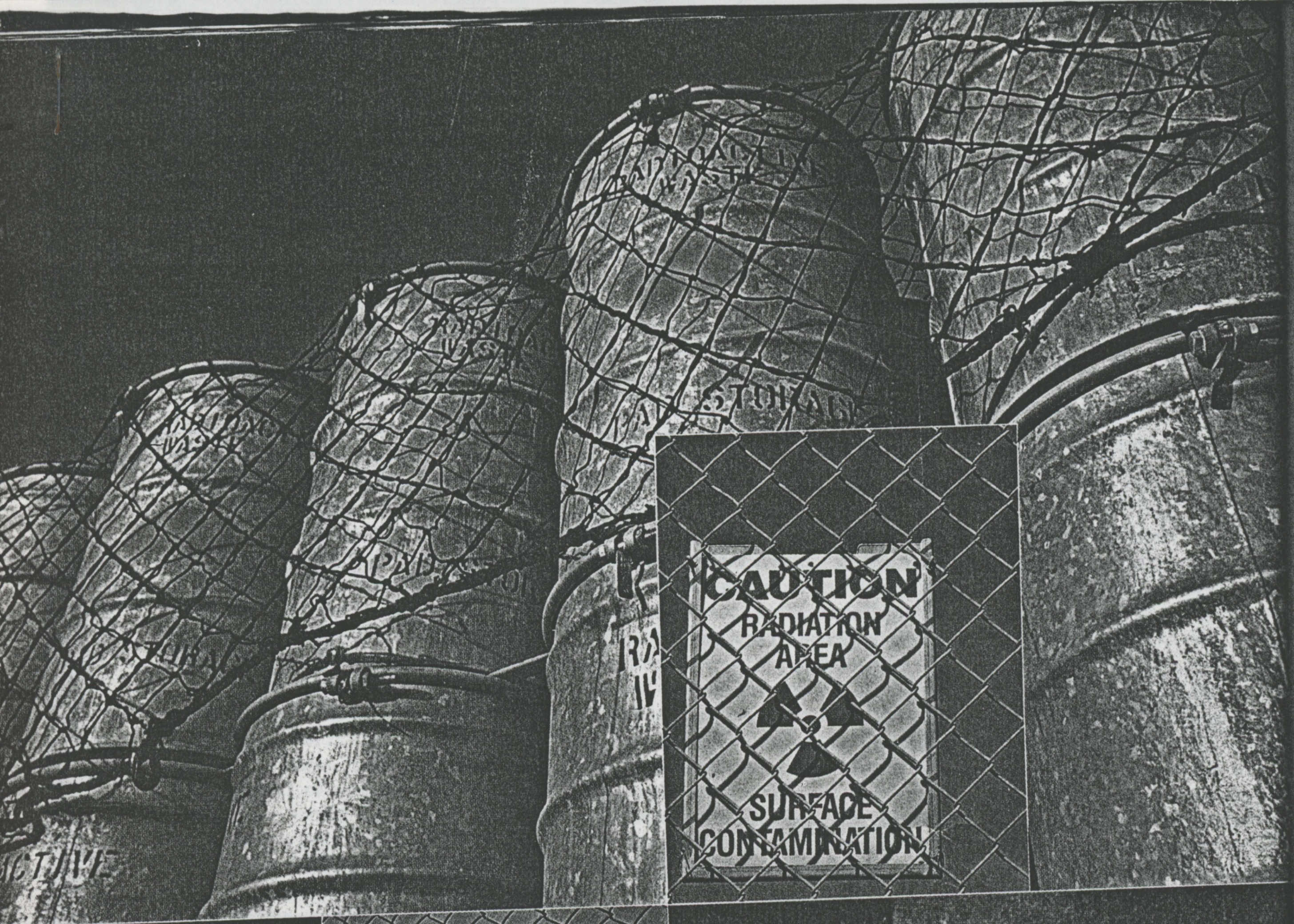
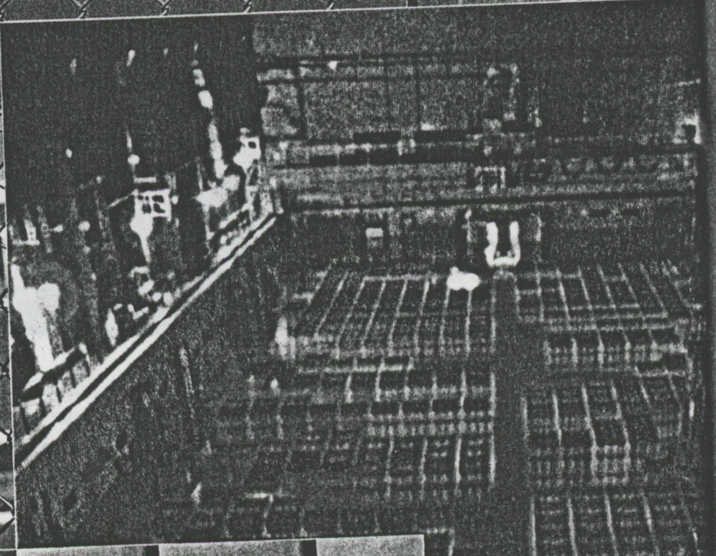


'Add a neutron or two to some of the most dangerous elements and you destroy them. Plutonium splits asunder, while the most intractable fission products are rendered harmless'



ONCE upon a time, the grass was green, the sky was blue and there were no stockpiles of weapons-grade plutonium or nasty nuclear waste lying around waiting for a final resting place. If physicists are to be believed, those halcyon days could soon be coming back. They think they have come up with the ideal solution to the nuclear industry's biggest image problem. Their fix will destroy the existing inventory of plutonium and minimise the threat of nuclear terrorism. It will also reduce the amount of hazardous radioactive waste, making underground storage a cinch. It could even generate electricity into the bargain.

This panacea is called transmutation. Add a neutron or two to some of the most dangerous radioactive elements and you destroy them. Plutonium, for example, is split asunder, while the most intractable fission products are rendered harmless.

Consider what transmutation can do to one of the most noxious constituents of radioactive waste. Technetium-99 is a fission product of uranium and reactors around the world throw out about 6 tonnes of it a year. It has a half-life—the time it takes for its radioactivity to decay

Nuclear lifeline

Latter-day alchemists believe they have a way of dealing with the nuclear industry's biggest bugbear. *Michael Brooks* reports

to half its initial level—of 200 000 years, and because it dissolves easily in water, technetium-99 accumulates in the food chain. Thanks to the nuclear industry, concentrations of technetium-99 in some areas of ocean have increased a hundredfold since the 1960s.

But add a neutron to this isotope and you transmute it into technetium-100, which has a half-life of just 15·8 seconds. In the time it takes to whip out your Geiger counter, it decays into ruthenium-100, which is stable and harmless (See Diagram, p 32).

It sounds too good to be true, and there is certainly a degree of scepticism about the whole notion. Nuclear power, after all, has turned out to be a double-edged sword. But just now there is a great surge of interest in transmutation. The governments of Spain, France and Italy are about to receive a report outlining what is needed to build a prototype transmutation reactor, and the US Department of Energy has just released $4 million for research and development.

There is, in fact, a race going on between European and American teams. Both hope that transmutation's time has come. For, although it is not a new idea (see "Nuclear alchemy: France's impossible dream?", *New Scientist*, 20 June 1992, p 12), it has never been seen as technologically and economically feasible. What has changed? Over the past few years researchers have rejected specially designed nuclear reactors as the natural home of transmutation, and turned their attention towards particle accelerators.

Nuclear reactions driven by a stream of subatomic particles can be made "subcritical"—which means they are not self-sustaining, so they stop when the accelerator is turned off. More importantly, the reactions can be tuned to destroy more radioactive materials than they create. Research on this idea began in earnest in the late 1980s at Los Alamos National Laboratory in New Mexico. Then, in 1993, scientists at CERN, the European centre for particle physics, near Geneva, announced that they were working on a similar project. Both projects have evolved quickly, and both teams believe the other has copied its ideas. The Europeans have turned down an opportunity to collaborate with the Americans because they are confident they can go it alone.

Persuasive energies

The main challenge facing the teams is to persuade isotopes to change their nature, which is no easy task. Whether or not a long-lived fission product, such as technetium-99, captures a neutron and transmutes is a matter of chance. But each isotope has a series of high, resonant energies at which that chance increases. If it encounters a neutron with one of these energies, it is more likely to transmute.

The other class of long-lived nuclear detritus is the transuranic elements (TRUs), such as plutonium, uranium and americium. Rather than transmute by capturing a neutron, these elements are destroyed by fission—and the probability that they will disintegrate increases as the neutron energy increases. "At high energy all the TRUs fission," says Jean-Pierre Revol, a member of the CERN team.

Disappearing waste

The problem facing physicists has been to produce neutrons with high enough energies. The latest generation of particle accelerators has made this feasible. These accelerators are smaller and more reliable than their predecessors. Whereas older accelerators turned only about 5 per cent of power from the grid into a particle beam, today that figure is 50 per cent.

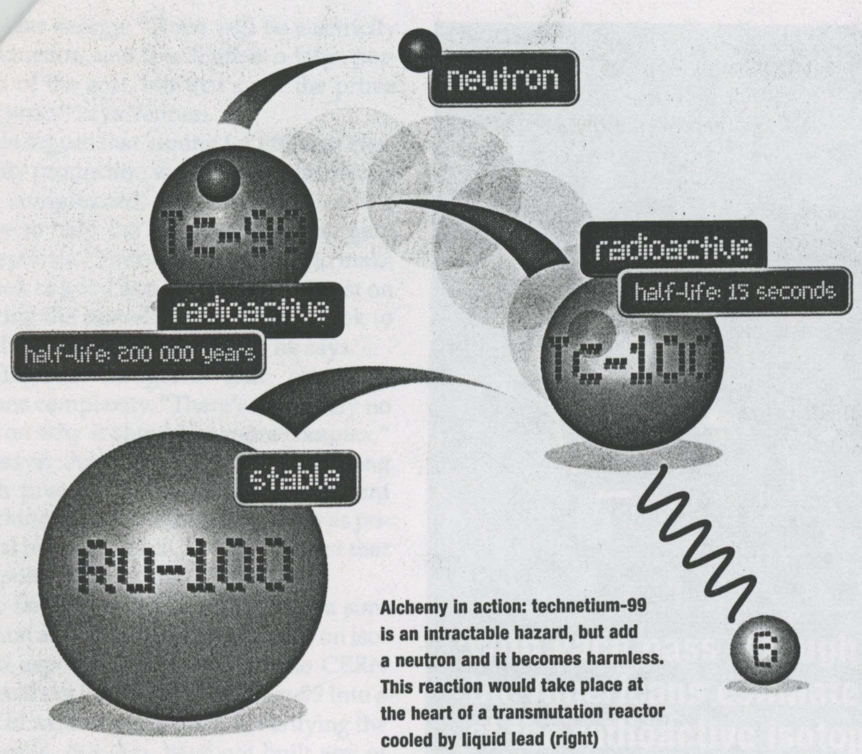
The result is a real possibility of making at least some radioactive waste disappear. The researchers calculate that, at the very least, the volume of waste can be reduced by a factor of 100. In theory, the volume could be cut further still, but that would be costly. "It will be a political decision as to how far you go with cleaning up," Revol says.

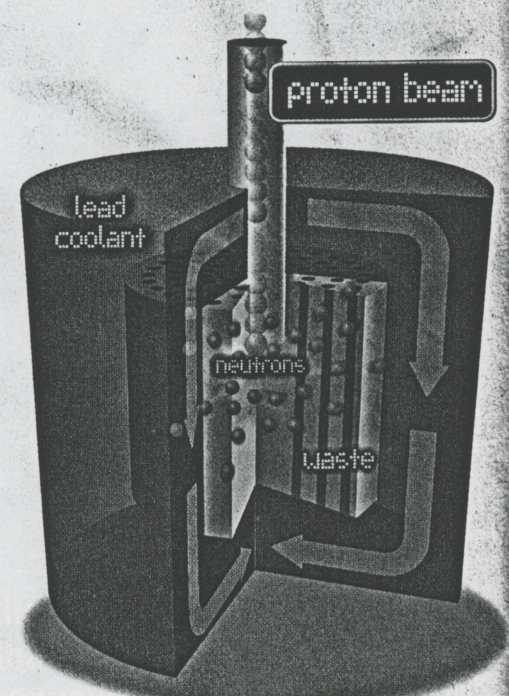
As the volume decreases, so too does the hazard. The governments of most nuclear nations plan to bury their long-lived waste in underground repositories designed to stay isolated from the world above for hundreds of thousands of years. After this time, the radioactivity would have decayed to a "safe" level. The trouble is that on such long timescales no one can predict what might happen. "If you have something with a half-life of 10 000 years, it essentially means relying on the storage for a million years," says Robert Klapisch, one of Revol's colleagues at CERN. "You really have to worry about earthquakes if you want to be sure these things don't return to the biosphere."

But with the TRUs split up into short-lived fission products and obstinate isotopes transmuted into stable elements, a repository would need to stay intact for a much shorter period. "We're talking about 300 years, compared to 1 or 2 million years," says Revol.

In the US, transmutation's ability to clean up waste is a strong selling point. Los Alamos researchers want to put plutonium into their system, fission it, and transmute the fission products. "One hundred years from now we could have less than 10 per cent of the existing inventory of plutonium," says Francesco Venneri,

W. McIntyre/SPL Katz M. Bond Environmental Images G. Rowell, R. Ressmeyer/Corbis





Alchemy in action: technetium-99 is an intractable hazard, but add a neutron and it becomes harmless. This reaction would take place at the heart of a transmutation reactor cooled by liquid lead (right)

head of the transmutation programme.

Transmutation could also, he argues, go a long way to solving the nation's repository problem—a hot potato for the Department of Energy. Back in 1982 the DoE promised to find a safe place to store waste by February last year. But when the deadline came, no site existed. Today, all that does exist is an investigation into the suitability of Yucca Mountain, Arizona, as a dumping ground. And if American reactors keep spewing out radioactive waste at their present rate, such a site would be full within 50 years anyway. Venneri wants to add waste from nuclear reactors to the plutonium and give it the neutron treatment too. By transmuting the waste first, Venneri reckons that Yucca Mountain would not fill up for hundreds of years.

So how would a transmutation machine work? The radioactive isotopes are packed into long tubes and lowered into channels inside a huge lead block. A beam of protons from an accelerator is then fired at the lead. The colliding protons generate a hail of neutrons with energies high enough to fission the TRUs. And as the neutrons collide with lead nuclei, they gradually lose energy, sweeping down the energy scale. As they pass through the resonant energies of isotopes such as technetium-99, the neutrons are more likely to trigger transmutation.

As well as generating neutrons, the lead also acts as the system's coolant. Heat from fission melts the lead, which rises in the reactor vessel (see Diagram, above). It then passes through a heat exchanger, where it cools and sinks again. The waste heat is converted into electricity.

Although lead is efficient at cooling by convection, it also has a downside. American scientists abandoned previous attempts to use liquid lead as a coolant because it is so corrosive. But, they now have what the CERN scientists reluctantly admit is a great asset: the Russians. Five years ago, the Russian Navy announced, to everyone's surprise, that it already had a fleet of submarines powered by reactors which used molten lead.

The Russians have solved the corrosion problem by bubbling oxygen into the lead, which encourages the reactor's structural alloys to grow a protective, self-healing film of oxide. They still regard their technique as a military secret. But, in exchange for research funding, they are sharing it with the Los Alamos scientists.

Assuming the lead can be made to behave itself, the machine would cook up its charge of waste and plutonium for perhaps three years. Afterwards, what's left would go to be reprocessed by a technique pioneered at Argonne National Laboratory in Idaho, called pyrochemical separation. This turns the waste into a molten electrolyte and draws off any unfissioned TRUs at a superheated electrode. The TRUs can then be mixed with any remaining long-lived fission products and new waste, and returned to the reactor. With each pass, the Americans estimate that at least 20 per cent of the radioactive isotopes would be destroyed. Short-lived fission products are sent to the repository.

Icing on the cake

That's the American pitch. The Europeans have added the icing on the cake. On top of destroying plutonium and reducing hazardous waste, they also want to produce competitively priced electricity. Their proposed machine has been dubbed the Energy Amplifier by its designer, Nobel prize winning physicist Carlo Rubbia. "The cost of building an Energy Amplifier will only be known after the main technical options have been chosen and a demonstration prototype has been built," admits Klapisch. "But the cost of electricity should be comparable with a pressurised water reactor because there is less maintenance and the fuel is cheap."

This cheap fuel is a mixture of thorium and oxides of the TRUs. Although thorium is not used as a nuclear fuel, it is considered to be attractive because it produces smaller amounts of TRUs—especially plutonium—than the uranium used in today's reactors.

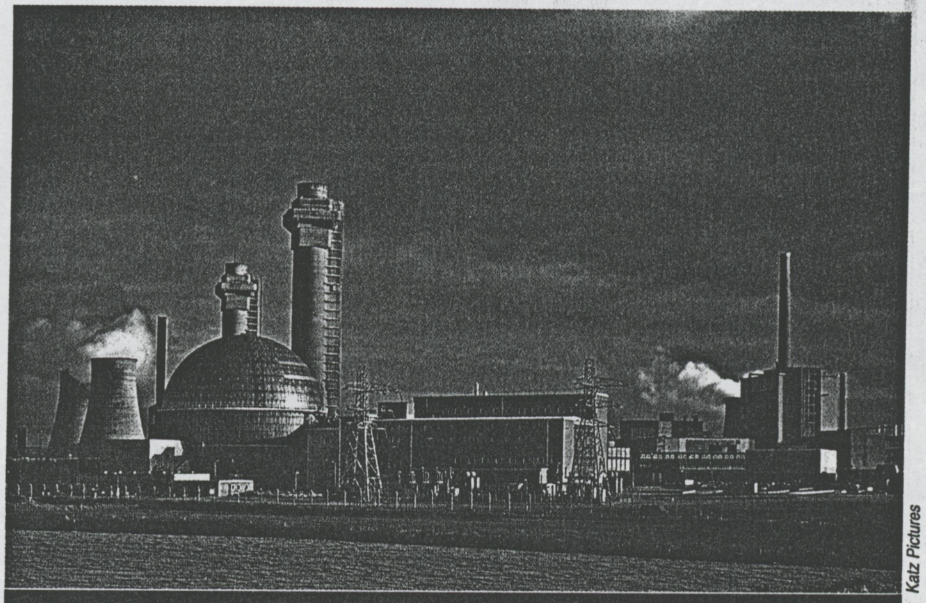
The political climate in the US doesn't encourage generating electricity with ear energy. "There will be electricity oduction, and it will offset a large portion of the cost, but that's not the prime purpose," says Venneri.

He argues that aiming for efficient electricity production would make the reactor too complicated, and that the idea is a ploy to help the European scheme gain acceptance. "Everyone would like to make it look as good as possible, but to insist on getting the best efficiency doesn't look to me like the best thing to do," he says.

Klapisch disagrees that efficiency means complexity. "There's absolutely no reason why it should be more complex," he says. And there is nothing wrong with presenting the most cost-efficient machine. The American plan is just as political in its approach, he says, it's just that the political priorities are different.

So far, the researchers only have a simulation and a series of experiments on isolated aspects of the system. The CERN researchers have put technetium-99 into a lead block and transmuted it, verifying the principle. But they have not built any of the reactor's structures. The Americans are building a target block, and aim to construct a prototype plant within five years. "I think we've made enough inroads in the last year to get started now," Venneri says.

Both teams are bullish about their prospects, but those watching from the sidelines are more cautious. "I don't think it's an idea that should be dismissed, but it requires advances in a whole range of technologies," says Richard Bush, the fuel processing manager at AEA Technology in Oxfordshire. He suggests that too many untested claims are being made. Lawrence Lidsky, a professor of nuclear engineering at MIT, is equally cautious. "Technically, it's on the edge of possible," he says. "Whether it makes any economic sense is another question."

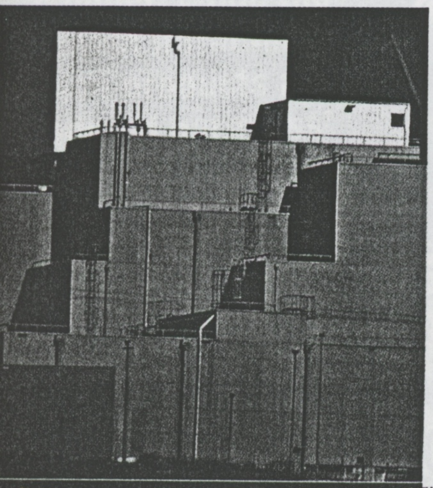


Katz Pictures

'With each pass through the transmutation reactor, the Americans estimate that at least 20 per cent of the radioactive isotopes would be destroyed'

Lidsky sat on a panel reviewing the Los Alamos work. Although impressed by the technology, the panel also had concerns. Stealing plutonium from the proposed machine would, in principle, be just as possible as from one of today's reactor. Once pyrochemical separation has recovered the TRUs from the machine's waste, the concentration of plutonium is actually higher than in spent reactor fuel. These plants would need high security, Venneri admits.

Lidsky is also worried about reactor safety. Although the researchers claim that their machines would be safe because they would work subcritically, he is concerned by their complexity. Today's reactors are already too complicated. "This is every bit as complicated, if not more so," he says. "There's more things to go wrong."



Nuclear cycle: could transmutation reactors make existing reprocessing plants like those in France (above) and Britain (top) redundant?

Short-lived

He predicts that the new optimism about transmutation will be short-lived. "What finally happens . . . is that somebody does a real analysis of how long it will take to accomplish any of these highly desirable political and social goals," he says. "Then we'll look at the real costs, where these things go, the shipping of plutonium to the sites, the degree of processing you need to do on site. You start doing an environmental impact study and it begins to look a lot less interesting."

But the CERN team is convinced that transmutation programmes will get the green light. "I think the EA prototype will certainly be built, and my guess is that it will be deployed," says Revol. "It's almost out of our hands now. The fundamental research and development is done."

Several European governments have expressed interest in transmutation, and nuclear companies such as Siemens and British Nuclear Fuels are carrying out their own research. The American company Westinghouse is backing the Los Alamos project. This, after all, is the break the nuclear industry has been waiting for—socially responsible action with nuclear power at its core.

Forgetting political caution for a moment, Venneri envisages a new era for power generation. "Eventually we'll be able to expand the role of nuclear power from the present-day 5 per cent to 25 per cent," he says. If you were looking forward to an era of calm, green technologies as an answer to global power and environmental crises, this may not have been exactly what you had in mind. □

Michael Brooks **is a science writer based in Lewes, East Sussex**

Further reading: **Details of the American programme are at:** ***www-adtt.lanl.gov***
Background on the European research is at: www.cern.ch/CERN/Announcements/1994/EnergyAmplifier.html