The Need for Nuclear Power

by Hans A. Bethe

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The Yankee Atomic nuclear plant, a 175-megawatt pressurized-water reactor in Rowe, Massachusetts, began commercial operation in 1961.

The nuclear age started on December 2, 1942, when Enrico Fermi achieved the first chain reaction in Chicago. This was terribly secret at the time, so the boss of the Chicago laboratory couldn't tell it directly to his boss in Washington. Instead he sent a telegram saying: "The Italian navigator has reached the new continent. The natives are friendly." The "natives," that is, the neutrons, are still friendly if we treat them right. But that hasn't always been done, and nuclear power has declined from the popularity it enjoyed in this country in the 1950s and 1960s. I believe it is important to revive nuclear power for three reasons: global warming, pollution from fossil fuels, and dependence on foreign oil.

One sign of the disillusionment with nuclear power in the 1970s and 1980s has been that many of the nuclear power plants ordered before 1973 were stopped, and not a single plant ordered after 1973 ever got completed. Nevertheless, at present nuclear power contributes about 20 percent of the electric power in the United States. In several other countries it contributes more than 50 percent, and in France as much as 75 percent. What are the problems with nuclear power in this country? The three biggest ones are high cost, safety, and waste disposal.

Cost

The cost of nuclear power plants—in dollars per installed kilowatt or millions of dollars per million-kilowatt plant—has increased prodigiously since 1970, when it was $170. By 1983 it had increased to $1,700 on the average, and by 1988 to $5,000. This is not just from inflation; the consumer price index increased by only a factor of 2.2 from 1973 to 1983, and by a factor of 1.2 from then until 1988. It has often been said that the tremendous increase in cost was due to the incompetence of the utilities. It's true that some utilities are incompetent to handle nuclear power. But a very competent utility, for example, which had built many nuclear power plants and did not just accidentally lose its competence after 1970, still had a cost in the late eighties that was 13 times its cost in 1970.

One cause of the increased cost was the lengthening of the construction time, mostly due to changing safety regulations and lawsuits—6 years in 1968 and 12 years for the plants completed in 1980. This has been catastrophic for the cost, because of inflation during construction and because the interest is particularly high before the plant is actually completed. In addition, the utility can't count the incomplete reactor as part of its investment, and because a utility's total investment is considered when the rates are fixed, it ends up with a lot of money tied up with no return on it. This time delay accounted for a factor of three in the cost, and caused several utilities to go bankrupt.

In 1976 most of the cost of a nuclear power plant was in material, and relatively little was in labor. But by 1988 labor cost much more than twice what materials cost. Labor was particularly high because so much of it was highly skilled professional labor—quality-control engineers and design engineers for example. Much of the design and control required by regulation had to be done at the construction site, which is much more expensive than doing it in the factory.

Nuclear power is supervised by the Nuclear Regulatory Commission (NRC), and of course there ought to be such supervision; regulation is necessary in a potentially hazardous industry. Mistakes have been made by the construction people. At the Diablo Canyon plant in California, for example, they built an elaborate earthquake-protection system, but they connected the supports for the left-hand reactor to the right-hand reactor, and vice versa. So the earthquake supports were useless. There has to be somebody who watches out for that sort of thing and doesn't license the operation until such mistakes are corrected. In addition to the NRC there is also an internal industry organization—the Institute for Nuclear Power Operation (INPO). Its purpose is to enable utilities to benefit from the experience of others operating similar reactors, and they tend to listen more easily to each other than to the government.

The NRC has generally done a good job. But tightening the regulations during construction, as they often did, meant that the whole design sometimes had to be changed in midstream. That costs much more than if you start with the new design from the beginning, which anyone who has ever built a house knows very well. And sometimes even successful adaptations to requirements did not end up as a help to the industry. For instance, the NRC required the installation of emergency cooling of the core. Such a system was designed to the NRC's specifications, but when an experiment in Idaho showed that the system worked much better than had been expected by its designers, it was thought that the NRC might then relax some of the requirements. But they didn't do so. Likewise, in the accident at Three Mile Island it was shown that the two most dangerous fission products, iodine and cesium, were retained in the water of the reactor and were never released to the outside. This also might have been expected to lead to a relaxation, but it did not.

France has had a very different experience with nuclear reactors. In France everything is done centrally by the government laboratory: It does the design; it supervises the construction. This made it possible to standardize their reactors, which the French did very early on. They built about eight reactors of one type, which gave them experience, and then they moved on to the next, more powerful type. So theirs was a straightforward development; no changes were made during construction. And they had a standardized design, whereas in this country every nuclear power plant was one of a kind. It still takes the French five or six years for construction—the same as it was here in 1968. By now about 75 percent of French electric power is nuclear, and they also export it to neighboring countries.

Standardization is *possible in this country.*

Standardization *is* possible in this country. Of three new reactor designs in the U.S., sponsored by the Department of Energy and by the Electric Power Research Institute at Stanford (an industry organization), I am particularly interested in one design for a standard pressurized water reactor. It produces power of 600 megawatts, whereas most of the recent power plants are twice as powerful. This is a model we could standardize; we could produce the parts in the factory instead of at the construction site. It's a simpler design than the older reactors; it has larger safety margins; and because of standardization, the company predicts that construction could be done in 5 years instead of the present 12. The designers hope that these reactors will have a lifetime of 60 years, whereas the expected lifetime of present-day reactors is 30 years (although many will go on for 40). And they hope that there will be very few of the small incidents that currently keep a plant available for power production only 65 percent of the time; they're aiming for 85 percent with the new design.

The current cost of production of nuclear plants is about 1.3 cents per kilowatt hour—low because it comes from old power plants constructed when they were cheaper to build, and

The 1979 accident at Three Mile Island in Pennsylvania created a partial meltdown, but the two most dangerous fission products, iodine and cesium, were retained in the water and not released. The release of radioactivity at Chernobyl was a million times greater than that at Three Mile Island.

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because fuel is relatively cheap. Decommissioning these plants will also be cheap, because it occurs at the end of the plant's life, and the cost can be discounted back over its whole lifetime.

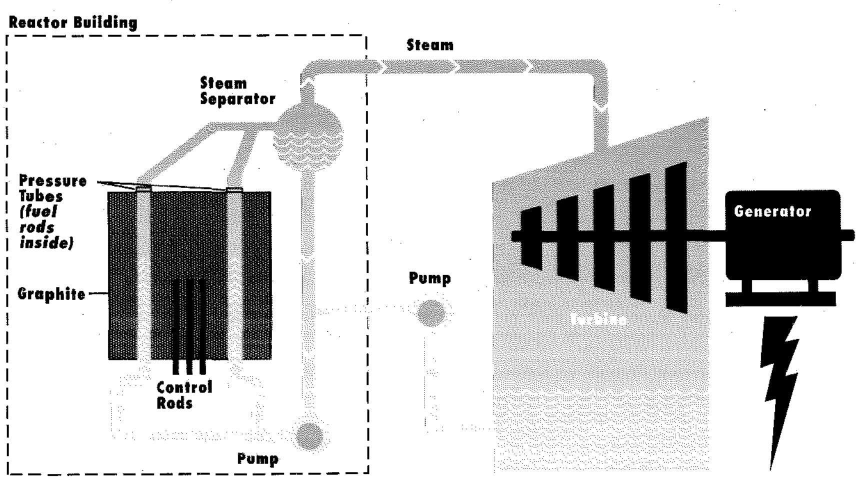
If we compare two pressurized water reactors, one designed on the old ideals of high (1200 megawatts) power, and the other as one of these new, smaller, 600-megawatt reactors, the capital costs are about the same—about 5.6 cents per kilowatt hour—but both are less than even the best figures of recent years. Operation is more expensive in the smaller reactor because you need two of them to get the same amount of power. Compared to the cost of a coal plant, however, the cost of this new generation of nuclear plants is expected to be just about the same. The initial cost of construction is, of course, still much greater for a nuclear than for a coal plant. On the other hand, fuel for a coal plant is much more expensive (and in Europe it would be twice as expensive again). In turn, operation of a coal plant is cheaper than that of a nuclear plant, and decommissioning a coal plant is really cheap. Adding together all the components, the new nuclear plants will be competitive with coal plants, which are already much cheaper than oil or natural gas plants, whose fuel is so expensive.

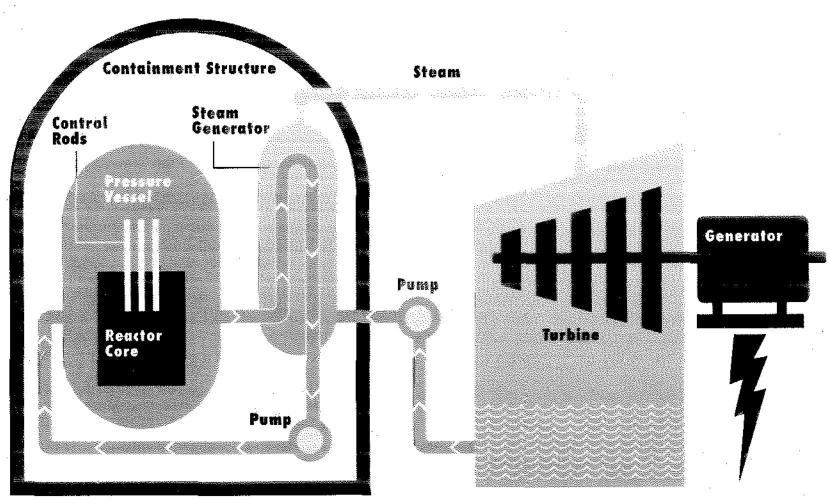
Safety

As for the safety of nuclear plants, there have been two fairly recent accidents—an absolute disaster at Chernobyl in the Ukraine in 1986 and a major accident at Three Mile Island in Pennsylvania in 1979. An accident such as occurred at Chernobyl *cannot* happen with any reactor in this country, in western Europe, or in Japan. This can be explained in terms of the Chernobyl reactor's design. The reactor is moderated with graphite; that is, the fast neutrons produced by the fission are slowed down to low (thermal) energy in the graphite. This is necessary to control the chain reaction of continued fission. The reactor is cooled by ordinary water, which just begins boiling when it exits the reactor at the top, producing steam to drive a turbine to generate electricity.

If there is excess heat produced, then the water will boil more vigorously, which means that the reactor loses water. In this particular type of reactor, water acts as a "neutron poison," that is, the hydrogen atoms absorb neutrons eagerly. The water does not contribute much to the moderation; that's done by the graphite, which does not absorb neutrons. But when the water absorbs neutrons, that means that fewer of them are available to make fission. So the water actually depresses the energy output in the reactor. But when the water is lost through boiling, fewer neutrons are absorbed and therefore more are available to create fission, thereby increasing the energy output. This means that whenever the heat is greater than that for which the reactor was designed, water will boil and increase the energy output still more. This makes for a very unstable situation: When you have lots of energy, you make more energy. So this reactor has to be controlled constantly by a computer, which keeps it as steady as possible. Why did the Soviets create such a stupid design? They did it because, along with power, they wanted to

Soviet reactors (top) have a graphite moderator (which slows down neutrons to facilitate the chain reaction). Water to cool the reactor begins boiling as it exits at the top, creating steam to drive the turbine. If water, which absorbs neutrons, is lost through boiling, the reaction can run away in a fraction of a second. A western pressurized-water reactor (bottom) uses water as a moderator, which will automatically slow down the reaction if any water is lost.





produce plutonium for weapons. For plutonium production they need excess neutrons and so need a moderator that does not absorb them—hence graphite.

In contrast, western reactors are stable. The moderator is water rather than graphite, so a loss of water means a loss of moderation. This means that power will automatically decrease as soon as any water is lost, because the neutrons have to be slowed down in order for the fission chain reaction to continue.

At Chernobyl there was a total loss of water, which made the reactor "prompt critical." What does that mean? Let's say we have 1,000 fissions occurring. They emit 1,000 neutrons, which are floating around the reactor. After a while a neutron finds a uranium 235 atom, and makes another fission. Now, 995 of these neutrons do this promptly; that is, they need only the time it takes to diffuse around—about a millisecond—in order to get slowed down in the graphite and to find another uranium nucleus. But 5 of those 1,000 neutrons do not act that quickly. These delayed neutrons are emitted between 1 and 50 seconds after the fission. In order to keep the chain reaction self-sustaining from one generation of fissions to the next (a state called "critical"), you have to wait for these delayed neutrons. But if you increase the density of neutrons because they're no longer absorbed by the cooling water, then the chance of a neutron finding another uranium nucleus becomes very high, and the reactor can go critical without waiting for these delayed neutrons. The prompt neutrons can do it themselves in the millisecond that it takes them to find another uranium nucleus. Therefore, once you are prompt critical, the reactor will run away in a fraction of a second—like a bomb.

There were other things wrong with Chernobyl. At the time of the accident the plant was in the charge of an electrical engineer who had no idea whatever about nuclear power. He disregarded all instructions. He pulled out all control rods (which control the reaction by absorbing neutrons); this meant that it was at maximum activity. That's how it got prompt critical. Fortunately, a record was kept of the way the power increased, so we know exactly what happened, although it happened, finally, in a fraction of a second. Because the Soviet reactor design requires frequent reloading of fuel, it had no containment building but was practically open to the air. So when the explosion occurred, radioactivity spread all the way to western Europe. In one of the hardest-hit areas in neighboring Byelorussia, inhabitants will get a lifetime dose of about 40 rem (a unit of radiation equal to a roentgen of x-rays in terms of damage to humans). For comparison, Americans receive from cosmic rays, from radon coming out of the ground, and from diagnostic x-rays, an average radiation dose of about 10 rem over 50 years. Four times that normal dose is likely to be somewhat hazardous, but not terribly so.

The one good outcome of the Chernobyl catastrophe was the application of *glasnost*. The Soviets immediately asked for western help on how to tame their reactors, and that help was willingly given through the International Atomic Energy Agency in Vienna.

A well-known report on safety, known as WASH-1400, or the Rasmussen report, discusses very unlikely combinations of troubles in western reactors and admits that with a combination of enough different and independent malfunctions at the same time, a western reactor could have an accident on the scale of Chernobyl, although due to entirely different causes. But such a combination is exceedingly improbable, and the report concludes that this might happen once in a billion years. Western reactors cannot become prompt critical no matter what we do.

But lesser accidents may still happen if the reactor is overheated and cooling water lost. The loss of water automatically shuts the reactor down so that no further reaction occurs; no Chernobyl can happen. But the reactor still contains lots and lots of fission products—radioactive iodine and others. These will continue to produce heat by radioactive decay, so a meltdown can still happen even after the reactor is shut down.

Three Mile Island had a partial meltdown, which came about because water was lost due to a valve remaining open that ought to have been closed. But it should not be mentioned in the same breath as Chernobyl. For one thing, the release of radioactivity in Chernobyl was more than a million times greater than at Three Mile Island. Second, the accident at Three Mile Island happened over several hours, whereas the Chernobyl accident happened in a fraction of a second.

In the new reactors that I've mentioned, if the reactor overheats, emergency cooling will be provided not by an engineered device that requires the functioning of complicated mechanisms, but automatically by natural convection. Pumps won't be needed for emergency core cooling; rather, the reactor and the water tank high above it are connected by a pipe, and since it's hot at the bottom and cool on top, convection will bring cool water down and hot water up.

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No human interference is needed to get this going; it's independent of engineered devices and of the intelligence of humans. A valve opens as soon as pressure in the reactor goes down due to loss of water. (I presume there are several valves so that you don't have to rely on only one.) The manufacturer's probability risk assessment estimates that core damage such as happened at Three Mile Island will happen in these new reactors once in 800,000 years of operation. I can't guarantee this, of course; such a claim should be looked at by independent people.

Core damage such as happened at Three Mile Island means a tremendous loss to the utility, but it does not endanger the public. For any real danger to happen, the containment has to break, and the chance of a breach in containment, according to the new reactors' manufacturer, is one in 100 million years. So, if you have 1,000 reactors operating, then such a break would happen once in 100,000 years, which is more than 10 times recorded history. This sounds pretty safe to me, but, again, I'm waiting for an independent assessment of that risk.

As for how dangerous nuclear power is, Bernard Cohen in his book, *The Nuclear Energy Option,* gives some nice examples of loss of life expectancy due to various causes. The most dangerous is to smoke, which causes the loss of an average of 2,300 days of life expectancy. But the next most dangerous is to be unmarried, making this a hazardous occupation! Averaged over the U.S. population, regardless of such hazardous exposure, all accidents together give a loss of life expectancy of 400 days; air pollution,

If all electricity were nuclear, then the average loss of life expectancy for the United States population would be somewhere between .04 and 1.5 days.

80 days; dam failures, only 1 day.

For comparison, people who live near a nuclear power plant lose 0.4 days of life expectancy due to radioactive releases and possible accidents. If all electricity were nuclear, then the average for the United States population would be somewhere between .04 and 1.5 days. The 1.5 comes from a competent antinuclear organization, the Union of Concerned Scientists, and the .04 comes from the Nuclear Regulatory Commission. But whichever is nearer the mark, it doesn't seem a big threat.

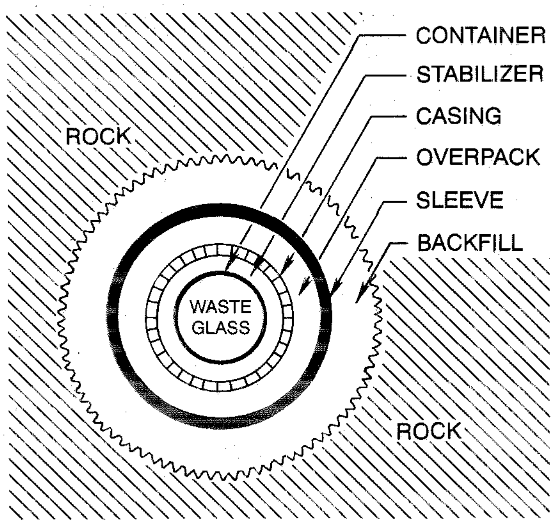
Radioactive Waste Disposal

The fuel remains in a reactor for three years. Every year one-third of the nuclear fuel is unloaded and replaced with fresh fuel. The unloaded fuel elements can be left as they are and encapsulated in borosilicate, a heat- and corrosion-resistant glass. This is how it is currently prescribed in the United States. By this method, the annual spent fuel from one reactor fills 10 cylinders, 10 feet long and 1 foot in diameter. Other countries, France and England for instance, chemically separate the spent fuel into fission products and transuranic elements, such as plutonium and curium, and then convert the separated waste into borosilicate or a similar substance.

The chemical separation is beneficial because the transuranics have a much longer lifetime than the fission products. The longest-lived of the latter, strontium and cesium, have half-lives of about 30 years, while transuranics live thousands of years. (Plutonium, for example, lasts 20,000 years.) Once you separate, the thermal power of a cylinder filled with fission products will decline from about 10 kilowatts after one year to 3 kilowatts after 10 years; after 300 years it's down to about 5 watts—just a flashlight per cylinder. The heat, which is a significant measure of the amount of radioactivity, decays very rapidly. So, if you separate the fission products chemically, the stuff becomes very mild after 300 years and couldn't do much harm anymore. This is important, because the borosilicate and its container will easily last a few hundred years, but they cannot last the tens of thousands of years necessary to contain the transuranic elements of the waste.

But what will we do with these transuranics? With present technology we would bury them separately, preferably in different locations. Precisely because of their long lives, they have very weak radioactivity, and therefore, although this is a great simplification, they will not thermally disturb the surrounding rock. Sometime in the future a much better method will become feasible. We will probably be building breeders to make more fissionable material, and if so, some of the transuranics—plutonium, for example—can actually be used, while others, although not useful, can be burned up. They will undergo fission, which reduces them to fission products with a short life of 30 years.

But if we *don't* separate the transuranics, how are we going to dispose of them? In the proposed system illustrated above, on the inside you have the waste itself, which is in this borosilicate glass surrounded by a container; the container



At Yucca Mountain (left) in Nevada, groundwater must flow 50 km before coming to the surface, which would take 100,000 years. Unseparated nuclear waste could be buried (right) at such a site in borosilicate glass surrounded by a container built to last several centuries. Then comes stabilizer, overpack, and a claylike backfill estimated to last 100,000 years.

can probably be made to last several centuries. Around that is a stabilizer, which is there to stabilize physical and chemical properties. And around this there is another casing—and that is the real safety—made of some very resistant material, such as copper, as has been proposed by the Swedes. Then comes something called "overpack." You now have this cylinder of material, which is let down deep into the earth and shoved into a tunnel.

Around that you then put the backfill, which is the most important of all. This is made of a special claylike material. Clay is impermeable to water, which is a very important property because the only way the waste could come up to the surface and into the biosphere would be through groundwater. So if you protect it carefully from contact with groundwater, then that stuff can sit there for a long time and nothing will ever come to the surface. This clay is not only impermeable to water, but when water touches it, it actually gets stronger—harder, denser, and more impermeable. So reasonable people have estimated that this backfill may easily last 100,000 years, which would certainly be long enough to contain plutonium and other troublesome elements. We can't wait 100,000 years to test it, of course, but experiments have been done on this backfill material to study its properties and determine how it would behave.

Now suppose all this fails—all the lines of defense, including the backfill—and we are exposed to transport by groundwater? Groundwater doesn't flow like a river; it creeps. At a disposal site in Nevada called Yucca Mountain, the Department of Energy has measured the flow of groundwater at 1 millimeter per day. And it has to flow a distance of about 50 kilometers before it comes to the surface, because it generally flows horizontally. With this alone, it takes more than 100,000 years to come to the surface. In addition to that, at Yucca Mountain the waste can be placed about 400 meters below ground, and the groundwater is 600 meters below ground, so the waste won't even touch it. This might change due to geological upheavals, but to start with it's a very good disposal site. And even if the groundwater is flowing 1 millimeter per day, experiments have shown that most dissolved elements take 100 times longer to flow than groundwater; they are constantly adsorbed by the surrounding rock and then put back into solution again. And plutonium, which is the element people are so afraid of, takes 10,000 times longer again to migrate than most elements. In other words, during plutonium's half-life of 20,000 years, you are insured 100,000 times over.

I firmly believe that neutrons are still "friendly" and that the three worries of nuclear power, namely cost, safety, and waste disposal, all have technical solutions. What we need now is public education against the misinformation that has been spread. And we need the political will to go ahead with developing this crucial source of energy. □

Hans Bethe's concern with nuclear power on earth has its roots in his influential work on the ultimate nuclear reactors—stars. His discoveries of how energy is generated in stars by nuclear reactions, work first published in 1938, won him the Nobel Prize in Physics in 1967.

Bethe is the John Wendell Anderson Professor of Physics, Emeritus, at Cornell University, where he has been a member of the faculty since 1935. He received his PhD from the University of Munich in 1928, and left for England in 1933 and the U.S. two years later. From 1943 to 1946 he was director of the Theoretical Physics Division of the Manhattan Project at Los Alamos, and afterward joined other concerned scientists in warning of the potential disaster of nuclear warfare.

A frequent visitor to the Caltech campus, Bethe came as the Lauritsen Lecturer in 1980 and as a Fairchild Distinguished Scholar in 1982 and 1985. During his most recent "unofficial" visit this past winter, he delivered the Watson Lecture from which this article is adapted. Willy Fowler introduced Bethe as "the Isaac Newton of our times. Newton showed how the earth orbits the sun. Bethe showed how the sun shines."