Nuclear Energy to Go

A Self-Contained, Portable Reactor

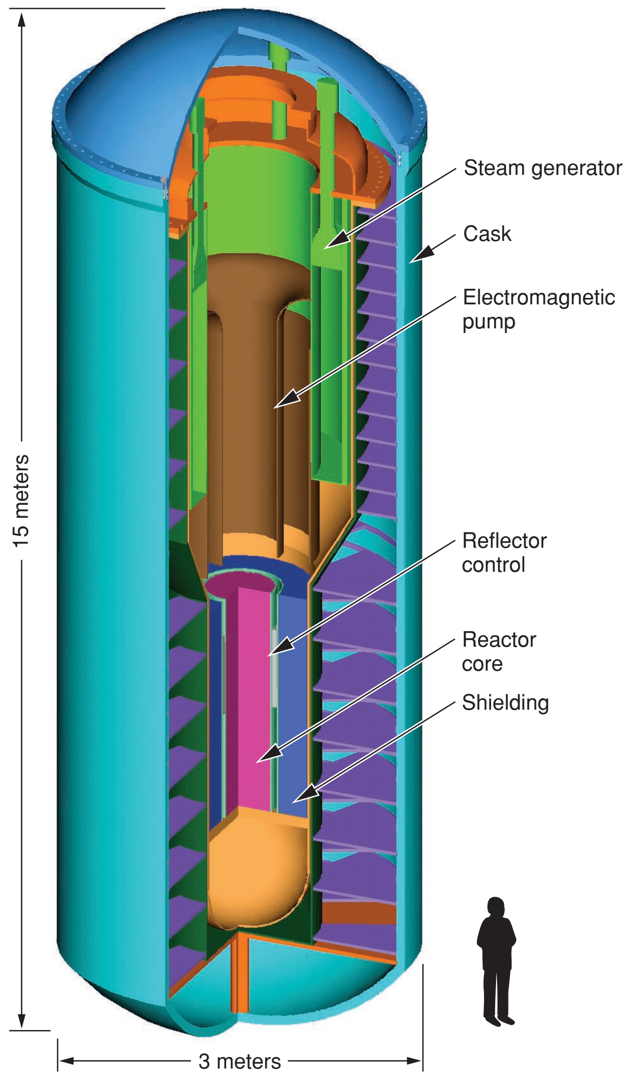
NUCLEAR energy supplies 20 percent of the electricity used in the U.S. and 16 percent of that used throughout the world. But as the global use of nuclear energy grows, so do concerns about the vulnerability of nuclear plants and fuel materials to misuse or attacks by terrorists. A Livermore team is part of a Department of Energy (DOE) collaboration that is addressing both the growing need for nuclear energy and the concern over nuclear proliferation by pursuing a concept called SSTAR, a small, sealed, transportable, autonomous reactor.

SSTAR is designed to be a self-contained reactor in a tamper-resistant container. The goal is to provide reliable and cost-effective electricity, heat, and freshwater. The design could also be adapted to produce hydrogen for use as an alternative fuel for passenger cars.

Most commercial nuclear reactors are large light-water reactors (LWRs) designed to generate 1,000 megawatts electric (MWe) or more. Significant capital investments are required to build these reactors and manage the nuclear fuel cycle. Many developing countries do not need such large increments of electricity. They also do not have the large-scale energy infrastructure required to install conventional nuclear power plants or personnel trained to operate them. These countries could benefit from smaller energy systems, such as SSTAR, that use automated controls, require less maintenance work, and provide reliable power for as long as 30 years before needing refueling or replacement.

Many of the countries in need of nuclear energy are among the 187 nations that have signed the Non-Proliferation Treaty (NPT) enacted in 1970. Under the terms of this treaty, the five acknowledged nuclear-weapon states—the U.S., Russian Federation, United Kingdom, France, and China—agreed not to transfer nuclear weapons, other nuclear explosive devices, or related technology to those signatory states that have no nuclear weapons. These nonnuclear states agreed not to acquire or produce nuclear weapons or nuclear explosive devices, and in exchange, they have access to peaceful nuclear technology developed by the five nuclear signatories. Unfortunately, the NPT has some weaknesses, as demonstrated by the recent disagreements with Iran and North Korea. Although both countries had signed the NPT, their nuclear energy programs are not in keeping with their treaty agreements.

To address this problem, DOE is funding an initiative to develop a conceptual design of a reactor that will deliver nuclear energy



Lawrence Livermore, Los Alamos, and Argonne national laboratories are designing a self-contained nuclear reactor with tamper-resistant features. Called SSTAR (small, sealed, transportable, autonomous reactor), this next-generation reactor will produce 10 to 100 megawatts electric and can be safely transported on ship or by a heavy-haul transport truck. In this schematic of one conceptual design being considered, the reactor is enclosed in a transportation cask.

to developing countries and significantly reduce the proliferation concern associated with expanded use of nuclear power. Three national laboratories are collaborating on this initiative. Lawrence Livermore, which leads the collaboration, is researching materials and coolants for the reactor and evaluating how it can be deployed. Argonne is designing the reactor, and Los Alamos is contributing its expertise on coolant and fuel technologies.

The SSTAR design will accomplish DOE's goals by allowing the U.S. to provide a tamper-resistant reactor to a nonnuclear state while still safeguarding the nation's sensitive nuclear technology. SSTAR will also secure the nuclear fuel because, after its operation, the sealed reactor will be returned to a secure recycling facility for refueling or maintenance.

Designed to be deployable anywhere in the world, SSTAR may also meet a national need. In the U.S., the Nuclear Regulatory Commission (NRC) oversees more than 100 nuclear power plants that were built during the 1960s and 1970s. SSTAR would provide a secure and cost-effective system to replace older nuclear reactors as well as aging fossil-fuel plants, particularly in an isolated location.

One Size Fitting Many Needs

SSTAR is designed as a lead-cooled fast reactor (LFR) that can supply 10 to 100 MWe with a reactor system that can be transported in a shipping cask. Fast reactors typically use liquid metal coolants, such as lead, lead–bismuth, or sodium, instead of water. Neutron kinetic energy is about 250 kiloelectronvolts in LFRs—much greater than in LWRs, where the low mass of hydrogen in the water coolant slows neutron velocity and, thus, energy to about 0.025 to 0.05 electronvolt. With fast-moving neutrons, SSTAR could produce the fissile material it needs to fuel continued operation at the same time that it generates energy. Spent fuel in the form of uranium and plutonium would remain in the reactor to generate power for up to 30 years. The spent reactor would then be returned to a secure recycling facility to close the fuel cycle and to minimize the high-level wastes generated by nuclear reactors, thus reducing the space and infrastructure needed for the long-term storage of radioactive wastes. The concept for recycling is to have almost all of the waste burned in the reactor's core.

According to project leader Craig Smith, a nuclear engineer in Livermore's Energy and Environment Directorate, the reactor will be about 15 meters tall by 3 meters wide and will not weigh more than 500 tons—small and lightweight enough to be transported on a ship and by a heavy-haul transport truck. "With SSTAR, countries won't need a large nuclear reactor industry to benefit from nuclear energy," says Smith. "Because the supplier nation will provide both the reactor and the associated fuel-cycle services, the host nation can produce electricity without needing an independent supply of uranium or other fuel at the front end of the cycle. The host nation also won't have to dispose of the nuclear waste at the back end of the cycle."

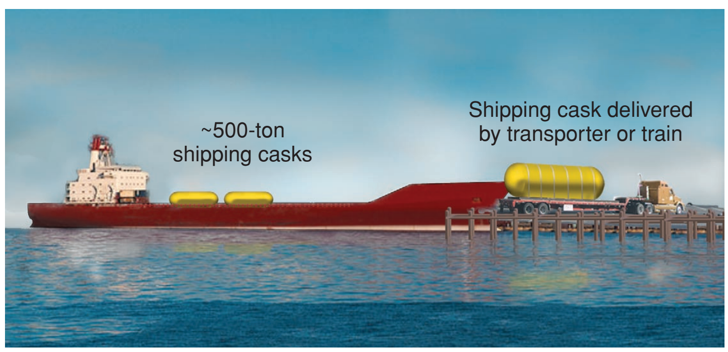
In addition, the current SSTAR design reduces the potential for a terrorist to divert or misuse the nuclear materials and technology. Nuclear fuel will be contained within the sealed, tamper-resistant reactor vessel when it is shipped to its destination, and the spent reactor core will be returned to the supplier for recycling.

SSTAR addresses proliferation concerns with other features as well. No refueling is necessary during the reactor's operation, which eliminates access to and long-term storage of nuclear materials on-site. The design also includes detection and signaling systems to identify actions that threaten the security of the reactor. And because of the reactor's small size and its thermal and nuclear characteristics, the design can include a passive method to shut down and cool the reactor in response to hardware or control failures.

Reduced Operating Costs

SSTAR also offers potential cost reductions over conventional nuclear reactors. Using lead or lead–bismuth as a cooling material instead of water eliminates the large, high-pressure vessels and piping needed to contain the reactor coolant. The low pressure of the lead coolant also allows for a more compact reactor because the steam generator can be incorporated into the reactor vessel. Plus with no refueling downtime and no spent fuel rods to be managed, the reactor can produce energy continuously and with fewer personnel.

SSTAR may also reduce costs for the transportation industry by providing a cheaper source of fuel to power passenger cars. Because LFRs can potentially operate at high temperatures (up to about 800°C), the reactor can be used to generate the heat required for efficient production of hydrogen, which is the preferred fuel for fuel-cell vehicles and hybrid vehicles burning hydrogen in an internal combustion engine. (See *S&TR*, June 2003, pp. 24–26.) As



When it is upright, SSTAR will be about 15 meters high and 3 meters wide, and its total weight will not exceed 500 tons. This compact size will allow the nuclear reactor to be transported on a ship and by a heavy-haul transport truck.

oil production becomes more expensive and constraints on carbon dioxide emissions tighten, the search for alternatives to fossil fuels becomes more important. SSTAR has the potential to address a critical national and international need for the future.

Tackling the Design Challenges

Several challenges must be addressed before the SSTAR design is ready for prototype testing. The Livermore team must develop materials for the fuel and coolant boundary that are compatible with the coolant. Lead, especially when alloyed with bismuth, tends to corrode the fuel cladding and structural steel. Controlling the oxygen in the coolant will help reduce corrosion. In addition, the team must identify materials that would best withstand the damaging effects of long-term exposure to fast neutrons. Structural damage could include material swelling and ductility loss, both of which may limit the life of the reactor.

In 2003, the Laboratory's SSTAR team participated in a feasibility study with a team from the Central Research Institute for Electric Power Industry (CRIEPI) in Japan. In this study, the two teams evaluated a modified design, developed by the Japanese team, for a small liquid metal–cooled reactor using sodium as a coolant. A scientist from CRIEPI is now working at Livermore, and the teams are sharing the results from their respective projects.

Passive safety features also will be developed to ensure that any failure in the control system will shut down the reactor and initiate a natural convection system to cool the reactor core and reactor vessel. The characteristics of these features will depend on the geometry and mechanical support system provided for the nuclear reactor. In addition, the prototype will test the performance of the passive safety features and the system designed to monitor them.

Because the spent reactor will be radioactive, the research team must develop packaging and transportation systems so the reactor can be removed safely. The team also must design a process to cool the reactor while it is being shipped to the recycling facility. The design criteria for meeting these challenges may affect the maximum power level that can be achieved.

License-by-Test Certification

NRC plans to certify the SSTAR design using a new license-by-test approach, rather than the license-by-design approach that it used to certify most of the existing commercial nuclear power plants. NRC's license-by-test process is similar to the certification process used by the U.S. Federal Aviation Administration for commercial airliners. To be certified, the SSTAR prototype must demonstrate in a test environment that it can safely withstand accidents, including the most improbable ones such as failure of the active shutdown and shutdown heat-removal systems.

But the tri-laboratory collaboration has more work to do before an SSTAR demonstration. According to Smith, the team plans to refine the SSTAR design and then develop a prototype reactor, which could be ready for testing as early as 2015. The Livermore team feels confident that SSTAR will provide a new-generation reactor—one that is safe, proliferation-resistant, and able to operate anywhere in the world.

—Gabriele Rennie

Key Words: Central Research Institute for Electric Power Industry (CRIEPI); lead-cooled fast reactor (LFR); Non-Proliferation Treaty (NPT); nuclear reactor; small, sealed, transportable, autonomous reactor (SSTAR).

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