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The Future of Nuclear Power

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Notes From the Editors

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The challenge posed by global warming and concerns about the future availability of oil have recently given a boost to nuclear power, which is finding supporters even among prominent environmentalists. Last year Al Gore declared that nuclear energy could play a "small part" in plans to avert global warming. James Lovelock, best known for his Gaia hypothesis, advocates the building of new nuclear power plants as the solution to impending ecological catastrophe. Jared Diamond, author of Collapse, *says that, "to deal with our energy problems we need everything available to us, including nuclear power." Even the Union of Concerned Scientists suggests that nuclear power despite the risks it poses might play a role as a "longer-term option" in combating global warming. At the same time many environmentalists and most environmental organizations remain adamantly opposed to nuclear power. For Barry Commoner, who warned of the dangers of both nuclear energy and global warming more than forty years ago in his* Science and Survival, *the fact that some individuals who have established reputations as environmentalists see nuclear power as a weapon against global warming is nothing short of "appalling" (*New York Times, *March 22 and June 19, 2007;* Christian Science Monitor, *July 19, 2007; http://www.ucsusa.org).*

The Bush administration is now providing additional subsidies to the nuclear industry, and applications are being filed for the construction of up to thirty-two new nuclear facilities in the United States over the next twenty years. Such construction if it were to be carried out would represent a major reversal. No nuclear plant has been licensed in the United States in over thirty years. The combined effect of vast environmental hazards and prohibitive economic costs has long created insurmountable barriers to nuclear power expansion. In July of last year an earthquake in Japan led to a major nuclear accident resulting in the dumping of 317 gallons of water containing trace amounts of radioactive materials into the Sea of Japan; while accidents at two nuclear plants last June in Germany induced Sigmar Gabriel, Germany's Environmental Minister, to demand early shutdown of all of Germany's older reactors. Memories of Chernobyl in the Soviet Union and Three Mile Island in the United States still linger.

Nevertheless, nuclear power proponents claim that the technology of nuclear power plant construction and of the disposal of radioactive wastes has markedly improved, and should now alleviate most concerns. New generations of reactors, we are told, enormously reduce the environmental risks and lessen the *economic costs.*

How true is this? In order to answer this question and in order for the public to be able to make informed judgments it is necessary that the technical aspects of this issue be put clearly by experts in a way that is accessible to lay readers. The following article on "The Future of Nuclear Power" by Robert D. Furber, James C. Warf, and Sheldon C. Plotkin, scientists with a long history of addressing this issue, seeks to lay bare the realities of nuclear power. Although much more difficult to read than the typical MR *article, we encourage all of our readers to study it closely. Its conclusion?: "any building of new [nuclear] plants would be a serious mistake....the future of nuclear power, as we know it, is very poor at best."*

The careful analysis of Furber, Warf, and Plotkin thus points to the irrationality of current proposals to resort massively to nuclear power as an answer to global warming. In order for nuclear power to make a dent in the global warming problem it would be necessary to build hundreds of nuclear power plants around the world, each one taking ten years to construct, and each an enormous hazard to the earth, generating radioactive wastes lasting for hundreds or thousands or millions of years. The most important principle of environmental thought is that of safeguarding the earth for future generations. To turn to nuclear power as a solution to global warming would be to abandon that trust.—Ed.

Understanding the future of nuclear power requires a few basic principles regarding atoms. Each chemical element is distinguished by a particular number of positively charged protons in the nucleus. An equal number of negatively charged (and much less massive) electrons may be bound to the nucleus by the attractive electric force between the oppositely charged nucleus and the electrons. Such an electrically neutral system is called an atom of the element. The simplest and least massive atom is hydrogen, an atom consisting of a single proton and a single electron in the bound state.

The nucleus usually contains neutrons as well as protons. The neutron is electrically neutral and is only slightly more massive than the proton. Neutrons and protons are mutually attracted by the strong force. The strong force also acts between protons and between neutrons. Unlike the electron, each neutron and proton is a compound system with internal structure, and is best described as a system of quarks and gluons. These latter are called "elementary particles." The electron is another elementary particle. Protons and neutrons are called nucleons. In this discussion the internal structure of the nucleon will not be considered.

The deuteron is a form of hydrogen with a nucleus consisting of a single proton bound tightly to a single neutron. There are four basic forces in nature: the strong nuclear force (or simply strong force), gravity, the electromagnetic force, and the weak nuclear force. As its name implies, the strong force is the strongest of the four. However, it also has the shortest range, meaning that particles must be extremely close before its effects are felt. The strong force is very strong when nucleons are in close proximity. However, as the separation between a pair of nucleons increases, the strong force weakens. (At extremely small separations, on the order of the separation between nearest neighbors in nuclei, the force becomes highly repulsive.) This is quite different from the electric force between charged particles. The electric force is an example of a long-range force, and the strong force is an example of a short-range force. Between a pair of protons in a small nucleus, the attractive strong force is much greater than the repulsive electric force. However, in a very large nucleus containing many nucleons, such as uranium-235 with 235 nucleons, the separation between a pair of protons can become sufficiently large that the electric force of repulsion can compete effectively with the attractive strong force. This can lead to the breakup of the nucleus, called fission.

Fusion involves the merging of small nuclei, and is in that sense the opposite of fission. In order to discuss nuclear fusion a few more examples of small nuclei will be helpful. Two cases of hydrogen, hydrogen-1 and hydrogen-2 or deuterium, have already been described. A third example of hydrogen is tritium, hydrogen-3, in which the nucleus contains two neutrons and a single proton. These three forms of hydrogen are called isotopes of hydrogen and are the only relatively stable isotopes of hydrogen. In order to understand why a stable “hydrogen-4” cannot exist, the laws of physics must be applied to the general behavior of this system of three neutrons and a single proton. This branch of physics is called quantum mechanics. When quantum mechanics is applied to this system, the result shows that such a system can exist only in the unbound state. That is, one of the four nucleons cannot remain part of the nucleus, but instead must immediately be ejected from the system. Nevertheless, physicists do study the properties of unbound, or unstable isotopes of nuclei. Therefore, for example, a typical handbook of the properties of nuclei will contain those of hydrogen-1 through hydrogen-7. After hydrogen, the next element is helium. There are only two stable forms of helium, helium-3 and helium-4. The nucleus of helium-3 has two protons and a single neutron, and the nucleus of helium-4 has two protons and two neutrons. The handbooks will also provide the properties of the unstable isotopes helium-5 through helium-10.

The history of nuclear power plants for generating electricity goes back to 1951, when the first commercial reactor was built. This was a breeder reactor. Most commercial units were of the boiling water type, which involved running cooling water directly over the reactor to produce steam to drive the turbo-generators. A certain amount of radioactive particles would leak through the fuel rods into the water, some of which then would become airborne from the cooling tower. Because releasing radioactivity into the air is unacceptable, a pressurized water design was developed. This involves a dual heat transfer loop, i.e., high pressure and superheated water pass through the fission reactor, which then transfers energy through a heat exchanger into the secondary low-pressure loop. This secondary loop produces steam pressure to the turbo-generator for electric energy output. Most of the 103 power reactors in the United States at present are of this pressurized light water type.

Rather than using water for moderating the neutron flow, i.e., slowing down their velocity, carbon can be used instead. Such graphite-moderated reactors are used in the United States to produce useful isotopes for medical purposes, tritium (hydrogen-3), and plutonium for bombs. The reactors in the former Soviet Union have used graphite moderation for electric power generation. Chernobyl was of this type. Unfortunately, this results in energy storage in the carbon (Wigner effect) from neutron bombardment. Release of this energy occurs under high temperature conditions when output power is raised beyond design limits. Such abrupt releases of excess energy create explosions, as the world knows.

A small educational reactor at the University of California, Los Angeles was graphite moderated and almost blew up on at least one occasion. This could have contaminated Westwood and some of the surrounding area. Nuclear power accidents are not confined to any one country. However, it should be noted that satisfactory education of the operators should prevent most such accidents because operation beyond design limits are always under operator control.

Another type of nuclear reactor is the breeder, which generally uses plutonium-239 as a fuel. This type of reactor uses the neutron flux to bombard uranium-238, the preponderant isotope in the fuel, to create plutonium-238, 239, and 240. The idea is to create more plutonium-239 than that used in the fission process in the reactor. Liquid sodium is the cooling medium of choice for these breeder reactors.

All reactors discussed above are of the slow neutron variety, which requires a moderator to slow down the neutron speed for the fission process. In order to shut down the reactor, cadmium control rods are inserted to absorb the neutrons and stop the fission process. Fast neutrons would cause the uranium-238 to undergo fission in addition to causing the uranium-235 or plutonium-239 to undergo fission. Fast neutron reactors operate at high temperatures, use liquid sodium as a coolant, and create plutonium-239. Production of plutonium-239 results in the risk of proliferation for bomb making, and is the reason its control is the subject of the non-proliferation treaty.

Another facet of nuclear reactor operation, perhaps the major impediment, is the high-level waste created, and the associated disposal problem. After some length of time, several months to several years, the major components are the shorter-lived cesium-137 and strontium-90. Both have half-lives of about thirty years, and the longer-lived transuranics, i.e., uranium and heavier species, last many thousands of years. These waste components are mixed together within the fuel rods along with the non-fissioning uranium-238, the most prevalent isotope.

To date no acceptable technique has evolved or been developed to handle properly these ionizing radioactive waste components. At present they have to be stored, monitored, and repackaged when necessary. This inability to satisfactorily dispose of the high-level waste from power reactors has stopped all construction in the United States. All U.S. nuclear plants are protected by the Price-Anderson Act, which forces the taxpayer to be responsible for any large-scale accident. Utility companies cannot afford the insurance for full coverage and would have to shut down operation if Congress rescinded the Price-Anderson coverage.

Such has been the nuclear power reactor development situation until global warming became an issue and the end of cheap petroleum became evident. The nuclear power industry has always argued that nuclear power should be one of the energy options to be considered, but now they use the global warming issue to argue that nuclear power should be the option of choice. Interestingly, the high-level waste disposal problem is barely mentioned, and then, only to claim that a potentially acceptable solution is now on the horizon.

Safety and High Costs

Attempts to reduce the high cost of nuclear power consists of specifying a generic reactor, the design of which will not have to be reviewed every time an application is made for a construction license. Another tactic is to reduce the stringency of safety requirements, which would significantly reduce the processing time for the license and automatically reduce costs.

Of course a few problems arise with these approaches. Freezing reactor designs precludes the inclusion of improvements without a return to lengthy licensing procedures. Relaxing safety requirements to reduce costs is just exactly the industry approach that stimulates massive public opposition. Perhaps some acceptable technique for high-level waste disposal would allay public concerns to the point where higher costs for safety would be acceptable. However, all estimates of nuclear power costs include only a small fraction of the real cost of waste disposal and decommissioning.

The latter involves a form of low-level waste disposal. What is most interesting regarding the cost is the efforts of the nuclear power industry to put the burden onto the general public as opposed to accepting the responsibility themselves. The public is persuaded to think the cost of nuclear power is acceptable by minimizing ratepayer costs while the substantially subsidized costs are buried in public taxes.

Safety Basics

Basic engineering principles as applied to safety acknowledges that nothing is 100 percent safe, but that a level of safety can be achieved by spending enough money. As applied to nuclear power plants, sufficient money must be expended to train operators in the areas of plant operation and plant security. Critical components of the physical structure can always incorporate redundant units or multiple units for even higher safety levels.

Maximum cost should be provided and a determination of whether the concomitant safety level would be acceptable. Unfortunately, the safety level that is satisfactory for one person may not be for another. Obviously, some type of technically justifiable decision making process should be established.

Waste Problems

Considering the long time required for the high-level radioactive waste to decay, the ethics of leaving this problem to future generations points to the irresponsibility of the United States over the last fifty years. Other countries share in this irresponsibility. It is wishful thinking to assume that authorities are people of good character and that technology will produce a satisfactory solution to the problem of waste disposal.

Given that about half the U.S. waste is at the Hanford, Washington site in the form of radioactive sludge acquired during the building of nuclear weapons, only about half of the U.S. waste is from the use of nuclear power plants. Plans have been made to solidify the sludge and to vitrify the solid waste into large glass logs. While the waste in this form will not disperse into the environment because of its solidity, and while it will not undergo fission because of the neutron absorbing chemicals in the glass, the question remains as to what can possibly happen after several thousand years. Can these large stockpiles of potentially hazardous material break up into smaller elements, which could mix with normal rocks and soil? Pulverization could conceivably release particles into the atmosphere. This is just one scenario to lead us to ask: Is this what we want to allow to happen by chance?

Another factor, which has not been determined yet, is the cost of such a process. It will be expensive and the taxpayer will certainly be stuck with the bill. Thus far no government has risked tackling this problem. So, it is ignored and is left to future administrations.

Unfortunately the leaking Hanford tanks are getting worse as the waste is beginning to contaminate the Columbia River. Gradually, it is becoming evident that the United States must do something. As contaminated as much of the world is, particularly the former Soviet Union, the Hanford area is among the most contaminated of any place.

Reactor Waste

Most of the 103 U.S. nuclear power reactors today are of the pressurized light water type—they use control rods and build up high-level radioactive waste in them. The spent fuel rods are stored in what are called swimming pools. Water is used for cooling the physically hot radioactive materials. So, now that these storage areas are pretty full, the problem of what is to be done needs to be faced. Building more and larger swimming pools only delays the day for carrying out a decision of what the long-term future will be for the troublesome material. A multitude of geological burial techniques has been proposed, but all have been found to have significant problems, and do not yet meet long-term engineering standards.

It is not necessary to present details here other than to mention the basic engineering system principle that requires the testing of any new system for at least one life cycle in order to make sure that there has not been a mistake or that an inadvertent design error has not been made. Needless to say, we cannot do this before deployment. The life cycle of any waste disposal system depends on one’s point of view. However, the estimates vary from 10,000 to 240,000 years, which are all impracticably long. Thus no geologic burial will ever meet basic engineering requirements, which would be necessary for us to bury the waste in good conscience.

Industry Plans

The nuclear industry, knowing all of the above too well, has resorted to newer designs and techniques, while claiming the problems are solved. There is the reuse of nuclear fuel in the waste by the development of breeder reactors. These bombard the uranium-238 isotope fuel blanket with neutrons to create larger quantities of plutonium-239 than are consumed in the original fission process. The idea is to create increasing quantities of nuclear fuel in an already-operating reactor, while waste is also being increased. This would increase the supply of fuel.

The waste in the new reactors would be treated by new pyro-processing separation techniques. The transuranics, or heavy long-lasting waste components of uranium and heavier elements, would be separated from the lighter and shorter-lived isotopes such as cesium-137 and strontium-90. With half lives of about 30 years, the effective period during which these shorter-lived isotopes pose a danger is on the order of 300 to 600 years, depending on one's point of view.

Because the heavier isotopes are only a few percent of the waste stockpile, there are a few problems the industry tries to sweep under the rug. The transuranic separation requires a molten cadmium bath at high temperature. That is the origin of the term "pyro-processing." This very toxic separation process, like that of any electroplating approach, is not perfect, and the separation is something less than 100 percent efficient. The industry plans for building new nuclear power reactors will add to the problems that exist. In the end, we have the original disposal problem.

The new pyro-processing techniques have only been achieved in laboratory apparatus at present. As engineers are well aware, there is a big jump much of the time between theoretical and experimental successes and the final commercially manufactured version.

Present efforts to solve the disposal problem for high-level nuclear waste have not resulted in any acceptable solution. Disposal in monitored, retrievable containers for at least 10,000 years is the only ethically responsible alternative. Essentially all future generations will be plagued by our nuclear power folly. Using nuclear fission to boil water for electricity generation is a flawed concept. The authorities that expressed faith that future engineers and scientists would develop satisfactory waste disposal techniques did not do their homework. They were, instead, driven by corporate profit interests and bureaucratic power.

The Future of Fusion

Since the middle of the last century physicists have conducted both theoretical and experimental research to lead to the development of practical nuclear fusion to produce power. If this were possible, the advantages of fusion over fission would be realized. One of greatest of these advantages is that of safety. The products of the fusion of light nuclei are other light nuclei, as opposed to the toxic and long-lived radioactive products of fission events. The fuel is also relatively benign. The simplest and most likely controlled fusion process that can be expected in the future will use helium and hydrogen isotopes as fuel.

Unfortunately, for decades this goal has been out of reach. Several concepts are under development. The one receiving the greatest financial investment is the plasma confinement concept. At the center of a star, such as our sun, the light nuclear material (hydrogen, helium, etc.) present in mid or early life exists under conditions of very high temperature and density, forming what is called plasma. As noted above, in this environment positively charged nuclei move at such high speeds that a significant fraction in any given time will be able to overcome their mutual electrical repulsion and come close enough that the strong short-range nuclear force can act to cause fusion to occur. The result is the conversion of light nuclei to heavier nuclei. The product nuclei have less mass than the sum of the masses of the light nuclei undergoing fusion. The difference in mass appears as energy in accordance with Einstein's famous equation, E=mc2. This energy is present both in the form of motion and of radiation (gamma rays). In the sun, the gravitational compression of the enormous mass of the body itself confines the material. In the laboratory, confinement must be achieved by other means. The preferred method of confinement has been by the effect of carefully designed magnetic fields on embedded plasma. This branch of physics, called magneto-hydrodynamics, is too involved to describe here.

Success for such schemes has proven very difficult to achieve. One reason is that the confined plasma must not be allowed to come into contact with the walls of the confining vessel. Instabilities in the plasma have plagued these efforts for decades. However, over time many lessons have been learned, and today many in the fusion community have confidence that the probability of success of the confinement method is dependent upon an increased size of the device.

At a Geneva superpower summit meeting in November 1985, after conferring with President Mitterand of France, Premier Gorbachev proposed to President Reagan that an international effort be undertaken to build an advanced fusion reactor of this kind, called a tokamak. Agreement was reached to go forward. While the project has had many twists and turns, it has nevertheless continued and construction of the facility for the International Thermonuclear Experimental Reactor (ITER) began in Cadarach, in the south of France, in 2007. The participants today are the European Union, represented by the European Atomic Energy Community, Japan, the People's Republic of China, India, the Republic of Korea, the Russian Federation, and the United States. Cost of the project is on the order of ten billion euros. There are many phases, and the schedule is of necessity a very long-range one. Full operation is not expected until 2050.

The ratio of the output to input power for these devices is called Q. A Q larger than one means the device can deliver net power. A Q equal to one breaks even. At the present time the most advanced tokamak is the Jet project, which has produced a Q of 0.65. The goal of ITER is to achieve a Q greater than 5.

The basic reaction involved is the fusion of hydrogen-2 and hydrogen-3 (deuterium and tritium) to produce a helium-4 nucleus and a neutron. This reaction is preferred over others, because the charge to mass ratios of the deuterium and tritium are small. Therefore, the coulomb barrier (mutual electrical repulsion) is lower and the probability of fusion occurring is higher.

However, the neutron produced by the reaction is somewhat disadvantageous. A free neutron undergoes beta-decay in a matter of minutes, resulting in a proton, an electron, and an electron neutrino. This time is long enough that before decay can occur, the neutron will penetrate into the structure. In addition to causing some radioactivity of the container, this process leads to the eventual breakdown of the structure and the need to replace it.

A more difficult feat would be the fusion of deuterium and helium-3, resulting in the production of a helium-4 nucleus and a proton. This is more difficult because the charge to mass ratio of helium-3 is higher than that of tritium, and the coulomb barrier is more difficult to overcome. The device would have to achieve higher density and temperature than the deuterium and tritium process. However, the resulting fast moving proton constitutes an electrical current and would allow coupling to a direct electrical energy output without the structural degradation caused by neutrons.

Conclusions

Regardless of how attractive it may seem or how hard the Bush administration promotes the interests of his nuclear power industry supporters, electricity from nuclear fission is still so hampered by the problem of high-level waste disposal, that any building of new plants would be a serious mistake. The analysis that two of the authors performed some years ago is still valid.* Recent technical advances are still grossly inadequate, and the future of nuclear power, as we know it, is very poor at best.

* James C. Warf and Sheldon C. Plotkin, “Disposal of High-Level Nuclear Waste,” Global Security Study No. 23, Nuclear Age Peace Foundation, September, 1996; and James C. Warf, *All Things Nuclear* (L.A.: Figueroa Press, 2004).

In contrast, experiments using nuclear fusion, appear to offer sufficient promise that the efforts should not only be continued but enhanced if possible. Electricity generation from this source is very attractive; however, it will be so long in coming, 2050 at least, that other nonpolluting sources of electricity have to be developed as soon as possible to address the global warming problem