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Peaceful Nuclear Explosions

A Practical Route to Fusion Power

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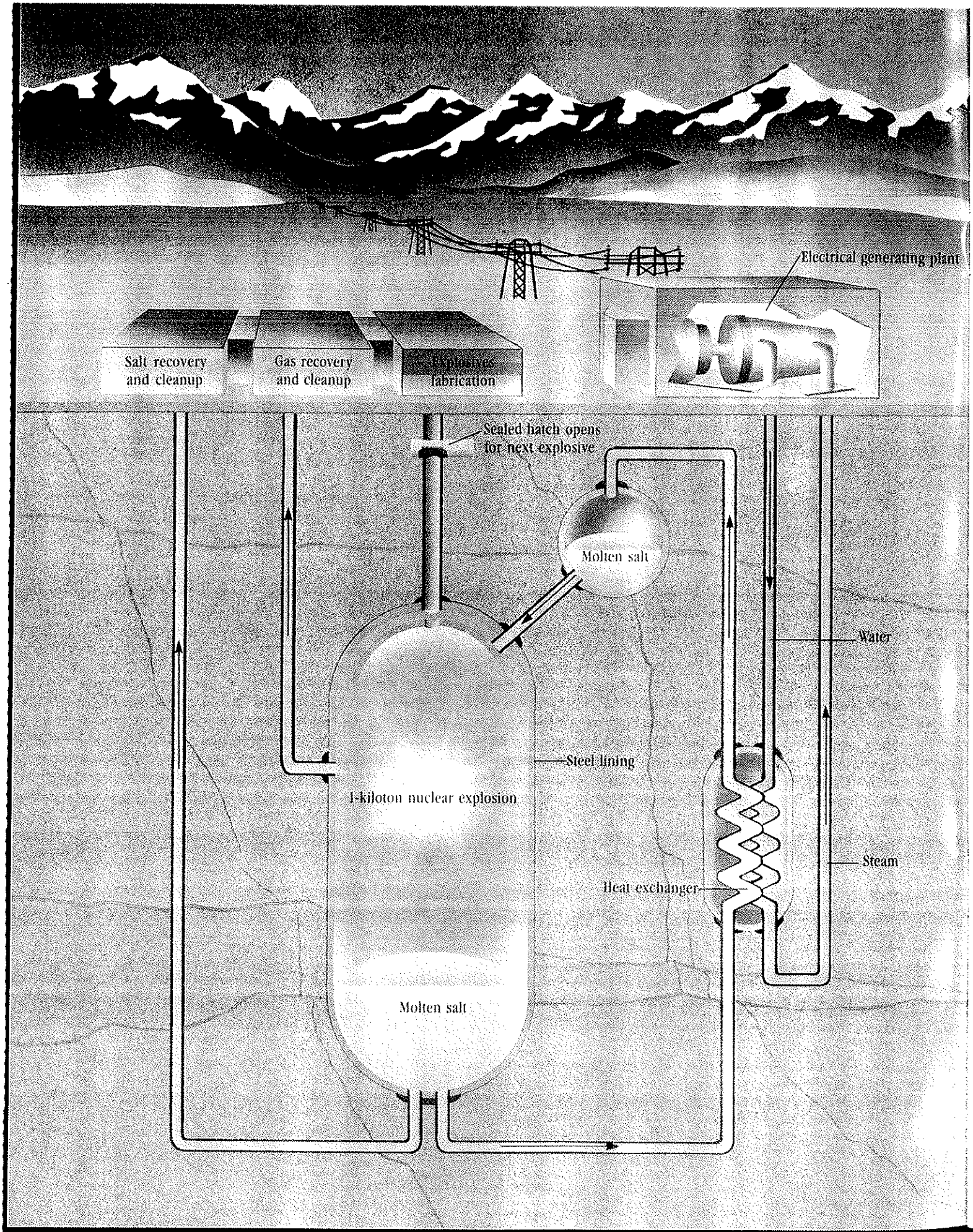
Electrical generating plant
Salt recovery and cleanup
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Sealed hatch opens for next explosive
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A Practical Route to Fusion Power

Small underground nuclear explosions could supply the world's electricity for centuries to come. Unlike other forms of fusion, this technology is feasible and affordable now.

THE taming of fusion energy—the force that makes stars shine and thermonuclear weapons explode—has proved one of the most tantalizing and frustrating quests of science and engineering. The world has enough fusion fuel to satisfy humanity's energy needs for centuries. But despite close to 40 years of research, laboratories have been unable to generate more energy from fusion than is required to get it started. A commercial reactor remains a mirage.

Yet a possible solution lies under our noses. Startling as it might seem, the most practical and economical course is to detonate small fusion blasts a few times an hour in underground chambers and extract the energy that's released. Jets of molten salt would carry the heat of the explosion through

BY ABRAHAM SZÖKE AND RALPH W. MOIR

ILLUSTRATIONS: GARDINER MORSE

a heat exchanger to create steam, which would drive conventional turbines to generate electricity. The salt jets would also carry waste and unused fuel from the chamber to an on-site plant that would recycle the usable materials into fresh explosives. The rest would be solidified, packaged, and stored deep underground, possibly at the reactor site.

We call the system peaceful nuclear explosives, or PNE. A PNE power station would use fission explosions to ignite the fusion explosions. At first, the fission explosions would supply most of the total PNE energy. We hope that over time, engineers would find ways to set off fusion explosions with smaller and smaller fission explosions, evolving to a system that produces as little as 10 percent of the energy from fission and reducing the amount of waste produced by a proportional amount. Even if that never happened, however, a PNE plant would still be economically competitive with—and as safe as—other nuclear technologies. In fact, a PNE plant would produce a tenth as much waste as a conventional fission plant.

Peaceful nuclear explosives would not be self-contained and transportable and so would be of little value to terrorists.

The key advantage of fusion is that the fuel is essentially inexhaustible. A fusion reactor would work by forcing the energy-releasing merger of deuterium and tritium—isotopes of hydrogen with one and two extra neutrons. Deuterium is abundant in water. Tritium is scarce in nature, but can be created by bombarding lithium with neutrons, which the fusion reactor would produce in abundance. In a sense, then, fusion plants really burn lithium, which is common enough to allow centuries of fusion power.

Nearly all the research aimed at producing electric power from nuclear fusion has so far focused on two broad approaches: magnetic confinement and inertial confinement. In magnetic fusion, magnetic fields confine a hot "plasma" of deuterium and tritium. In inertial-confinement fusion, or ICF, a laser beam or stream of high-energy subatomic particles strike a tiny pellet, heating and compressing its small load of deuterium and tritium.

Barring dramatic breakthroughs, magnetic fusion is decades away from producing a practical commercial power plant. ICF is also far from practicality. In fact, the bulk of the funding for ICF comes from the defense side of the Energy Department—the principal use is to aid weapons designers by simulating thermonuclear explosions.

No doubt the idea of producing repetitive nuclear explosions sounds alarming. However, a PNE plant would actually be safer in some ways than today's fission plants, and it would be just as safe as one based on magnetic or inertial-confinement fusion. In fact, PNE has many of the strengths and weaknesses of all fusion schemes. And since PNE is possible in the relatively near term, it helps us think about fusion and compare it with fission in a realistic way. Also, PNE is not the terrorist's dream it might seem to be at first blush. The explosives would not be self-contained and transportable. The fissile material would be no more vulnerable to diversion than the fuel transported to and from a reprocessing plant of the sort operated or planned by many countries that use fission power. (The United States has declared its intent to avoid reprocessing.)

PNE is not a new idea. In the early 1960s, physicist Albert Latter, then of the Rand Corp., devised a scheme called Pacer, which also would have captured the heat of nuclear explosions to generate electricity. But Latter did not plan to reprocess the unburned fuel—a crucial step that we believe makes PNE economically credible. Also, Pacer assumed Hiroshima-sized twenty-kiloton explosions. We believe PNE could work with explosions of one or two kilotons.

Over the past decade, scientists at nuclear weapons laboratories have taken a second look at designs like Pacer. Their aim has not been to develop an energy-production technology but to create a laboratory for studying matter at high density, pressure and temperature. They called it the High Energy Density Facility. Many of the technical ideas in this article come from that study.

Bombs into Energy

A PNE power plant would ignite nuclear explosives about every 20 minutes to produce 3,000 megawatts of thermal power. A generating plant would convert this heat into about 1,000 megawatts of electricity—the same output as a standard power plant based on coal or nuclear fission.

The cavity would have to be engineered to withstand the shock of the nuclear explosions. The elastic forces

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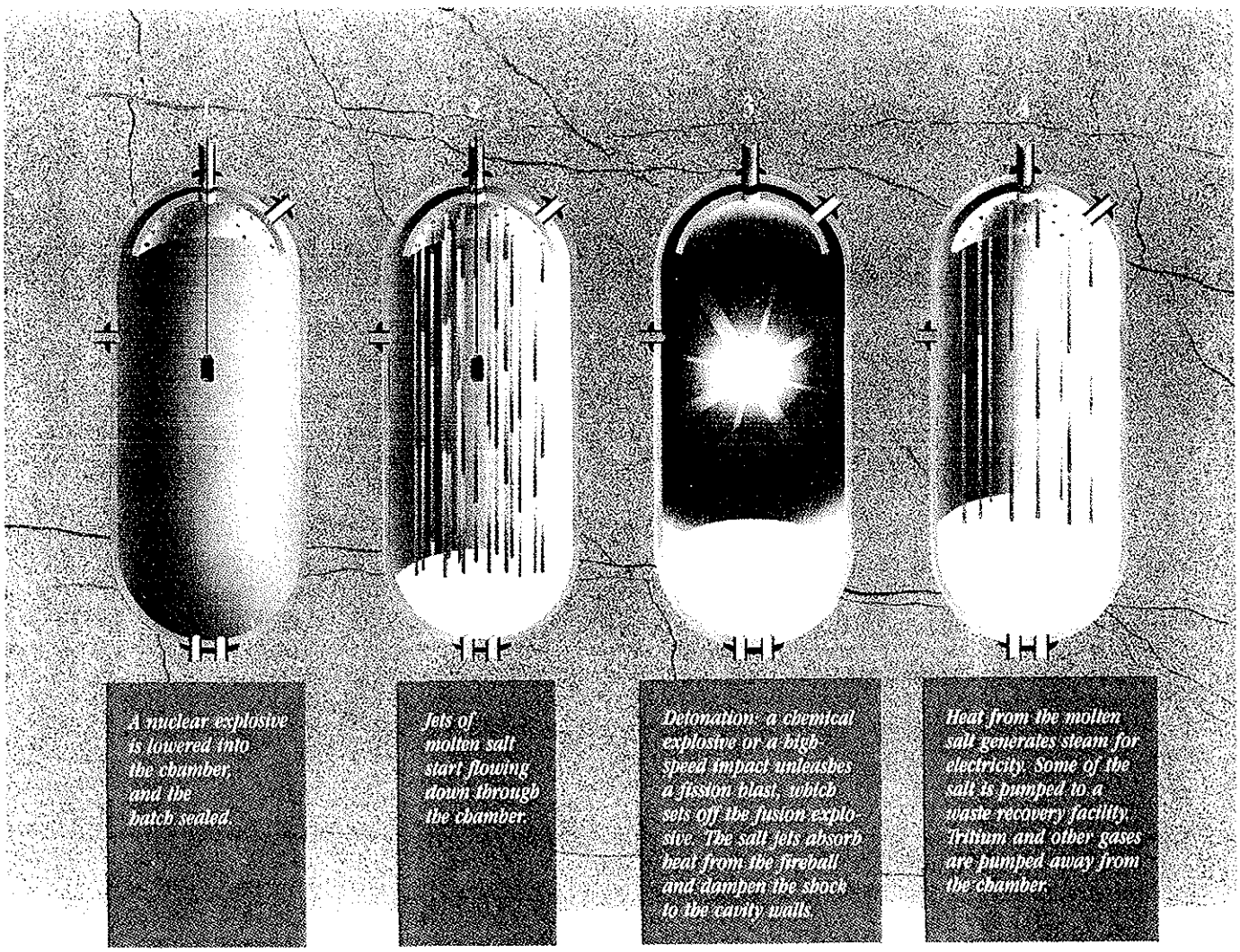


in rock would cause it to ring like a bell when hit by an explosion; with repeated blasts, the rock would crack into rubble and eventually the cavity would collapse.

One solution would be to mine a cavity in hard rock and line it with a thin layer of steel. This steel would be attached tightly by bolts anchored deep in the rock. Rock has enormous mass and is strong under compression, and a steel liner would ensure that it would stay compressed. That would prevent it from cracking.

It is also essential to protect the walls of the vessel from the hot gases and intense radiation of the nuclear fireball. This could be accomplished by surrounding the explosives with jets of liquids—the same liquids that are then used to extract heat. The jets also dampen the impact of shock waves on the wall. Two materials have been considered: one based on water, the other molten salt (lithium beryllium fluoride, or Li_2BeF_4—called Flibe). The advantage of water is that it is cheap, while the advantage of molten salt is that more fission products are soluble in it, and fissile and fusile materials can be recovered relatively inexpensively.

To minimize the fission material needed—and thereby generate less radioactive waste—engineers could take an approach they've known about since 1943: increasing the compression of the fission fuel. This way, both its mass and its yield can be lowered while the fraction that actually undergoes fission in the explosion goes up. These changes decrease the inventory of the fissile materials, make reprocessing cheaper, and reduce the cost of the containment vessel.

In nuclear weapons, conventional chemical explosives provide the force to compress the fission fuel, but PNE would probably use other means. One reason is that chemical explosives supply only so much pressure before even the hot gases they produce will condense. Moreover, if the materials being pushed accelerate to very high velocity, the hot gases cannot expand fast enough to "chase" them.

Several methods can deliver higher pressures than conventional explosives and also are capable of accelerating material to higher velocities. For example, engineers might wrap the fissile material in a cylindrical metal jacket through which they would pass a large electric current. The magnetic field generated by the current would produce a force that would squeeze the cylinder.

Or the PNE might contain one or two guns to hurl pieces of fissionable material at each other at speeds

three times that produced by high explosives. One possibility would be to use gas guns, which are similar to ordinary artillery but rely on compressed gases instead of gunpowder. An alternative would be a rail gun, in which electric currents induce a magnetic field that launches the projectile. The collision would compress the material into a supercritical state, and the resulting fission blast would ignite a fusion explosion in a deuterium-tritium fuel charge.

These compression schemes also lower the risk that explosives might fall into the wrong hands. A terrorist who somehow managed to steal from a PNE would not have a bomb, only bomb material. Nowhere in a PNE would one find fissile material conveniently packaged together with the machinery needed to compress and ignite it. In other words, nothing would be recognizable as a bomb. Gas guns and rail guns would be massive and bulky and totally unsuitable for producing nuclear weapons.

Each PNE plant, including reprocessing and waste disposal facilities, would sit on a highly guarded "nuclear reservation," from which nuclear material would never be allowed out.

Planning Development and Costs

Unlike magnetic fusion or ICF, PNE does not require solving any fundamental scientific problems. We envision an orderly sequence of engineering developments, starting with small facilities that could withstand explosions of 30 to 300 tons. These test facilities would verify PNE's key assumptions, such as the idea that the steel-lined cavity could take repeated nuclear blasts. Inspection of the chambers after each shot would show whether its radioactivity was in fact as low as predicted. In parallel, work would also go forward on improving the explosive.

The next step would be to build a cavity for testing explosions of one to two kilotons—the magnitude we consider useful for producing commercial power. Such a cavity would be the size of a sphere 60 meters in diameter—an underground bubble half a football field across and tall enough to hold a 20-story building. At this stage, automated plants would be built to manufacture fusion explosives and to reprocess unused nuclear material and separate wastes. This facility would probably be subject to international inspection, since it could produce nuclear materials. Successful operation would lead to the building of a full-scale power plant.

Despite its unconventional technology, a PNE could produce electricity at a cost comparable to that of today's baseload generating plants. We estimate that a PNE power plant using one-kiloton explosives would be economically competitive at $1,000 per explosion, which would include both producing the nuclear explosive and reprocessing the nuclear materials.

According to estimates made at Oak Ridge National Laboratory, reprocessing with a molten-salt system could cost as little as $10 per kilogram of recovered uranium, which could translate into $100–500 per explosion. Government secrecy makes a realistic and up-to-date estimate of the cost of manufacturing the nuclear explosive unavailable. The only one that exists was made some 30 years ago for Plowshare, a program to study peaceful uses for nuclear explosives, such as creating harbors and digging canals. The Plowshare estimate was orders of magnitude higher than the $500–900 that would make a PNE economical.

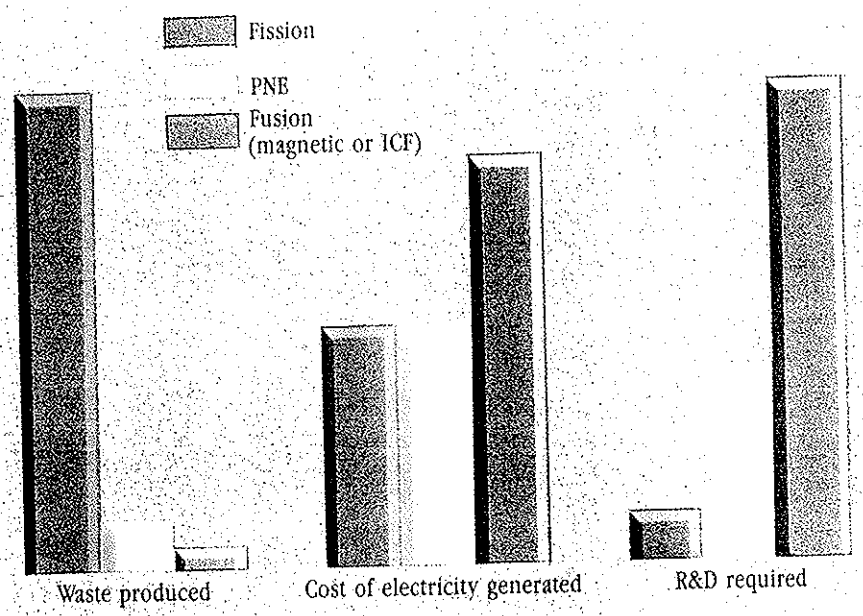
But PNE would differ significantly from Plowshare. For example, Plowshare required custom-made explosives for each application. PNE, on the other hand, would rely on many identical explosives—about 25,000 a year—so mass production should drive costs down. Plowshare also assumed that the explosive would have to be packaged for safe transport, and that there would be no recycling of fuel. Neither of these assumptions holds for PNE, which would therefore cost less.

The nuclear portion of the PNE electricity cost might be about half a cent per kilowatt-hour. Adding on the cost of the explosion cavity and conventional electrical generating machinery might bring the total to about four cents per kilowatt-hour—roughly what we now pay for electricity from a baseload generating plant using fission or coal. These estimates may be optimistic; we present them to show that the cost of electricity produced by a credible PNE station may well be competitive with ordinary electric power, even without extensive research efforts.

In Case of Accident

We believe that a steel-lined chamber mined into hard rock could withstand repeated explosions of the magnitude a PNE would use. But accidents do happen. If interlocks failed and the molten salt jets were not flowing at the moment of explosion, for example, the shock would hit the cavity walls at full strength. What would happen if the walls cracked?

Because the cavity is underground, leakage would



PNE compares favorably with other nuclear energy options. Because the technology is similar to that used in weapons, far less R&D would be required than for "pure" fusion using magnetic or inertial confinement. The economic comparison assumes a cost per blast of about $1000, which includes fabricating the explosive and recycling the unburned fuel. Thanks to continual on-site recycling, PNE would yield far less radioactive material for disposal than a fission reactor.

be small; the debris would contaminate the nearby rock and be detected. To leak into the atmosphere, radioactivity would have to penetrate the steel lining of the cavity, many feet of earth, and sealed doors that would stand between all underground tunnels and the surface. Such a leak would be highly unlikely.

And if a leak did occur, the worst contamination from it would be no more than 1 percent of that from today's fission plants. The reason is that a PNE plant would contain far less waste. Fission products would be removed from a PNE's salt jets perhaps once a week; in a fission reactor, wastes build up for about three years. Moreover, the PNE plant could be completely shut down simply by not lowering the next explosive into the chamber. There could not be the kind of runaway fire that exacerbates radiation release in a fission-plant accident because molten salt does not burn. By contrast, the graphite in the Chernobyl reactor burned for days.

The location of the PNE would have to be chosen so that the chamber would be acceptable for on-site burial of wastes. This is necessary because although most of the fission products will be continuously removed for burial, some wastes would accumulate on the walls of the cavity. Decommissioning might mean filling the chamber and auxiliary excavations with rock and concrete.

Proponents of fail-safe fission plants, such as small, gas-cooled reactors, similarly promise that no leak of gas or fluid could release significant amounts of radiation. One advantage of PNE is that it would continuously remove fission products from the plant. Also, as the design evolves to diminish the required size of the fission explosive, it would produce diminishing amounts of waste.

A practical goal would be to reduce the fission yield to 10 percent of the total, thus cutting waste by a factor of 10 compared with an all-fission plant. If researchers could find a way to initiate the fusion explosion without fission, we would eliminate fission wastes altogether, leaving only fusion wastes. Careful choice of PNE materials could make these wastes small. Flibe, for example, produces essentially no wastes and prevents the walls from becoming radioactive.

Although PNE would produce relatively little waste directly, there is an important caveat. Fusion reactions produce large quantities of neutrons. These neutrons could be used to "breed" material—either plutonium or uranium-233—for fission reactors, which would then produce their own waste. Such breeding would require surrounding the fusion reactor by a blanket of uranium-238 or thorium-232, abundant isotopes that can be mined from the earth. Indeed, a PNE plant might generate as much income from selling plutonium to fission reactors as from selling electricity. The same possibility exists for any fusion technology, however. In fact, the incentive to use magnetic-confinement or inertial-confinement fusion plants as breeders would be even greater, because the costs of these facilities are expected to be high.

Proliferating Plutonium?

The plutonium that could be produced in a fusion breeder is excellent bomb material. This is a problem that all fusion reactors will have to face, and that fusion advocates have spent years not talking about. To prevent plutonium breeding, a PNE—or any other kind of fusion plant—should be subject to thorough and in-

trusive on-site inspections by an international agency.

Fission reactors, by contrast, pose relatively little danger of weapons proliferation. These plants produce plutonium-239 in the spent fuel rods, but they also produce a lot of plutonium-238 and plutonium-240, which are not nearly as good for weapons. All three forms of plutonium are embedded in highly radioactive waste. It would be dangerous to steal the waste from a plant, and the bomb-grade plutonium would be difficult to separate.

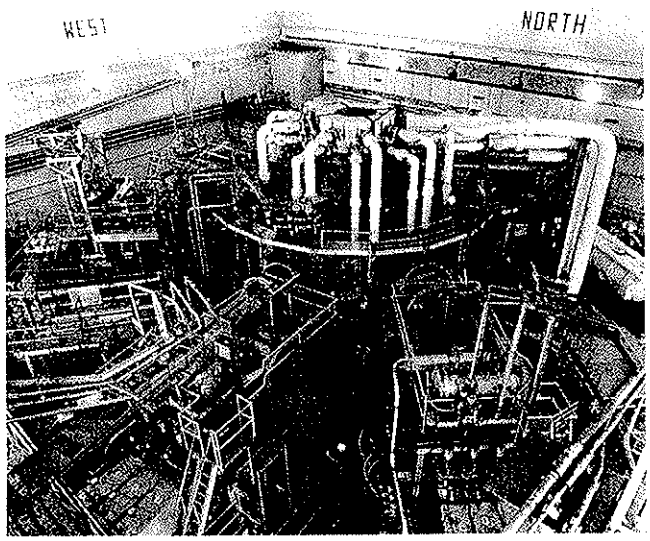
But many nations that use fission power are recycling the fuel or plan to do so. These countries—most notably France and Japan—recycle because they lack large supplies of uranium, and because separating the fissionable uranium-235 from the common uranium-238 is expensive. Unfortunately, recycling greatly raises the proliferation risk.

Spent fuel rods are sent to recycling plants, where the plutonium is separated and manufactured into new fuel rods, and it is difficult to detect if relatively small quantities of the plutonium have been stolen over a period of time. A malicious person or organization could accumulate enough to build a bomb. Thus, generating electricity with any kind of fission that depends on recycling poses just as much danger of weapons proliferation as fusion plants would if they were used to breed plutonium. Given the experience outside of the United States, it seems unrealistic to expect that operators of fission plants will agree to forego recycling.

Any nation that can design a PNE plant can produce nuclear bombs. For this reason, the international community should control the technology, permitting plants to be built only by states already possessing nuclear weapons or by non-weapons states under the supervision of an international agency. Any country that already has nuclear weapons would learn essentially nothing of military use from operating a PNE.

Proper siting and supervision of a PNE power plant would go a long way toward diminishing the admittedly serious problem of nuclear proliferation. Each PNE, including the power plant and the facilities for reprocessing and waste disposal, should be situated on a "nuclear reservation." To assure that no nuclear materials would ever be shipped out, these reservations would be extremely well guarded and located far from population centers, probably in deserts. Such siting would also address fears that a PNE accident might contaminate groundwater. Security at the gates of the reservation would have to be equivalent to that at a weapons facility.

One potential obstacle to PNE would be a tightening of the nuclear test-ban treaty. The treaty now observed (though never ratified) permits detonation of nuclear explosives up to 150 kilotons and so would allow a PNE plant of the type we propose. In fact, PNE could be developed and operated even if this threshold were lowered by an order of magnitude. But a comprehensive test-ban treaty, which would forbid all nuclear explosions regardless of size, would rule PNE out. We would hope that if such a treaty materialized, it would make exceptions for explosions used in PNE. This exception would be worth the intrusive verification that policing them would require.



PNE represents a radical departure from mainstream fusion research. In the leading approach, a doughnut-shaped chamber called a tokamak, like the one at Princeton (above), produces specially shaped magnetic fields to contain the hot fusion plasma. In a competing method—inertial-confinement fusion (ICF)—intense laser beams heat and compress a tiny pellet of fusion fuel in an attempt to touch off a microscopic thermonuclear explosion. ICF requires enormous lasers such as those at Lawrence Livermore Lab (right). Both magnetic fusion and ICF are decades from practicality.

Crazy? Consider the Alternatives

Today no ideal energy source for generating base-load electric power is in sight. Fossil fuels produce carbon dioxide, which the accumulating weight of scientific evidence suggests contributes to dangerous global warming. Conservation and increased efficiency, though essential, will not be enough to meet the energy demands of the world's growing population, especially in developing nations. We will undoubtedly have to turn to energy sources that do not produce carbon dioxide. There are three: solar, fission, and fusion.

All these sources have serious problems. Solar advocates typically minimize the potential role of nuclear power, and vice versa. Solar power sources, particularly photovoltaic cells, are growing cheaper and more efficient, and may become useful for daytime peaking power. They remain unsuited for base-load power generation, however, because the intermittent nature of solar power has no evident solution. Rechargeable

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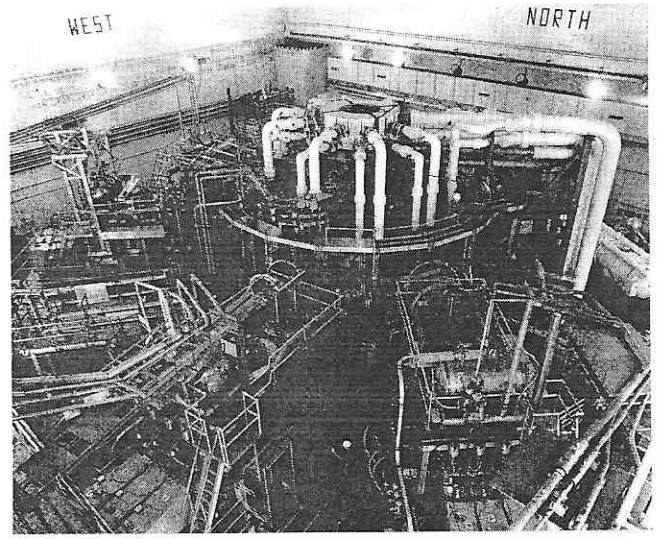

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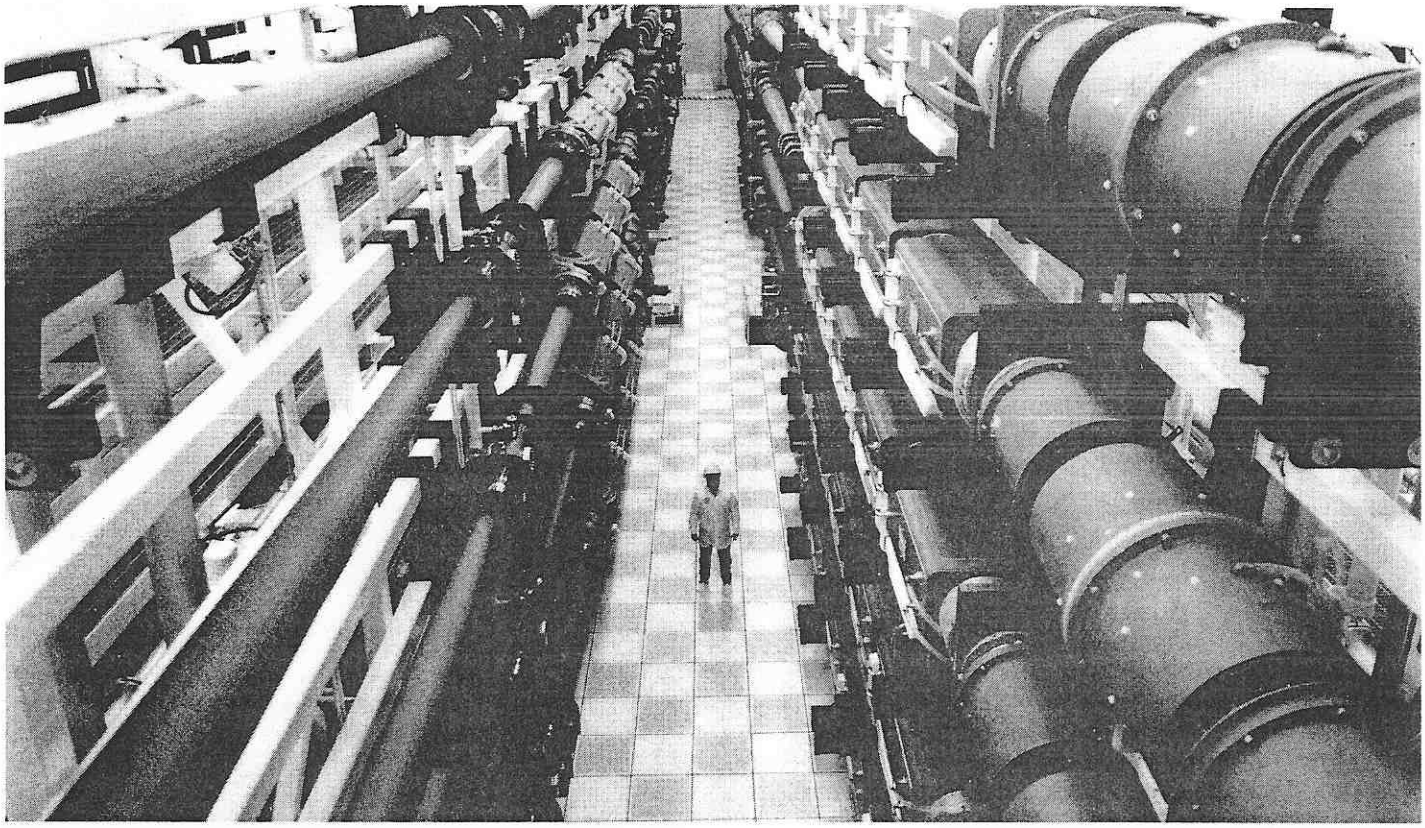

batteries, for example, continue to be inefficient, expensive, and short-lived, and foreseeable improvements are modest. Mechanical forms of storage such as pumping water into reservoirs and draining it to generate power when needed waste much of the energy. Flywheel storage is efficient but expensive. Photovoltaic production of hydrogen is an expensive way to generate electric power, though it may eventually prove cheap enough for applications where the hydrogen can be used directly, as in motor vehicles.

Fission, too, has large problems. There could well be another catastrophic accident, such as the explosion, meltdown, and fire at Chernobyl. And although we conclude that waste can be handled safely, much of the public obviously disagrees. Also, if fission involves reprocessing—and given the experience outside of the United States, it seems naive not to assume this—then the danger that fuel will be diverted to make weapons remains.

The United States alone is putting some $500 million a year into fusion research; worldwide spending amounts to three times this. In our opinion, PNE is by far the most practical route to fusion. Unlike other approaches, which require fundamental scientific advances, PNE is based on mature technology. For perhaps $50-100 million a year, we could embark on a PNE program that would be highly likely to result in an operating power plant decades before either magnetic or inertial-confinement fusion could.

Indeed, attempting to go straight to pure fusion would be as if James Watt had tried to build a steam turbine engine because it was thermodynamically more efficient and less polluting than a piston engine. But ordinary steam engines drove the industrial revolution, which eventually made turbines possible. Similarly, incremental development of PNE could lead to efficient fusion.

We do not wish to dismiss the issue of weapons proliferation. Rather, we point out that this same concern will arise with all nuclear technologies relevant to truly long-term energy production: PNE, pure fusion, and fission with reprocessing of fuel.

PNE will require institutional and technological safeguards against proliferation. But an early advent of PNE would actually give us a head start in developing such safeguards. This would also protect the plutonium in fission reprocessing plants and assure that neutrons from a pure-fusion reactor are not being used to breed bomb material. The inevitable hazards are essentially equivalent for PNE and for fission with reprocessing, and are quite similar to those of pure fusion. Since we cannot afford to forego nuclear energy entirely for the long term, then the sooner we put PNE in place, the more secure our energy future will be. ■

PHOTOS: PRINCETON UNIVERSITY PLASMA PHYSICS LAB