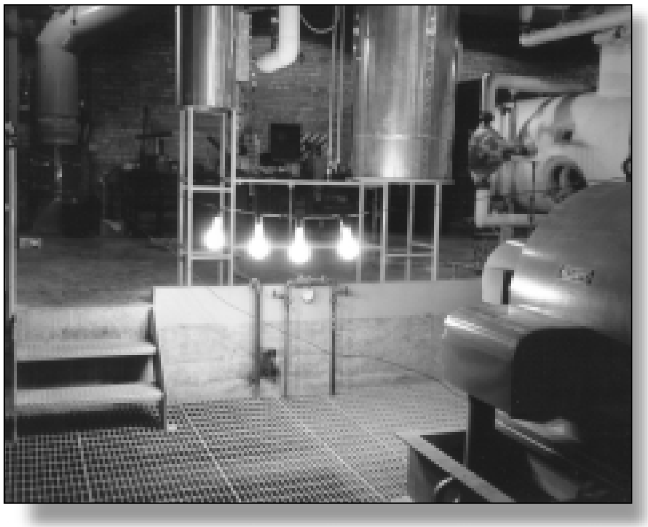
*Argonne researchers work to improve energy efficiency and supply while maintaining and improving environmental quality.*

# Technology pioneered at Argonne shows promise for next generation of nuclear reactors

A nuclear reactor technology pioneered by Argonne has the potential to provide safe, reliable electricity for generations to come. At the same time, it promises to reduce emissions of greenhouse gases and other pollutants. Both actinides recovered from spent nuclear fuel and weapons plutonium could be used as fuel in such a system, greatly reducing proliferation risks and the amount and toxicity of nuclear wastes that need long-term isolation from the environment.

The nonproliferation and waste-reduction benefits of Argonne's technology, called "pyroprocessing," were recognized by Vice President Dick Cheney's National Energy Policy Development Group, which recommended:

"... in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods *(such as pyroprocessing) that reduce waste streams and enhance proliferation resistance.* In doing so, the United States will continue to discourage the accumulation of separated plutonium worldwide." [Emphasis added.]



*Argonne has always been at the forefront of nuclear power research. Argonne's EBR-I, also known as Chicago Pile-4, was the fourth in the series of Chicago Pile reactors, which started with Enrico Fermi at the University of Chicago. EBR-1 was the first nuclear reactor to generate electricity, powering these four 200-watt light bulbs on Dec. 20, 1951.*

Today, commercial light-water reactors provide about 20 percent of commercial electricity in the United States. Over the last decade, the costs and environmental concerns of generating electricity from fossil fuels have risen, while nuclear power plants have become more efficient and safer. In addition, nuclear energy is now recognized as the only proven technology that can generate large amounts of electricity without producing the greenhouse gases that most scientists believe contribute to global climate change.

*The Birth of the Atomic Age was captured by Gary Sheahan to remember Enrico Fermi, Chicago Pile-1 and the first sustained nuclear chain reaction. Used with permission of the Chicago Historical Society.*

The national energy policy recognizes that nuclear energy, along with conservation and many other technologies, can play an important role in providing energy for continued economic growth, both nationally and internationally. To help meet growing U.S. electrical demand over the next decade or two, the nuclear industry has designed evolutionary and advanced light-water reactors. The U.S. Nuclear Regulatory Commission has certified three such designs.

For the longer term, there is a growing international consensus that to be broadly acceptable for the 21st century and beyond any advanced reactor system must:

- Reduce the volume and toxicity of nuclear waste;
- Be passively safe based on characteristics inherent in the reactor's design and materials;
- Keep nuclear materials unsuitable for direct use in weapons;
- Provide a long-term energy source not limited by resources; and
- Be economically competitive with other electricity sources.

"The only concept we know of that can meet all five requirements is a fast reactor system with a closed fuel cycle based on pyroprocessing," said Yoon I. Chang, Argonne's associate laboratory director for Engineering Research. (See page 27 for sidebar on fast reactors.)

Pyroprocessing is a nuclear-fuel treatment and recycling technology developed at Argonne. It is a multi-step process that removes actinides — uranium, plutonium and other transuranic elements that take hundreds of thousands of years to decay — from used nuclear fuel and recycles them back into new fuel. The reactor then burns them to make electricity, destroying them in the process. The shorter-lived fission products remain and are incorporated into ceramic or metallic waste forms for isolation from the environment in a specially designed and maintained geological repository.

## Nuclear waste reduction

Since the long-lived wastes are burned in the reactor, only the short-lived ones would need environmental isolation — and only for a few hundred years.

"After four hundred years," Chang said, "they would be less radioactive than the natural ore the original fuel came from. You'd still need a repository, but it would be much less technically demanding than one to isolate waste for thousands of years. Humankind has lots of experience creating and tending to buildings and other structures that last a few hundred years."

In addition, the pyroprocessing system is so compact that it could be built on the same site as the reactor plant. All the processing would take place on site, greatly reducing both the costs and the environmental risks of transporting spent fuel from the site.

## Passive safety

If cooled by liquid sodium, a fast reactor would be passively safe; that is, safety would be inherent in its design and materials and not solely dependent on engineered safety systems. This passive safety was demonstrated in two landmark tests Argonne conducted at the EBR-II reactor, a small, prototype fast reactor operated at Argonne-West in southeastern Idaho from 1964 to 1994.

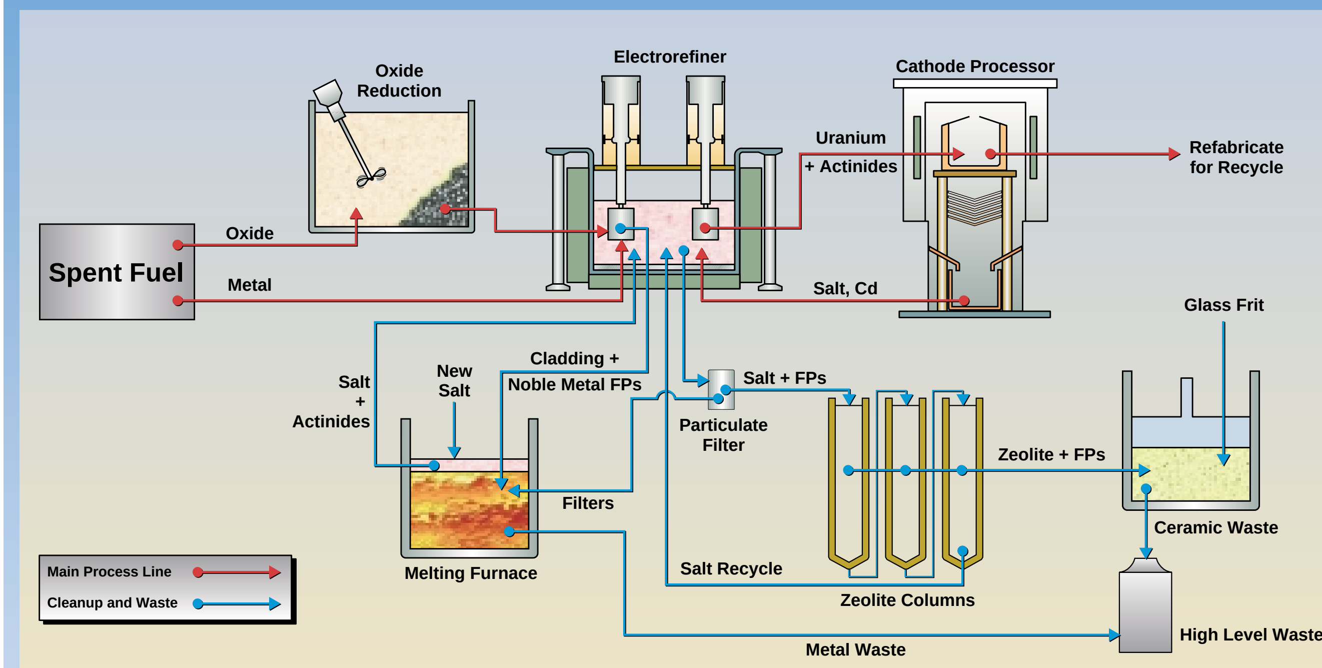
The tests demonstrated that even the most severe accidents would not damage the reactor or release radioactive material. "In one test, we shut off the power to the pumps that circulate coolant through the core," Chang said. "And in the other, we cut off all heat removal. In both tests the reactor safely shut itself down without human or mechanical intervention. In most other reactor types, this would cause a severe accident."

## Proliferation resistance

Pyroprocessing eliminates the ability to use the reactor's nuclear materials directly in weapons because it cannot separate pure enough plutonium. Instead, it keeps the major nuclear fuels, uranium and plutonium, mixed at all times with other actinides and fission products. This mixture is protected against theft or unauthorized diversion because the mixture is extremely radioactive and must be handled remotely with sophisticated and specialized equipment.

Fast reactors could further aid nonproliferation by helping to eliminate the existing stockpile of weapons-grade plutonium. Incorporating the plutonium into fuel for the first fast reactors would make it unsuitable for weapons.

## Argonne's pyroprocessing technology




*A nuclear fuel cycle based on Argonne's pyroprocessing technology offers substantial improvements in waste management, proliferation resistance and economic potential compared to conventional processing technologies used overseas.*

***Fuel recycling:*** *The key step is "electrorefining," which removes uranium, plutonium and the other actinides (highly radioactive elements with long half-lives) from the spent fuel, while keeping them mixed together so the plutonium cannot be used directly in weapons. Spent fuel from reactors that use metallic uranium fuel can go straight to the electrorefiner. Spent fuel from commercial reactors, which consists of uranium oxide, would first undergo an "oxide reduction" step to convert it to metallic form. Next, the uranium and other actinides are sent to the cathode processor to remove residual salts and cadmium from electrorefining. The actinides are cast into fresh fuel, while the salts and cadmium are recycled back into the electrorefiner.*

***Nuclear waste:*** *The waste consists of two forms. The stainless-steel cladding that encased the spent fuel is combined with noble metal fission products in a metallic waste form. Salts and other fission products are combined with zeolites and converted into a ceramic waste. Both metal and ceramic waste forms are highly radioactive when they are created, but in less than 400 years, their radioactivity decays so they are less toxic than the natural ore the original fuel came from.*

## Centuries worth of clean electricity

Fast reactors can deliver 100 times more energy than today's reactors, which currently extract less than one percent of the total energy potentially available from natural uranium. Today's reactors burn uranium-235, a fissile form that accounts for less than 1 percent of natural uranium. The remaining portion, uranium-238, is not fissionable and is discarded as waste. But in a fast reactor, the uranium-238 is converted into fissile plutonium-239. By recycling used fuel and burning the plutonium, fast reactors can use essentially all of the natural uranium to produce energy.

"This is an enormous increase in fuel efficiency," Chang said. "There is enough uranium in the world's known reserves to fuel fast reactors for centuries."

## Economics

One major economic advantage is the ability to use so much more of uranium's natural energy than is possible in today's commercial reactors. A second is the short-lived waste form, which could markedly lower disposal costs.

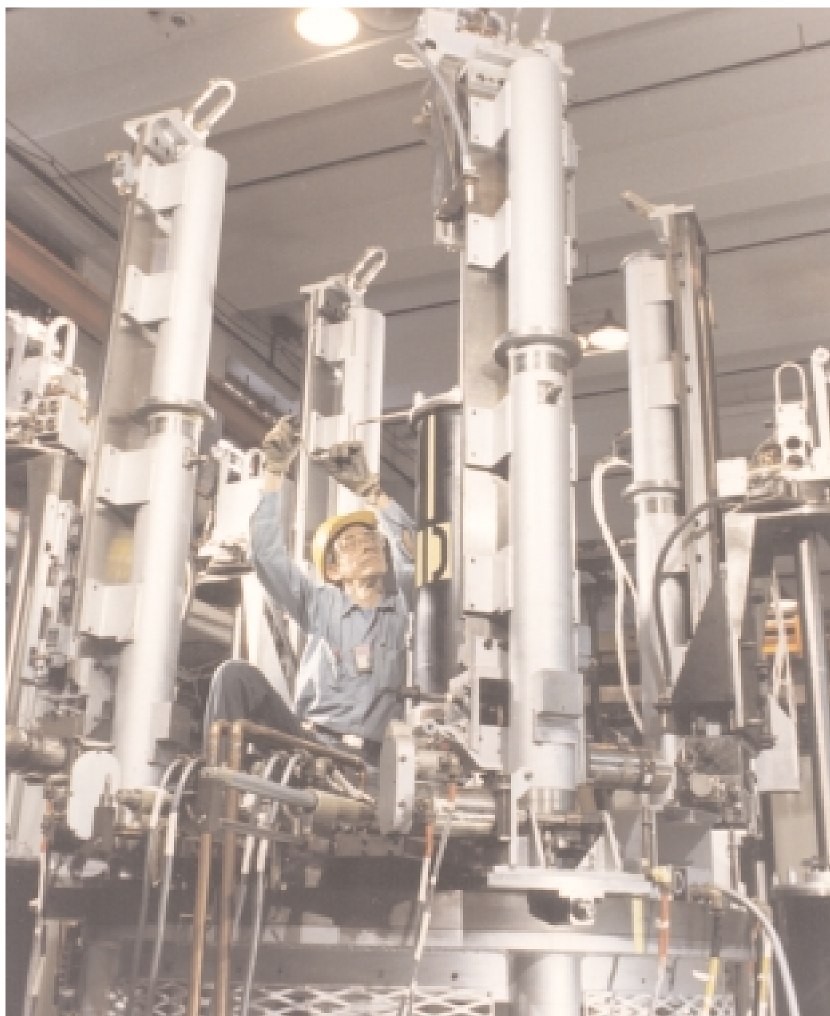
But sodium-cooled, fast reactors have other economic advantages as well. Because the sodium boiling temperature is very high, the cooling system can operate at essentially atmospheric pressure. Sodium is also non-corrosive to the structural materials used in the reactor. These unique characteristics of a sodium-cooled system result in superior reliability, operability, maintainability and long lifetime, all of which contribute to low life-cycle costs.

## Further environmental benefits

Pyroprocessing was developed for fast reactors, but it could treat spent fuel from today's commercial reactors with the addition of a single step to convert commercial spent fuel, which is made of uranium oxide, to metallic uranium. With this addition, the pyroprocess would provide the same benefits for commercial fuel that it would for fast-reactor fuel — removing long-lived elements from the waste, greatly reducing the waste's volume and toxicity, and easing the cost and technical burden of building, licensing and maintaining a repository.

## Progress on pyroprocessing

Pyroprocessing is already a well understood and largely proven technology. The centerpiece of pyroprocessing is the "electrometallurgical" step that separates uranium from used fuel. Electrometallurgical technology was successfully demonstrated at Argonne-West between 1997 and 2000. This three-year demonstration project treated 100 EBR-II driver fuel assemblies and 18 blanket assemblies. A special committee of the National Academy of Sciences found that Argonne's electrometallurgical



*Norb Saber works on an electrorefiner, a device that removes unburned fuel and long-lived radioactive wastes from spent reactor fuel. Electrorefining is a key step in an Argonne-developed reactor technology that can burn long-lived wastes as it generates electricity. The remaining nuclear wastes would be as safe as the natural ore they came from after only 400 years.*

demonstration project met all the criteria for success, and DOE followed with a formal decision to use electrometallurgical technology to treat the remaining 25 metric tons of EBR-II spent fuel.

*Using Argonne-West's existing facilities, the full pyroprocessing technology could be demonstrated in about three years.*

## The future

Going beyond EBR-II spent fuel treatment, a full pyroprocessing demonstration could be accomplished using Argonne-West's existing facilities. It would take about three years, said Chang, and would demonstrate all the advantages of this fuel-treatment technology, including recovery of actinides, qualification of waste forms and enough production capacity to show that it can work on a commercial scale. It would also demonstrate the conversion of commercial oxide fuels to the metallic form and the ability of compact metal and ceramic forms to safely contain short-lived wastes.

A successful demonstration at Argonne-West would provide a solid technical foundation for a commercial-scale demonstration of an advanced fast reactor and its accompanying fuel cycle facility. The demonstration would test the reliability, safety, economics, proliferation resistance and waste management of the fully integrated system. If the nation decides to place a high priority on early construction of a commercial-scale demonstration plant, Argonne and its collaborators stand ready to proceed with the design activities in parallel with the technology demonstration program.

## What is a fast reactor?

*Nuclear reactors produce energy by a process called fission. Fission occurs when an atom of fissile material is struck by a neutron, becomes unstable and splits, producing fission fragments and high-energy neutrons. In an operating reactor, one of these neutrons will strike another fissile atom to maintain a steady chain reaction. Fission also releases heat, which is used to produce steam to spin an electrical generator.*

*Reactors can be classified according to the energy of the neutrons that cause fission. Present day commercial power reactors are called "thermal" reactors because the neutrons have been slowed to thermal energy using a "moderator" - usually water. By contrast, a "fast" reactor uses neutrons of much higher energy to cause fission. A fast reactor does not have a moderator.*

*The only fissile material found in nature is uranium-235, which makes up less than 1 percent of natural uranium. While some fissile plutonium is produced in a thermal reactor, it is not enough to replace the uranium-235 used. In a fast reactor, however, enough plutonium can be produced to more than make up for the uranium-235 used. In addition, many of the long-lived actinides that can not be fissioned in a thermal reactor can be burned in a fast reactor, so the fast reactor is capable of destroying the major source of long-lived radiotoxicity in spent fuel. Thus, the fast reactor can create new fuel and destroy long-lived nuclear waste while it produces electricity.*