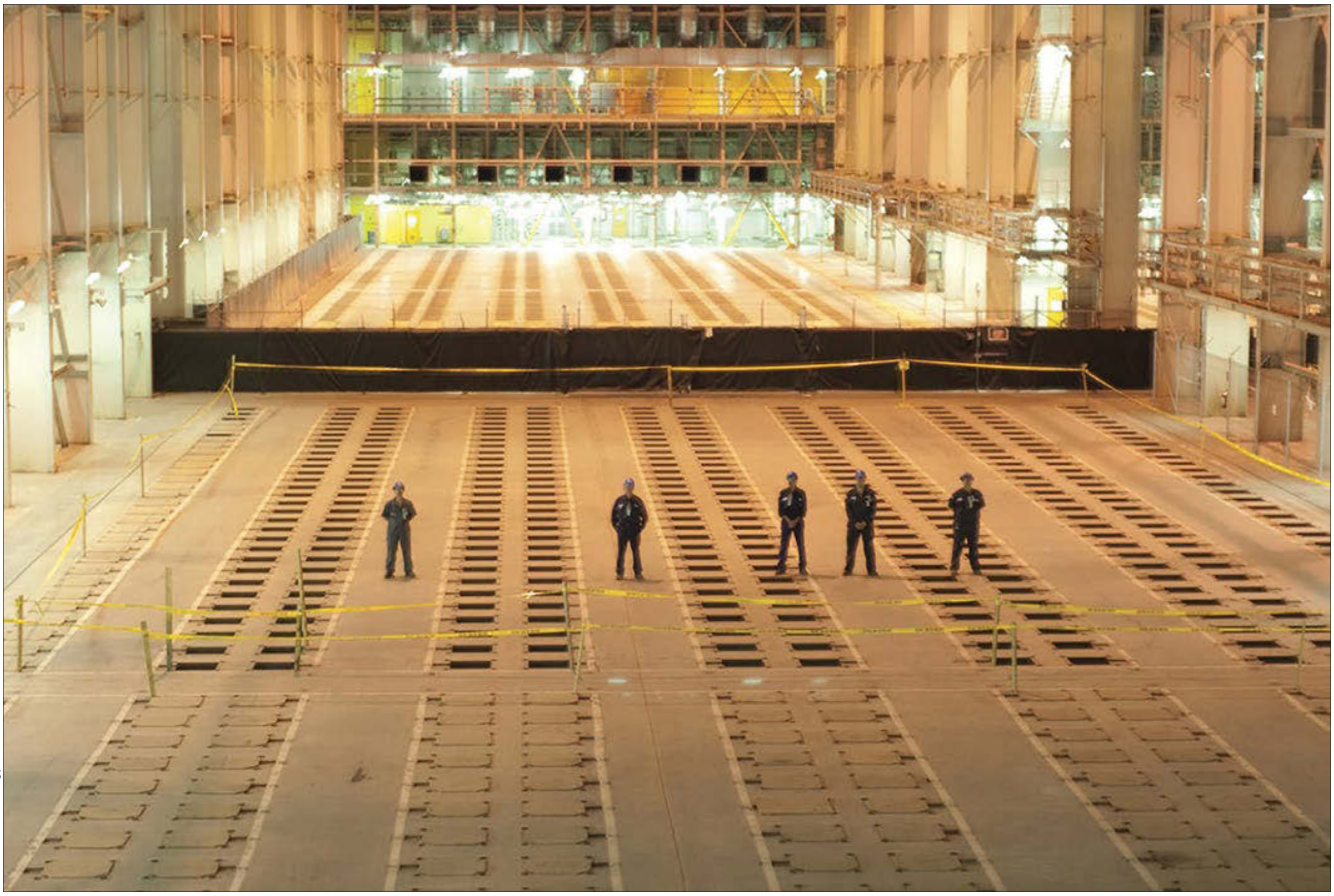


Photo: Centrus Energy

The interior of the process building at the American Centrifuge Plant in Piketon, Ohio, where Centrus Energy plans to operate a HALEU demonstration cascade by June 2022.

Looking high and low for HALEU

Demand for high-assay low-enriched uranium has set off a scramble to secure a supply to test microreactor concepts, fuel advanced reactors, and coax more efficiency from today's light-water reactors.

By Susan Gallier

Advanced reactor cores are being designed for higher efficiencies and longer lifetimes, but to get there, they need high-assay low-enriched uranium (HALEU).

Enriched to between 5 and 19.75 percent fissile U-235, HALEU is packed with nuclear potential. It can be used as a feedstock for the demonstration of new fuel designs, from uranium alloys to ceramic pellets and liquid fuels. Those fuels can enable advanced reactor and microreactor demonstrations. Operating light-water reactors could potentially transition to HALEU uranium oxide fuels for extended operating cycles and improved plant economics.

For HALEU to fulfill its potential, fuel cycle infrastructure upgrades will be required to address safety, safeguards, and security, and the development of a HALEU-certified transport package is critical. Yet before HALEU can fuel advanced reactors or fill transport casks, it must be obtained. That first step poses a challenge, because no U.S. facility is currently capable of enriching uranium beyond the 5 percent U-235 limit for LEU.

An initial supply is needed as a bridge to advanced nuclear deployment, and the options are clear. To get feedstock between 5 and 19.75 percent U-235, you can either go up (through enrichment) or down (by downblending high-enriched uranium).

Scarcity of supply

Daniel Vega, a nuclear engineer at the Department of Energy's Office of Nuclear Energy, talked about the agency's efforts to provide an interim supply of HALEU for industry during a panel session—"Prospects for a High-Assay Low-Enriched Uranium Supply to Support Advanced Reactors and Advanced LWR Fuel Applications"—held during the ANS Annual Meeting in June. The session was organized and cochaired by Morris Hassler, senior director of global security and strategic partnerships for Consolidated Nuclear Security at the Y-12 National Security Complex, and Everett Redmond, senior technical advisor at the Nuclear Energy Institute, and was sponsored by the ANS Fuel Cycle and Waste Management Division and cosponsored by the Nuclear Nonproliferation Policy Division.

"We were directed by Congress to scramble and figure out a plan for this," Vega said, "so I didn't have any qualms about asking the dumb questions pretty early on, which were basically, 'Why do we need HALEU now? We make naval fuel all the time. We make research reactor fuel. Why can't we just use that process?'" The answer, he learned, has everything to do with the timescale. The HEU feedstock for naval and research reactor fuel is spoken for and will be depleted by 2040. The Department of Defense must ensure that its future uranium requirements will be met, including for potential microreactor deployments. "I found that we can't just call, ask for some HEU, and write an IOU," Vega said.

Before advanced reactor developers accelerated the growth in demand for HALEU, the need for the material was already increasing in other sectors. Medical isotope production once relied on HEU, but the National Nuclear Security Administration now supplies U.S. medical isotope producers with HALEU. More and more research reactors around the world have been converted from HEU to HALEU, further increasing demand. The same power density that appeals to advanced reactor developers is also attractive to NASA. HALEU-based systems could deliver surface power and nuclear thermal propulsion.

During the HALEU supply panel session, Jeffrey Chamberlin, a senior advisor for the NNSA, described the agency's sourcing of HALEU for medical isotope production and research reactors as a "just-in-time" operation. "The material that we use to supply HALEU for research reactors is not all ready to go in metal form on the shelves at Y-12," he said. "We do have some, but it's in very limited quantities." The NNSA wants to have its own enrichment capability up and running by the time its supplies run out, Chamberlin said.

NEI drew attention to the growing demand for HALEU in a July 2018 letter to Energy Secretary Rick Perry. The letter was supplemented by a table of estimated annual requirements for HALEU through 2030, generated through a survey of advanced reactor developers and fuel designers. Collectively, HALEU needs were predicted to increase from 1.532 metric tons (t) in 2019 to 589.5 t in 2030.

"To help bridge this gap in supply, NEI, on behalf of the industry, requests that the Department of Energy provide an interim supply of HALEU and thereby accelerate the development of both HALEU fuel infrastructure and advanced reactors and advanced fuels that require HALEU," the letter stated. "Without a HALEU supply chain, many advanced reactor designs and advanced fuels will simply not be developed."

Photo: Chris Morgan/INL

INL fuel development researcher Scott Wilde observes the layer-by-layer creation of advanced fuels using additive manufacturing (3D-printing) techniques that enable shapes and forms impossible to duplicate using traditional fabrication techniques.

The Nuclear Energy Leadership Act (NELA), which was approved by the Senate Energy and Natural Resources Committee in July, would (as of this writing in August) require the DOE to provide 2 t of U-235 in HALEU form (totaling about 10 t of HALEU) by the end of 2022, and 10 t of U-235 in HALEU form by the end of 2025 (or about 50 t total). NELA would also mandate a research, development, and demonstration program resulting in one or more HALEU transportation packages for certification by the Nuclear Regulatory Commission.

Enrichment is critical

Because HEU stocks are finite, the long-term solution is enrichment. In May, the DOE signed a three-year, $115-million contract with American Centrifuge Operating LLC, a subsidiary of Centrus Energy, to develop a HALEU demonstration production line at the American Centrifuge Plant in Piketon, Ohio. The company has committed to deploying a 16-machine AC-100M HALEU cascade and producing uranium enriched to 19.75 percent beginning by June 2022. The contract will also demonstrate the capability to produce HALEU with Centrus's U.S.-origin enrichment technology.

Contracting with Centrus is "a way to get an initial amount of material for the early movers," Vega explained, "the idea being that after successful proof of that, we'll have timed it up just perfectly to expand." In about three years, private industry could step in to scale up the technology just as companies are putting in their first HALEU purchase orders.

In the interim, the DOE is rummaging through its laboratories for downblendable HEU, typically in the form of spent research reactor fuel awaiting disposal. One of the biggest sources of HEU the DOE can turn to is stored at Idaho National Laboratory.

In January, the DOE issued a final environmental assessment and finding of no significant impact for glovebox-scale fuel fabrication at INL's Materials and Fuels Complex. According to the DOE, the final environmental assessment covers the use of about 10 t of HALEU to fabricate ceramic and metallic fuels to "support near-term research, development, and demonstration needs of private-sector developers and government agencies, including advanced reactor developers."

Microreactor RD&D

Because the DOE can't sell HALEU outright, getting it into the hands of developers as quickly as possible has posed a challenge. The solution: a competitive opportunity for microreactor developers to carry out research and demonstrations at INL under cooperative agreements. INL is offering HALEU in different compositions to suit the fuel specifications and fabrication needs of various advanced reactor designs, including, but not limited to, metallic and oxide forms at different enrichment levels.

"The material that was specifically identified for this opportunity cannot leave the Idaho National Laboratory," an INL representative told *NN*. Among the reasons for the restriction are that the final environmental assessment only covers use at INL, the material remains the property and liability of the DOE, and the goal is to demonstrate a microreactor in as short a time as possible.

A draft notice of opportunity was released on July 22, and the final opportunity was issued on August 22, with requests due by October 11. Microreactor developers will be selected by merit, based on feasibility (45 percent), a well-defined schedule with performance milestones (25 percent), a financial plan corresponding to milestones (20 percent), and a commercial deployment plan (10 percent). The draft notice of opportunity states, "The number of selections may range from zero to multiple participants up to the quantity of material that is being made available based on the review criteria." An announcement of chosen participants is expected within two months of the request due date.

Microreactor developers' needs were discussed at a Gateway for Accelerated Innovation in Nuclear (GAIN) microreactor workshop held at INL in June that was attended by representatives of 11 developers: General Atomics, HolosGen, Hydromine, MicroNuclear, NuGen, NuScale Power, Oklo, Ultra Safe Nuclear, Urenco, Westinghouse, and X-energy.

Downblending

EMT of sodium-bonded fuel

Most of the 10 t of HALEU earmarked for microreactor demonstrations will come from previously irradiated sodium-bonded HEU metallic fuel from the Experimental Breeder Reactor-II. EBR-II driver fuel is treated at INL's Materials and Fuels Complex through an electrometallurgical treatment (EMT) batch process—also known as pyroprocessing—that has been used to condition sodium-bonded fuels for disposal for over 20 years.

Irradiated fuel is prepared and placed into a molten salt electrorefiner, where uranium metal is recovered from fission products and transuranics. Vacuum distillation removes electrorefiner salt from the recovered uranium, which is then downblended to enrichments of less than 20 percent U-235. The HALEU can be cast into forms tailored for disposal or reuse. In 2018, INL had 3.86 t of HALEU in the form of 30–40 kg ingots—a size and shape chosen to facilitate disposal, storage, and hot-cell handling.

While ideal for some uses, for glovebox-scale fuel fabrication, "the ingots' high dose rate, large mass, and level of transuranic impurities were identified as unfavorable characteristics," according to a March 2019 INL report, *HALEU Decontamination Investigations for EBR-II Recovered Uranium*. The report describes the development of a stackable, two-piece crucible system to recast ingots into smaller shapes. The graphite crucible allows molten uranium to drip through a single hole in the top tier into multiple cascading pockets, forming 1.5–3 kg uranium reguli and leaving slag behind. Preliminary results from experimental trials described in the report "indicate elevated levels of cesium and plutonium in the slag relative to the reguli samples, which suggests a successful separation of the contaminants."

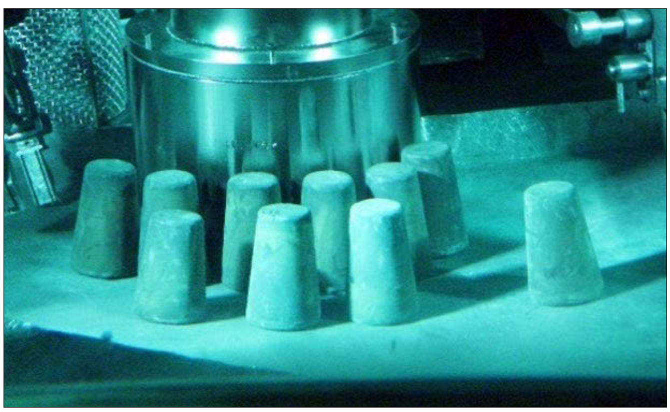
An initial batch of reguli was produced by drip-casting early in 2019, and 600 kg of HALEU material in fuel fabrication–ready reguli is to be available for microreactor demonstrations by the end of the year.

Hybrid ZIRCEX process

Another process that could yield HALEU from federally owned fuels is ZIRCEX, short for zirconium extraction. INL is currently using a one-fourth scale pilot facility for R&D which could lead to integrated ZIRCEX process demonstration with naval reactor spent fuel.

Previous HEU recovery from irradiated fuels has used a liquid head-end process that dissolves entire fuel elements, including the cladding material. ZIRCEX is considered a hybrid process because it starts with a dry head-end process to remove the zirconium or aluminum cladding prior to a liquid process that INL calls "a very compact, modular solvent extraction system." The uranium is then downblended to HALEU levels with the addition of natural uranium prior to solidification and fuel fabrication. ZIRCEX reduces the amount of liquid waste generated by a factor of over 1,000 and includes the vitrification of fission products and residual liquid waste, according to INL.

Other national laboratories are also involved in the development of the ZIRCEX process. Argonne National Laboratory is working on solvent extraction, Pacific Northwest National Laboratory on waste treatment, and Oak Ridge National Laboratory on product solidification.



EMT-derived HALEU in the form of 30–40 kg ingots (top left) are recast in a multi-tier crucible system (top right) to yield 1.5–3 kg fuel fabrication–ready reguli (bottom right).

Photos: INL

Photo: Chris Morgan/INL

INL aqueous separation chemistry researchers Rich Tillotson and Amy Welty at work in INL's Hybrid Zirconium Extraction (ZIRCEX) Material Recovery Pilot Plant, a key facility in the DOE's multi-laboratory effort to supply HALEU for developers of advanced reactor technologies.

Hybrid ZIRCEX processing of naval fuel "would involve combining defense missions with civil missions, and there's a lot to work out there," said the DOE's Vega. If a decision is made to deploy ZIRCEX processing, a plant could be operating around the mid-2020s, he said.

SRS H-Canyon

Also speaking at the HALEU supply panel session was Bill Bates, deputy associate laboratory director for nuclear materials management at Savannah River National Laboratory, who suggested that tanks in the Savannah River Site's H-Canyon could be tapped for another source of HALEU. H-Canyon, which has been in operation since the mid-1950s, was initially an integral part of the DOD's weapons material supply. "More recently, between 2003 and 2011, we produced 301 metric tons of 4.95 percent LEU for TVA as part of an agreement between NNSA and TVA for fuel that goes into Browns Ferry," Bates said.

Aluminum-based spent nuclear fuel is processed in the H-Canyon. "All the material since that 2011 time period is stored today in vessels and tanks in the canyon in HEU solution form," Bates said. Although earmarked for downblending to LEU around 2022, the HEU solution could be downblended to HALEU instead. "On the surface it's easy, because all we're doing is changing the blend ratio," Bates said. "But that doesn't mean that we don't have some things that we would have to do to make this work." Those would include physical modifications, staffing increases, and transportation containers.

"What's in there today is literally about 2 metric tons of what we call HALEU equivalent," Bates continued. "What I mean by that is if we were to downblend that to 19.75 percent enrichment, it would yield 2 metric tons." If a lower enrichment level was sufficient, the same HEU solution would yield a correspondingly greater amount of fuel feedstock. H-Canyon could potentially produce 19–32 t from spent fuel that is expected to arrive at the Savannah River Site through the 2030s, Bates said, with an annual HALEU production rate of about 1.5–2 t starting in late fiscal year 2022.

From feedstock to TRISO

In the United States, there are currently three Category III fuel fabrication facilities licensed to produce LEU-based fuel and two Category I facilities that can process HEU for research reactors and military requirements. HALEU is Category II, the one fuel category with no licensed fabrication facility.

X-energy aims to change that by licensing and constructing the TRISO-X Fuel Fabrication Facility to manufacture HALEU-based uranium oxycarbide (UCO) tristructural isotropic (TRISO) particles. Backed by cooperative agreement funding from the DOE, X-energy is leading a project to assess fuel design and

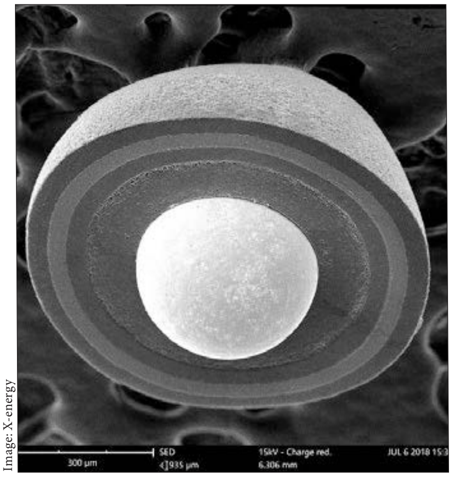


Image: X-energy

A TRISO particle produced in X-energy's TRISO-X pilot facility.

utility/operator requirements, complete the preliminary and final designs of the TRISO-X facility, and complete the licensing application process.

Pete Pappano, X-energy's vice president for fuel production, spoke about the company's TRISO fabrication pilot line at ORNL during the HALEU supply panel session. "We call it a pilot facility because we have one piece of equipment for every operation, but the scale of that equipment itself is commercial," he said. "Small and modular is not just for reactors—we're actually doing that on the fuel facility here as well." In addition to TRISO-X, X-energy is developing the Xe-100, a high-temperature, gas-cooled reactor design, and HALEU is key to both projects. The company is looking to produce TRISO fuel made from HALEU in the second quarter of 2024 using equipment with an annual capacity of 5 t.

In November 2018, Centrus and X-energy signed a services contract to begin the preliminary design of the planned TRISO-X facility. Under the agreement, Centrus will provide X-energy with technical expertise and resources to support the preliminary design of a facility to produce UCO TRISO fuel forms using HALEU.

"We've invested a lot in reactor design and that's great, but it's all for naught if the fuel supply chain is not in place," Pappano said. He described the "chicken-and-the-egg" situation for reactor development: Investors are reluctant to put money into reactor designs with no established fuel supply chain, and fuel suppliers are equally unwilling to license the necessary enrichment capabilities until reactor developers have customer commitments. "We're starting to get beyond this 'chicken-and-the-egg' that companies like X-energy have faced for years," Pappano said. "With what we're doing here, we're at least trying to do our part to get the fuel supply side up and running." NN