Industry teams offer ideas for moving GNEP forward

BY RICK MICHAL

The DOE is investigating various paths for closing the nuclear fuel cycle in the United States.

BECAUSE OF FUNDING uncertainties and critics' claims that spent-fuel reprocessing promotes nuclear proliferation, the future of the Global Nuclear Energy Partnership is anyone's guess at this point. But the Department of Energy, which is leading the GNEP effort, continues moving the program down the road.

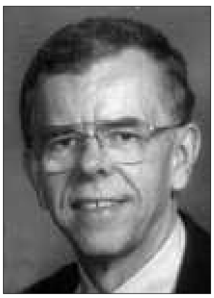
Four industry teams selected by the DOE—following an initial request for expressions of interest in August 2006 and a funding opportunity announcement in May 2007—have produced reports filled with designs for spent fuel recycling facilities and fast reactors, as well as technology development proposals and business plans to close the nuclear fuel cycle. The reports were submitted to the DOE in January and released publicly in May. The teams—EnergySolutions, GE-Hitachi Nuclear Americas, General Atomics, and the International Nuclear Recycling Alliance—at the end of July filed more detailed plans on the conceptual designs, business models, and "road maps" for moving ahead.

GNEP was introduced by the DOE in February 2006 as a strategy to encourage the expansion of domestic and international nuclear energy production. Its components, as outlined at the time by Energy Secretary Samuel Bodman, include the development and deployment of new nuclear recycling technologies and advanced burner reactors that would produce energy from recycled spent fuel. The initiative also aims to reduce the volume, thermal output, and radiotoxicity of spent fuel before disposal in a geologic repository, to establish a fuel services program that would allow developing nations to acquire and use nuclear energy economically while minimizing the risk of nuclear proliferation, and to design and construct small-scale reactors to fill the needs of developing countries.

Currently, 21 nations have signed on as GNEP members, and other countries seem interested. At the same time, a U.S. House of Representatives appropriations bill for fiscal year 2009 zeroed out funding for GNEP (*NN,* Aug. 2008, p. 19), while the Senate's appropriation bill didn't even consider it (although Senate appropriators did provide funding for the DOE's Advanced Fuel Cycle Initiative, a precursor to GNEP). In addition, recent reports from the National Academy of Sciences and the Government Accountability Office were critical of GNEP's plan to develop and deploy advanced recycling reactors (ARR) and reprocessing facilities.

For now, the DOE is working under a business-as-usual premise. Buzz Savage, deputy director of technology for GNEP, said that reviewers from the DOE and its national laboratories were analyzing the latest reports from the industry teams. The review is being done in order to make a recommendation to GNEP Deputy Program Manager Paul Lisowski about the areas that should continue to be researched and whether any or all of the teams should be kept on for the research work.

The recommendation, which is due soon, might focus research on different inputs from each of the teams, according to Savage. "Let's say one or two teams had very strong proposals in spent fuel separations, and a different set of teams had really strong proposals or concepts for fast reactors," he said. "We can do a mix-and-match, perhaps. We haven't decided yet. That is what the review is doing—seeing what we have right now and what the government will want to support."



Savage

While the teams all have ideas for advanced recycling reactors and spent fuel reprocessing centers, three of the four offer proposals for establishing a joint government–private sector partnership, similar to the Tennessee Valley Authority, to manage an integrated spent fuel strategy that would continue with the plans for the Yucca Mountain repository but would also look at ideas for what to do when Yucca Mountain is full. The proposals also call for tapping into the Nuclear Waste Fund (NWF) as a means of making a spent fuel strategy economically viable.

So far, the DOE has awarded over $34 million of a possible total of $60 million to the teams for their GNEP work. The balance of the $60 million could be awarded in fiscal year 2009, based on the recommendation and a congressional appropriation.

Part of the DOE's objective is to help the nuclear industry commercialize GNEP facilities, since Congress has stressed that it will not make funding available to the DOE for a construction program. "One of the things that is very clear, particularly from the feedback from Congress in their appropriations language, is that the commercialization of any of these recycling facilities will need to be led by industry and not by the government," Savage said.

The energy secretary's Record of Decision—which basically is a determination of whether to go forward with GNEP or to pull the plug—was due in June, but that date was missed. The new goal is to have the decision within the next six months.

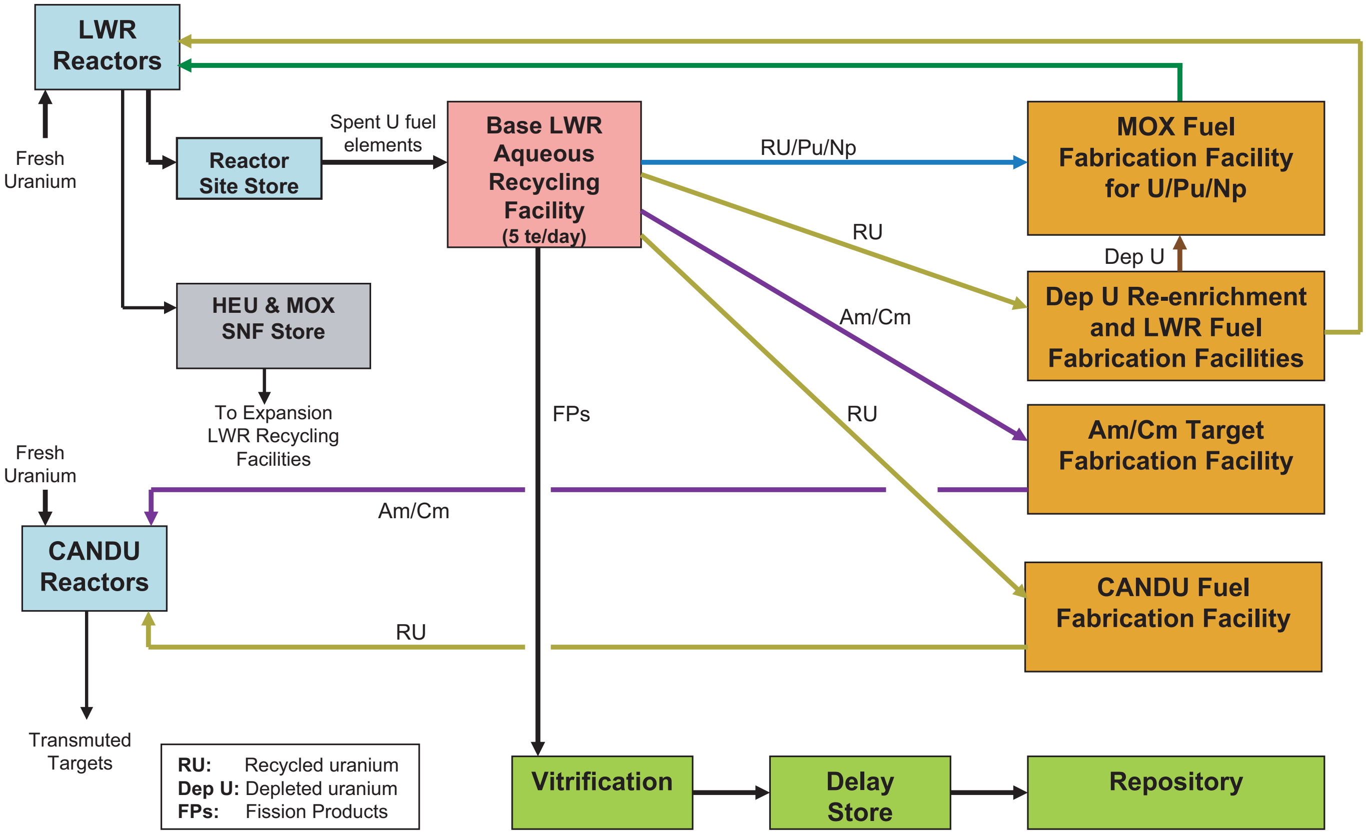
The members of the industry teams and the funding to date are as follows:

- EnergySolutions, $10.2 million: The Shaw Group, Westinghouse Electric Company, Atomic Energy of Canada Limited, Booz Allen Hamilton, Nexia Solutions, Nuclear Fuel Services, and Toshiba.
- GE-Hitachi Nuclear Americas, $10.3 million: General Electric, Hitachi, Ernst & Young, Fluor Corporation, IBM, and Lockheed Martin.
- General Atomics, $2.9 million: General Atomics, CH2M Hill, United Technologies Corporation–Hamilton Sundstrand Space, Land, & Sea/Rocketdyne Division, Korea Atomic Energy Research Institute, LISTO, OKB Mechanical Engineering, the Kurchatov Institute, and Potomac Communications Group.
- International Nuclear Recycling Alliance, $11.3 million: Led by Areva and Mitsubishi Heavy Industries, the other members are Japan Nuclear Fuel Limited, Babcock & Wilcox Technical Services, Battelle Energy Technology, and URS's Washington Division.

The teams' reports are available online at <www.gnep.energy.gov/gnepParticipation.html>. What follows are summaries of each of the reports.

EnergySolutions

The recycling of light-water reactor spent fuel can be accomplished today on a commercial basis using advanced aqueous processes in commercially proven equipment, according to Alan Dobson, EnergySolutions' senior vice president for fuel cycle and spent fuel management. Dobson, who heads up the EnergySolutions GNEP



The flowchart shows the EnergySolutions team's short-term plan for recycling spent fuel before ARRs are built and brought into operation. In this plan, which includes americium and curium separation, technology demonstrations would start right away to support LWR aqueous recycling operations in the 2023–2035 time frame without the use of ARRs. The plan would be dependent on successful completion of the development of a separations process and of target manufacture. (Chart: EnergySolutions)

team, said that recycling could be done without requiring government appropriations to fund the construction or operation of the facilities necessary for the task.

According to the EnergySolutions proposal, an initial separations facility, together with the associated waste treatment facilities, is estimated to cost $12.6 billion and could be fully operational by no later than 2023, and possibly as early as 2020. A new mixed-oxide (MOX) fuel fabrication facility to allow for the recycling of mixed uranium and plutonium as fresh fuel for LWRs would cost $4 billion and could be operational by 2023.

Building these facilities and a waste repository would require reliable funding that is not subject to annual appropriations, and so a change in the way nuclear waste is managed today would be necessary. A new government entity, the Federal Corporation (FedCorp), would be created to effectively manage spent fuel and nuclear wastes as a business enterprise. Serving as a potential role model would be the Tennessee Valley Authority, which was created by congressional charter in May 1933 to provide flood control, electricity generation, and economic development, among other things, in the Tennessee Valley. FedCorp would generate revenues by recycling both recovered uranium and plutonium/uranium mixtures into new reactor fuel.

FedCorp would manage the NWF going forward, but would not use the existing dollars in the fund. FedCorp would be responsible for waste repository construction and operation and for contracting with the nuclear industry for the construction and operation of recycling facilities under a long-term contract. Its duties would include transporting spent fuel from reactors to the recycling facilities, supporting defense and DOE legacy waste disposal, and supporting international programs through spent fuel take-back.

These initial facilities for recycling LWR spent fuel, fabricating MOX fuel, and treating waste "would substantially meet all of the goals of GNEP in an economic manner," Dobson said. GNEP's goals include significantly reducing the amount and long-term radiotoxicity of high-level waste requiring disposal (thereby greatly improving repository utilization), providing energy security by recycling nuclear materials and reducing the dependency on foreign supplies, and meeting nonproliferation requirements, both intrinsically and extrinsically, with the full capability to satisfy the safeguards requirements of the International Atomic Energy Agency.

Two cases were evaluated in the proposal with regard to the use of the existing NWF. In the first case, which is the approach the EnergySolutions team recommends, the existing fund would not be used to pay for the construction of the recycling facilities. In the second case, the existing NWF would remain unused through 2016, but would then be used incrementally over a 25-year period to supplement the "new" fund managed by FedCorp.

The EnergySolutions team estimates that the NWF fee would need to be increased to 1.95 mils/kWh starting in 2010 and to be held at this level throughout this century, providing for significant growth of nuclear power and the construction and operation of commensurate expansion of recycling, fuel fabrication, and associated waste treatment facilities.

Under the EnergySolutions plan, HLW would be converted into glass—vitrification—and stored for 70–100 years. Dobson is a big proponent of this option because he has been involved with vitrification during his career. For example, he was responsible for the startup and initial operation of the Thermal Oxide Reprocessing Plant (THORP) in the United Kingdom, which has a vitrification line.

"Today in the U.K., in a building that's about 100 feet wide by about 70 feet tall by about 90 feet deep, there is already about 3000 tons of high-level waste glass," Dobson said. "It's the product of reprocessing. It contains the fission products' waste, including the cesium and strontium, from reprocessing over 50 000 tons of fuel. All of the real waste—the fission products—are in about 3000 tons of glass. And the glass is in a building that's not even half the size of a football field."

Vitrification would allow the high heat–generating isotopes—cesium and strontium—to decay sufficiently to remove the initial heat problem for the repository, thereby greatly simplifying disposal.

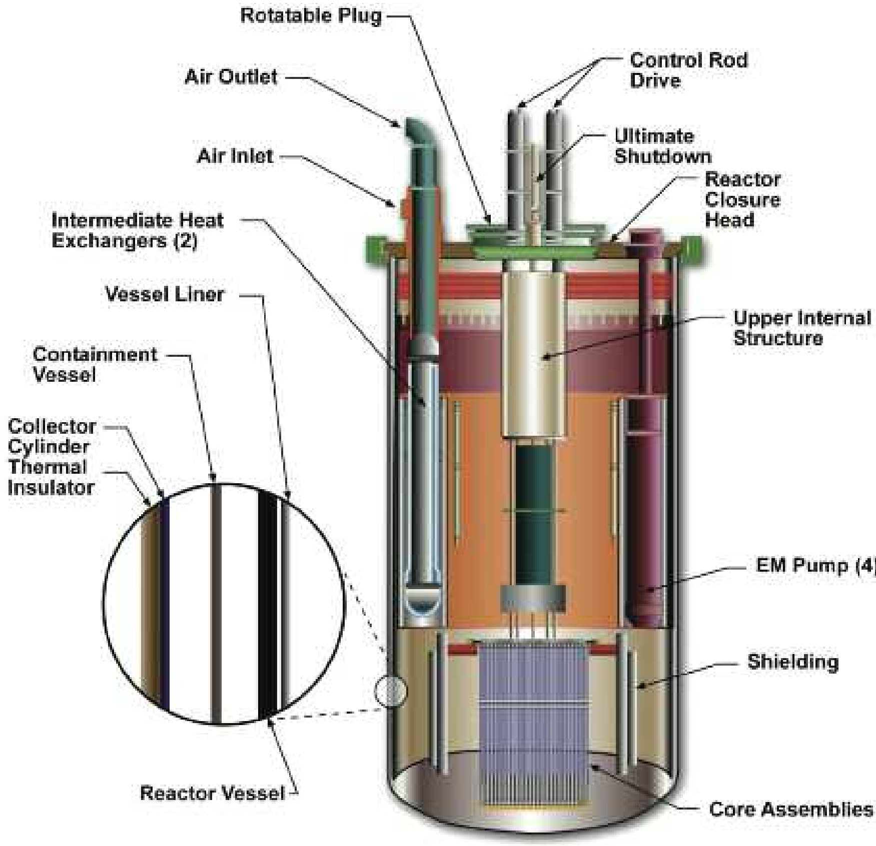
If FedCorp were created and LWR recycling undertaken by 2025, the effective capacity of the geologic repository could be increased by at least five- or sixfold, "and it may even be that only one such repository is required ever," Dobson said.

The proposal also notes that sodium-cooled fast reactor technology is not sufficiently developed for burning transuranic fuels to proceed with commercial deployment of an ARR today. "A commercially sized prototype ARR, however, deploying several extremely innovative features that improve safety and reduce capital and operating costs, can be operational by 2025 and [ready for] commercial licensing by 2031," according to the proposal.

Toward that end, "recycling reactor campuses," which would deploy four ARR units and deliver about 1650 MWe of total power output, would be built. Estimates are that the first suite—a module of four—of fully commercial ARRs could be brought on line in 2045.

The estimated cost for the development and construction of the first-of-a-kind ARR is $4.4 billion. Fuel development costs are anticipated to be another $670 million. The estimated cost of the first fast reactor fuel recycling and fabrication facility is $1.2 billion. All costs are in 2007 dollars.

The cost of the first campus module of four commercial reactors is estimated to be $7.5 billion in 2007 dollars. Comparisons with the anticipated costs of advanced light-water reactors show that the ARR costs per kilowatt-hour are still slightly higher, but the EnergySolutions team proposes that the utilities be given an incentive by discounting the fast reactor fuel at least through 2070. The ARRs would have no waste fee, and, in addition, FedCorp would make construction loans at competitive rates. "These incentives recognize the ARR's crucial role in destruction of the transuranic waste and strategic role in increasing U.S. energy security," the proposal notes.



The internals of the GE-Hitachi team's PRISM reactor (Illustration: GE-Hitachi)

GE-Hitachi Nuclear Americas

The GE-Hitachi team's plan introduces the Advanced Recycling Center (ARC), which consists of two major elements: an ARR—a Power Reactor Innovative Small Module (PRISM) sodium-cooled fast reactor capable of using LWR spent fuel actinides as a fuel source—and a nuclear fuel recycling center (NFRC), which would use electrometallurgical technology for LWR and fast reactor fuel separations.

The PRISM is a modular, pool-type reactor that incorporates passive shutdown and decay heat removal features because of its metallic fuel. The standard power block plant is made up of two 311-MWe reactors, for a total of 622 MWe per power block. In the conceptual design, the PRISM is located in a below-grade silo and is connected to its own intermediate heat transport system and steam generator system. In addition, the steam generator and secondary system hardware would be located in separate buildings connected by a below-grade pipeway.

Each reactor module would supply steam to a shared electrical turbine generator that would maintain electrical production output during individual reactor module refueling.

All reactors on the PRISM power block site would share a common reactor assembly facility, maintenance facility, remote shutdown facility, and radwaste facility. Up to three power blocks (six reactor modules) could share these common facilities, resulting in cost savings. PRISM's modular system is suitable for factory fabrication and provides a high degree of passive and natural safety characteristics, according to the GE-Hitachi team.

The PRISM concept was developed by GE and its partners in the early 1980s as an alternative solution when technical problems became apparent in the DOE's liquid metal program, which was then in the construction phase of the Clinch River Breeder Reactor (CRBR). The CRBR was a large loop-type reactor that used oxide fuel and many active safety systems. The different approach that PRISM offered was a key factor in the launch of the DOE's advanced liquid metal reactor program, which was halted in the mid-1990s by the Clinton administration. GE continued to improve upon the reactor design until stopping all internal work in about 2001 because no near-term customer could be identified.

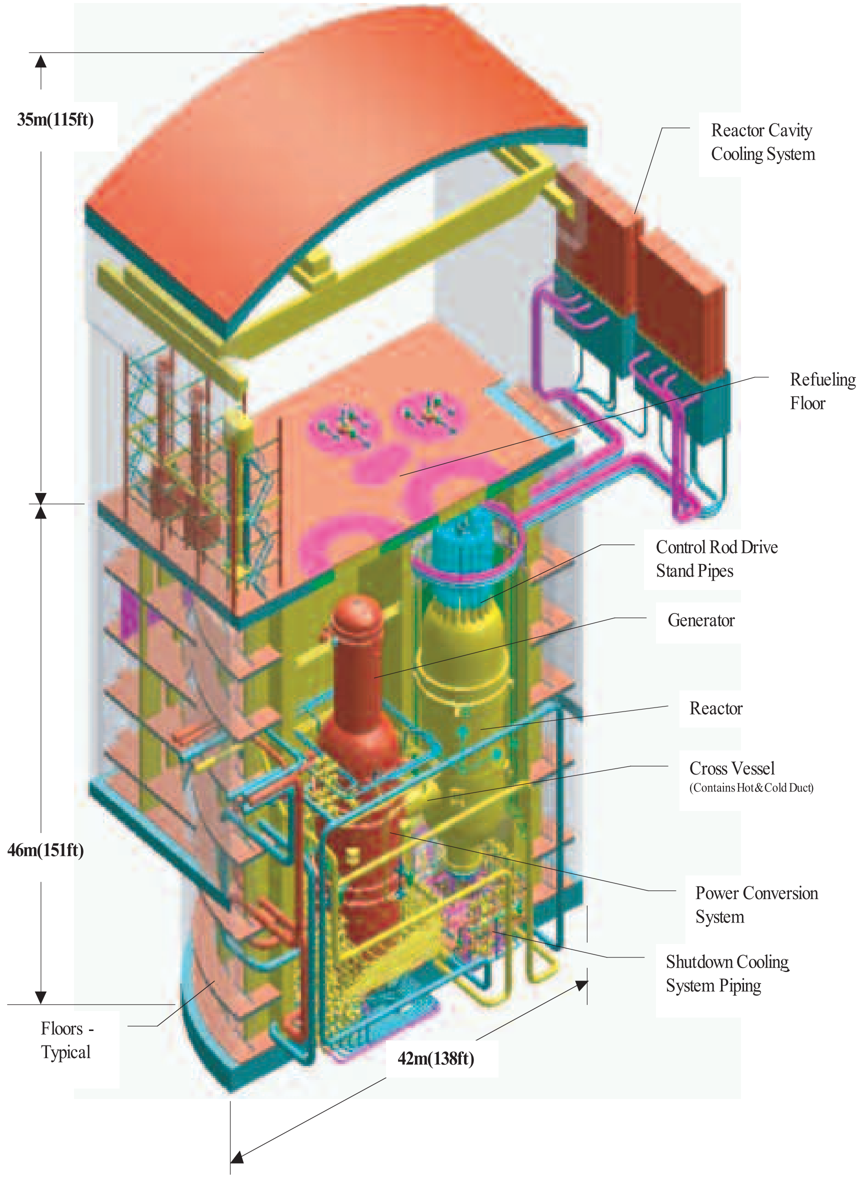
Since then, new features and plant design improvements have been developed for the PRISM as part of the GNEP program. These improvements include a design arrangement that locates the reactor, the intermediate heat transport system, and the steam generator system (including the sodium water reaction pressure relief subsystem) on a seismically isolated platform, a permanent refueling enclosure for each reactor module, and an increased cycle efficiency that is achieved by increasing the mixed mean core outlet temperature to 930 °F and the core inlet temperature to 680 °F. In addition, as proposed to the DOE by the GE-Hitachi team, the net power for a three power block arrangement could be increased to 1866 MWe, the refueling interval would be boosted to between 12 and 24 months, and the flexible skirt reactor support would be replaced with sliding brackets attached to the closure to accommodate reactor closure head thermal expansion and seismic and accident loads.

The second component of the ARC—the NFRC—would use metallurgical separations technology to separate spent fuel into metallic transuranic actinide-bearing fuel for the ARR, along with recyclable uranium, and would separate the waste fission products into ceramic and metallic waste forms for permanent disposal. Unlike aqueous PUREX separations, GE-Hitachi's approach does not generate separated pure plutonium, thus making it more proliferation-resistant. The plutonium remains with the minor actinides from separations, so it stays with its more intensely radioactive brethren and is used as fuel for the PRISM reactor.

The GE-Hitachi team indicated that the NFRC design would accomplish the following over the 60-year life of one 1866-MWe (six 311-MWe reactors) ARC:

- Consume about 4600 metric tons heavy metal from LWR spent fuel (this represents approximately 13 000 pressurized water reactor or 30 000 boiling water reactor spent fuel assemblies).
- Produce fuel for 900 000 GWh of power.
- Increase the capacity of a geologic repository to accept HLW.
- Recycle spent fuel assemblies removed from PRISM cores.
- Process fission products and other waste for geologic disposal.
- Recover uranium for use in other reactors.
- Fabricate actinide fuel assemblies on site that are prepared from LWR spent fuel.

Since the ARR burner core would consume actinides, a constant supply would need to be available to support continued power operation. To obtain the actinides, spent fuel would be processed in the NFRC, and the actinides—particularly americium, plutonium, curium, and neptunium—would be extracted and placed into new fuel for insertion into an ARR burner core. Once burned in the core, a portion of the long-lived isotopes would be transformed into short-lived fission products—the actinides with half-lives from tens of thousands to millions of years would fission into shorter-lived (less than 500 years) isotopes. The result would be that the ARC would reduce the total burden of long-lived radioactive wastes that are presently stored in LWR spent fuel, as well as the burden on waste repositories, while producing power. The GE-Hitachi team's plan demonstrated that the power generation would cover the capital costs of an ARR and a separations system, in addition to operating costs, without government subsidy.



The MHR design features passive safety, deep-burn fuel, and high thermal efficiency. (Illustration: General Atomics)

General Atomics

The General Atomics team analyzed three GNEP deployment scenarios for closing and commercializing the nuclear fuel cycle in the United States. All three strategies involve UREX+1a reprocessing of spent fuel from current and future LWRs and using the recovered plutonium and other transuranic (TRU) elements as fuel in advanced reactors. In addition, all three strategies allow for significant expansion of nuclear power while significantly reducing the quantity of HLW that requires permanent disposal.

Two of the scenarios employ the use of gas-cooled modular helium reactors (MHR) because of their ability to use the highly versatile tristructural-isotropic (TRISO) fuel, according to Amy Bozek, the GA team's project manager. TRISO fuel consists of spherically shaped fuel kernels most commonly composed of uranium dioxide in the center and then covered with four outer layers. TRISO fuel particles act as tiny pressure vessels and are designed not to crack as a result of reactor-induced stresses such as differential thermal expansion or fission gas pressure at temperatures beyond 1600 °C.

Bozek

Bozek said that if the TRISO fuel were made with TRU materials, a burnup of 55–60 percent of the TRU could be achieved without any reprocessing. "So, if the DOE were looking for more near-term deployment of GNEP facilities, the MHR could be used while the fast reactor is being developed and demonstrated," she said. "It's important to realize that the DOE has an ongoing program to deploy the MHRs in the relative near term under its Next Generation Nuclear Plant [NGNP] program."

Bozek added that GNEP's goals could be largely achieved by using MHRs. "The MHR uses a thermal neutron spectrum, and while there may not be the complete burnup that happens using a fast reactor, there would not be creation of some of the higher order nuclides, either," she said. "In addition, the useful capacity of the permanent repository would be greatly enhanced."

In summary, the GA team's three scenarios are as follows:

- Scenario A consists of what is known as the standard GNEP fuel cycle, where TRU from LWR spent fuel is processed through a fast-spectrum ARR to reduce the waste sent to the Yucca Mountain repository.

■ Scenario B is made up of a two-tier reactor system by which most of the energy is extracted from the spent fuel in one pass through an MHR, where it is converted with high efficiency to electricity. The reduced quantity of plutonium and minor actinides in the spent MHR fuel is then burned in ARRs to reduce the TRU waste going to the repository.

■ Scenario D is a two-tier system similar to Scenario B, but in this case the MHRs gradually replace the retiring Generation III LWRs to supply the electricity and satisfy the growing nonelectricity applications for nuclear power. In this scenario, as in Scenario B, fast ARRs are used to reduce the waste to the repository and eventually to provide new fissile fuel for the growing nuclear industry.

(A fourth option, Scenario C, is an all-thermal reactor scenario employing LWRs and MHRs. The GA team found that modifications are needed to the original Scenario C, including a study of the introduction of thorium into the fuel cycle. Therefore, this scenario was excluded from the plan GA submitted to the DOE.)

While the GA team found that Scenarios A, B, and D all satisfy GNEP's goals, the two-tier strategy retains the advantages of the one-tier system but with additional benefits. Of the two two-tier systems, Scenario D is the one that offers significant economic and other benefits, such as lower GNEP costs and an increase in the long-term profitability of the GNEP program by roughly 10 percent, from $2 trillion for the standard GNEP cycle (Scenario A) to $2.2 trillion for Scenario D, according to Bozek. The increase in value for GNEP is mainly due to the long-term cost of electricity being more than 20 percent lower for Scenario D than for Scenario A.

In addition, in Scenario D, the number of ARRs is reduced from 153 to 27, and their reprocessing requirements are reduced by a factor greater than five. Finally, Scenario D provides additional benefits in terms of energy security and greenhouse gas reduction because of the versatility and ability of MHRs to catalyze other forms of energy (such as liquid fuels) rather than electricity.

Bozek noted that MHRs, which are highly efficient and passively safe, can be employed in GNEP at very low risk because of the domestic history of their successful operation (specifically, the now retired Fort St. Vrain and Peach Bottom-1 units). As mentioned previously, the MHR is also being investigated by the DOE's NGNP program, and there are helium reactor initiatives ongoing throughout the world—in China, South Africa, Japan, Russia, Korea, and Europe—that indicate that there is motivation and intent to build and use these reactors in a variety of applications.

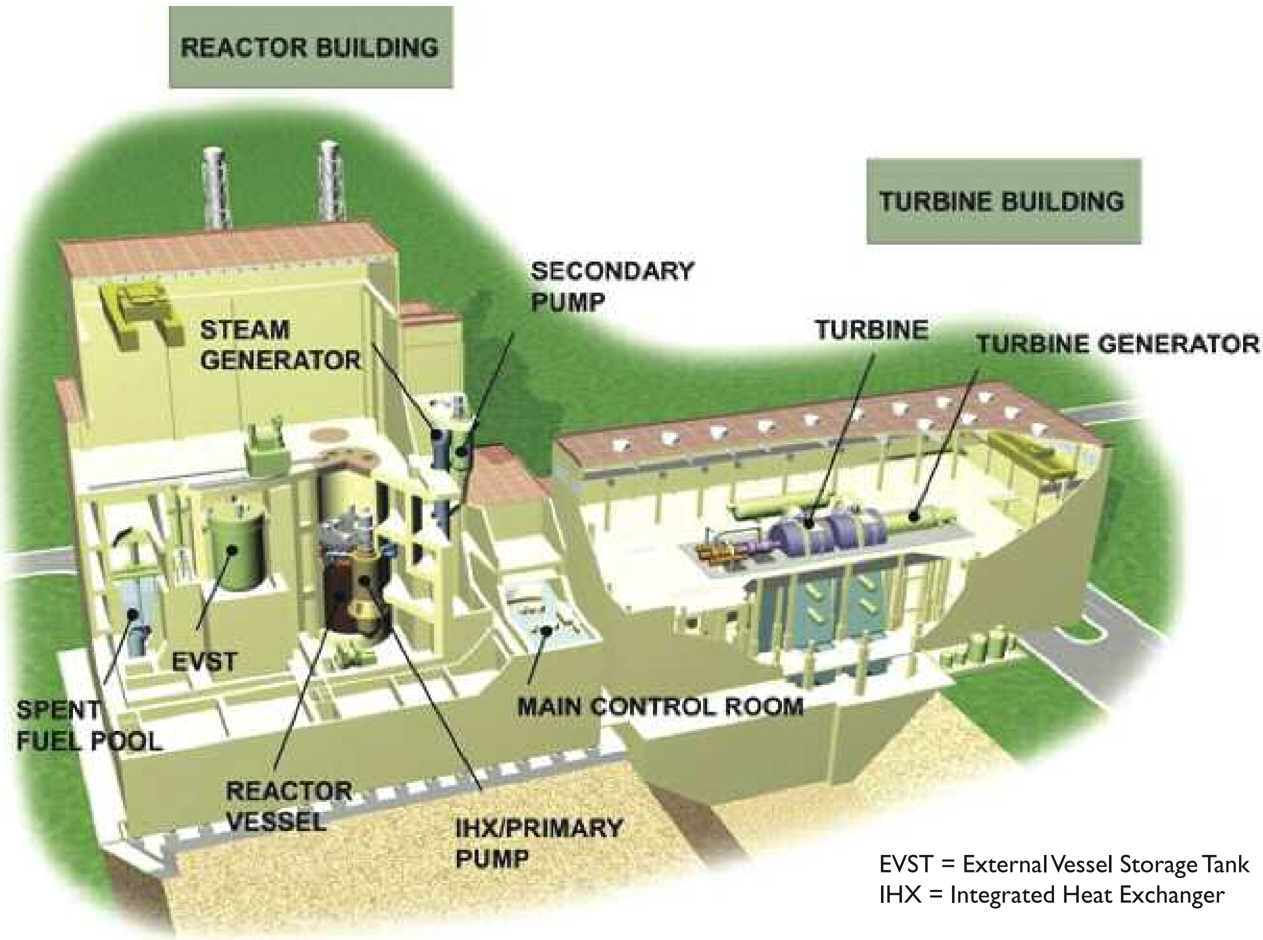
The GA team stressed that studies should be conducted to determine how the MHRs that are built for nonelectrical applications—such as process heat, hydrogen production, and synthetic fuels—can be used for the disposition of LWR TRU.

INRA

The International Nuclear Recycling Alliance has concluded that closing the fuel cycle is a viable complement to the direct disposal of spent fuel in a geologic repository, according to Dorothy Davidson, vice president for Areva Federal Services and INRA's GNEP program manager.

Davidson

After investigating the business model for a closed fuel cycle, INRA suggested establishing a used fuel management entity (UFME) to manage an integrated strategy for nuclear waste. The UFME would be a government-owned corporation that would allow utilities to have some level of oversight. At the same time, federal



A view of INRA's ARR, which uses Japan Atomic Energy Agency's sodium-cooled fast reactor as its basis (Illustration: INRA) ownership of the UFME could keep capital costs down. This entity would make the final recommendation on closing the fuel cycle in the United States based on input from ongoing studies performed by industry, national laboratories, and universities.

The INRA proposal calls for a consolidated fuel treatment center (CFTC) that could be implemented commercially using available, mature technology to fabricate recycled fuel for ARRs and LWRs.

The capacity of the initial CFTC should be market driven, Davidson said, and INRA's preconceptual design studies focused on a CFTC that is comparable in capacity (800-tHM/yr) to the La Hague modules in France and the Rokkasho Reprocessing Plant in Japan, using state-of-the-art COEX technology, which does not separate pure plutonium. The initial CFTC, which could be operational in 2023–2025, is based on the application of the continuous improvement gained from 50 years of commercial experience at La Hague and at the Melox MOX Fuel Fabrication Plant in France.

Davidson said that the preconceptual design for the initial CFTC incorporates 14 technology options to enhance safety, improve operations, reduce construction and operations costs, and optimize use of the geologic repository. The baseline design does not include the separation of minor actinides because the technology has not been demonstrated as sufficiently mature for commercial deployment. The design, however, "has the flexibility to accommodate evolutionary strategies, both for size and for separations technology advancements, as they become available," she said. INRA would work with the national labs from the beginning of design to accommodate the new separations technology.

INRA has developed cost estimates for recycling facilities of various sizes, with appropriate levels of contingency commensurate with recent experiences in building nuclear fuel cycle facilities. Costs are based on reference INRA facilities. The cost estimates, which INRA has not released publicly because they are still under review by the DOE, show significant economies of scale between a 150-tHM/yr demonstration plant and an 800- or 2500-tHM/yr commercial plant.

INRA's proposal also incorporates a sodium-cooled ARR based on the concept of the Japan Atomic Energy Agency's sodium fast reactor, which facilitates the recycling and reuse of spent fuel by destroying certain heat-generating radionuclides that would otherwise require a large amount of repository space. The DOE has identified the sodium-cooled reactor as the preferred technology for an ARR because of the maturity of its design, according to INRA.

Davidson said that while sodium-cooled reactor technology exists today, enhancements and developments are needed to demonstrate the economics, safety, and reliability required for a commercial ARR to be competitive with LWRs. Thirteen technology enhancements are being investigated in three broad areas, as follows:

- *For safety:* A recriticality-free core; a passive reactor shutdown system and DHRS (dimer/heterodimer regulatory site) by natural circulation; and a seismic response evaluation of the reactor.
- *For reliability:* A double-walled piping system; a steam generator with straight double-walled tubes; and an inspection and repair technology in sodium.
- *For economics:* The ARR would need to use minor-actinides fuel that has a high-burnup ODS (oxide dispersion–strengthened) fertile-steel cladding tube. In addition, the ARR design would need a two-loop arrangement, high chrome steel for shortening the primary piping, a compact reactor vessel system, a simplified fuel-handling system, an integrated intermediate heat exchanger with primary pump, and a steel plate–reinforced concrete steel structure for the containment vessel.

"Cost estimates have been developed that indicate that the proposed technology enhancements provide a path to get to the point where ARRs can be a viable choice in the future," Davidson said. NN