much easier to use to destroy than to build- and reach out together to embrace the energy from our sun, which has for a very long time sustained all life on Earth.

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