

Russian strikes on Ukrainian nuclear plants stir talk but little action in Western nations

Even as shelling of Ukrainian facilities threatens a radiological disaster, Russia's sales of enriched uranium to the US and the EU continue.

US Department of Energy officials say they are urging other countries to ignore sales pitches from Russian nuclear power plant suppliers in response to attacks on Ukrainian nuclear facilities. But the US and other Western nations have so far done little to shed their dependence on Russian nuclear fuel.

Russia supplied 28% of US low-enriched uranium (LEU) in 2021, according to the Energy Information Administration. The US also imports natural uranium from Russia, most of which originates in Kazakhstan.

US lawmakers have introduced several measures to ban uranium imports from Russia, although none have been enacted. Most recently, identical House and Senate measures introduced in February and March, respectively, would prohibit imports—with annual exceptions provided for the Russian material that the US commercial industry has contracted for through 2027.

DOE and the International Atomic Energy Agency (IAEA) both recently have warned Russia that continued attacks on Ukrainian nuclear plants and the nation's transmission grid are courting a radiological disaster. Russia is fully cognizant of that risk, says David Hoagland, who heads the Ukraine task force at DOE's National Nuclear Security Administration (NNSA). "We want the world to know that Russia knows what they are doing. They understand nuclear energy and the interconnectedness of the grid and the safe operation of the nuclear plants," Hoagland says. "If there were a nuclear accident, it wouldn't be an accident."

"The nuclear safety and security dangers are all too obvious, as is the necessity to act now to prevent an accident with potential radiological consequences



THE ZAPORIZHZHYA NUCLEAR POWER PLANT has been at the front lines of fighting between Russia and Ukraine for most of the war. Located on the eastern bank of the Dnieper River in Russian-controlled Ukrainian territory, the six-reactor plant has been shelled repeatedly, and ancillary buildings have been damaged. International Atomic Energy Agency director general Rafael Grossi has been attempting to broker an agreement to shelter the facility from further attacks.

to the health and the environment for people in Ukraine and beyond," IAEA director general Rafael Grossi said in a 25 March statement.

Most alarming, say Hoagland and Kathryn Huff, DOE assistant secretary for nuclear energy, are the March 2022 takeover by Russian forces of the Zaporizhzhya Nuclear Power Plant (ZNPP), the largest nuclear plant in Europe, and its continued occupation. The armed seizure of an operating civil nuclear power plant—and the combat that is continuing nearby—is unprecedented in the history of warfare, they note. No nuclear power plant has been built to operate in wartime conditions.

At the front lines of the conflict, the ZNPP is on the Russian-controlled eastern bank of the Dnieper River, with Ukrainian forces defending the opposite bank. Since its occupation, the ZNPP has been shelled repeatedly, with each side blaming the other. Strikes have damaged several buildings, including one located adjacent to the plant's spent-fuel storage facility. The last of the site's six reactors, which had sup-

plied around 20% of Ukraine's prewar electricity, was shut down last September, and the reactors have sustained no direct damage to date. But continuous power is required to cool the shut-down reactor cores and to maintain the spent fuel that's stored on-site in pools of water.

Deliberate attacks on Ukraine's electricity transmission system have caused the ZNPP to lose off-site power six times and be forced to resort to emergency generators, Hoagland notes. The loss of a backup power line on 1 March has left the ZNPP with a tenuous single-line connection to the power grid.

Meeting with Ukrainian president Volodymyr Zelensky on 27 March, Grossi said the situation at the ZNPP "is not getting any better," due to the ongoing fighting in the vicinity. Grossi visited the plant two days later in a largely unsuccessful attempt to broker an agreement between the warring parties to protect the plant. And in early April, he traveled to Kaliningrad, Russia, to continue his efforts in meetings with Russian officials. IAEA

staff have been stationed at the ZNPP since September to monitor the situation at the plant, assess equipment and other needs, provide technical support and advice, and report to the IAEA headquarters.

Russia's deliberate assaults on Ukraine's electrical grid caused all nine operating reactors at Ukraine's three other nuclear power plants to shut down simultaneously last November. The NNSA has been supplying the plants with emergency diesel generators and fuel and is offering consulting services to plant operators. Such US assistance is unavailable to the ZNPP.

Russian missile strikes over the past year have damaged buildings storing civilian radiological sources that contain cesium-133 and cobalt-60, according to DOE. The sources were not breached; had they been, they could have spewed highly radioactive material to the surroundings, adding further distress to the local population. Russian forces were fully aware of those facilities' locations, even if they hadn't been deliberately targeting them, says Hoagland.

Huff warns that radiological disasters precipitated by Russia's attacks would set back nuclear power globally at a time when expansion is critical to helping mitigate climate change. "The public needs to have confidence in nuclear facilities," she says.

Holding Russia accountable

Not only is Russia's nuclear enterprise the source for nearly half the world's enriched uranium, but it is by far the world's largest exporter of nuclear power plants. As of mid 2022, the state-owned company Rosatom had 17 reactors under construction in other countries, according to *The World Nuclear Industry Status Report 2022*. Rosatom claims 34 reactors in total are "at various implementation stages" in other nations and says its foreign orders are valued at \$140 billion. Companies from only two other nations, France and South Korea, are currently constructing reactors outside their borders.

As of mid-February, Rosatom had exported just over \$1 billion of nuclear-energy-related goods and materials since the start of the war, according to the Royal United Services Institute for Defence and Security Studies.

Hoagland says the "reckless and irresponsible actions" in Ukraine display to the world Russia's lack of regard for safety. It follows that potential buyers of



CYLINDERS OF URANIUM HEXAFLUORIDE are processed at Urenco USA's enrichment plant in Eunice, New Mexico. The sole US commercial uranium enrichment facility, it provides about one-third of the nuclear fuel used by domestic nuclear power plants.

Russian reactors should have no faith in the safety of those systems, he says.

The US has been cajoling other nations that are considering potential nuclear partnerships with Russia to abandon them, says Huff. "Isolating Russia in this marketplace economically for its bad behavior is critical because when you partner on nuclear reactor technology, you're engaged with them on their fuel supply, operations training, and technology upgrades for decades on decades."

Western dependence

Even as the US and the European Union (EU) have imposed full or partial embargoes on Russian fossil-fuel imports, nuclear fuel from Russia has continued to flow to the West. DOE's position is that restrictions on Russian imports should be coupled to new investments in US nuclear fuel facilities, says Huff.

The nuclear fuel cycle has multiple stages. Mined ores are first processed into triuranium octoxide (U_3O_8), known as yellowcake. Conversion plants chemically transform that to uranium hexafluoride (UF_6), which is gasified and then fed into centrifuges for enrichment from the naturally occurring 0.7% ^{235}U to the 4.5–5% LEU that fuels all US and most EU commercial reactors.

The capital-intensive enrichment stage is the main impediment to Western uranium independence. The US gets the rest of its enriched product from the European consortium Urenco, which operates three enrichment plants in Europe and one in New Mexico, and from the single plant operated by Orano in France. Urenco's US plant supplies about one-third of the domestic annual consumption on average.

"Conversion and enrichment services from trusted sources are insufficient to replace current US imports from Russia," Huff told the Senate Committee on Energy and Natural Resources on 9 March. "This strategic vulnerability is unsustainable."

A DOE analysis shows that the production of LEU will be 14% short of Western world requirements in 2024. The gap then widens to a projected average of 26% per year from 2025 to 2030. DOE says it hopes to incentivize the US domestic uranium supply chain to expand new enrichment capacity through competitively awarded public-private partnerships. Yet Congress has appropriated no funding for that. And regardless of the availability of funds, enrichment capacity will take years to build out.

Paul Lorskulsint, chief nuclear officer at Urenco USA, says the West has enough excess LEU to replace all Russian imports until 2028, when new enrichment capacity is scheduled to come on line. Japan, for example, has a stockpile resulting from contracts it negotiated prior to the Fukushima Daiichi nuclear disaster, he says. And some utilities have offered to share some of their surplus LEU if needed.

"If we decided as an industry that we wanted to end Russian imports, we could, through some creative means, cover that and be comfortable that we wouldn't have nuclear plant shutdowns because of a lack of enriched uranium," Lorskulsint says. "It would take some creativity and a lot of collaboration."

DOE says the global surplus, which it calls the strategic inventory, includes some of its own stockpiled LEU. Joseph Dominguez is president and CEO of

Country of enrichment	2017	2018	2019	2020	2021
China	W	W	W	W	W
France	W	0	W	W	W
Germany	437	1 444	1 238	1 175	1 825
Netherlands	1 183	2 864	1 367	1 885	1 583
Russia	2 912	3 473	3 087	3 220	3 953
United Kingdom	1 525	1 544	1 262	1 218	2 366
Europe	W	W	W	W	W
Other	W	W	W	W	W
Foreign total	7 305	10 034	7 992	10 012	11 481
United States	5 572	4 979	5 289	4 132	2 736
Total	12 877	15 013	13 281	14 144	14 217
Average price per SWU (US\$)	125.43	115.42	109.54	99.51	99.54

W = Data withheld to avoid disclosure of individual company data.

Totals may not equal sum of components because of independent rounding. Average prices are not adjusted for inflation.

Source: US Energy Information Administration, Form EIA-858, Uranium Marketing Annual Survey (2017–21).

LOW-ENRICHED URANIUM imports from Russia, expressed in separative work units (SWUs), the standard measure of the effort required to separate ^{235}U and ^{238}U during the enrichment process, totaled 28% of US demand in 2021, the latest figures available. The Department of Energy expects Russian imports to decline somewhat this year but increase again after 2024.

Constellation Energy, which owns and operates 21 nuclear reactors in the US. He told the Senate Energy Committee at the 9 March hearing that the company has secured enough nuclear fuel inventory and future supply contracts to meet its needs through 2028, even if its existing contracted Russian fuel supply was disrupted.

Urenco USA has been licensed by the Nuclear Regulatory Commission to produce up to twice its current capacity of LEU, and by 2028 it will have expanded enough that it could cover US imports from Russia, says Lorskulsint. Centrifuge manufacturing has been dormant for years, however, and Urenco and Orano haven't been replacing centrifuges as they wear out or break. Lorskulsint says the mothballed centrifuge assembly facility in New Mexico is now reopening, and manufacturing should resume early in 2025. Jessica Sondgeroth, deputy editor of *Nuclear Intelligence Weekly*, cautions that centrifuge operations can't be resumed overnight. A "learning curve" to building centrifuges includes training and clearing employees to work on the sensitive technology.

Overfeeding could help

Frank von Hippel, a retired Princeton University physicist, says the West could quit Russian imports relatively quickly without new enrichment capacity. He calculates that independence would require 4900 tons more natural uranium per year, which could easily be obtained from the mining capacity that Canada's Cameco plans to reopen next year.

"You can get more low-enriched uranium out of a given amount of enrichment capacity if you increase the natural uranium feed and you don't work as hard at extracting the last bit of uranium-235," von Hippel says. Known as overfeeding, the process he describes leaves behind depleted uranium tailings with a higher ^{235}U content compared with standard enrichment feeds. Those tailings can be stored to feed centrifuges when uranium prices are high.

With excess capacity because of market conditions, enrichers in recent years have been underfeeding—spinning their centrifuges longer and extracting more ^{235}U from a given amount of UF_6 . Lorskulsint says that Urenco USA recently ended underfeeding. Assuming that the other Urenco plants have done the same,

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he says, their combined output would increase by enough to offset about 40% of Russian imports to the US and the EU. Sondgeroth says the degree to which overfeeding could supplant Russian imports depends on the demand for non-Russian LEU from elsewhere in the world, how quickly centrifuge manufacturing resumes, and adequate supplies of UF_6 .

DOE says a combination of new enrichment capacity, the elimination of underfeeding at existing enrichment plants, and drawdowns from the strategic inventory are all needed to make up the shortfall in the event of complete disruption of Russian LEU supplies to the West.

Conversion is a second potential choke point in the fuel cycle. Cameco's Ontario facility was the sole North American conversion plant until last month, when ConverDyn reopened a facility in Metropolis, Illinois, that was closed in 2017. Von Hippel says the two plants should provide enough UF_6 feed to cover Russian imports. Doug True, a senior vice president with the Nuclear Energy Institute, notes that overfeeding would exacerbate any shortfall in conversion capacity.

The prospects for EU independence from Russia are clouded by the 19 Russian-

made VVER-440 reactors operating in eastern EU countries. Non-Russian-made fuel assemblies for those do not currently exist, although Westinghouse is close to producing substitutes. "That makes it virtually impossible for Europe to implement sanctions," Sondgeroth says. A partial EU ban with the 19 exceptions could cause Russia to retaliate by halting shipments to those reactors, she adds.

An inconvenience?

Edwin Lyman, director of nuclear power safety at the Union of Concerned Scientists, says the US nuclear industry has made little effort to lower its dependence on Russian LEU. "Industry came out of the gates saying no, we can't do it. I didn't see any kind of effort on the part of the US industry to get together and say let's see how we can do this."

If Constellation could do without Russian uranium, "the question is why didn't they just do it?" says Lyman. "They don't want any perturbation of their Russian supply that could inconvenience them or raise costs. I find that kind of outrageous." A Constellation spokesperson says the Russian supply contracts were negotiated before the Ukraine invasion,

and none have been made since then.

The US nuclear industry has long urged the federal government to subsidize new domestic enrichment capacity, arguing that all the world's enrichment plants are essentially government-owned enterprises. The options seem limited, however. Centrus Energy, the remnants of the once federally owned enrichment enterprise, will this year begin producing under DOE contract a relatively tiny quantity of high-assay, low-enriched uranium, a specialty product needed for advanced reactors that's enriched up to as much as 19.75% in ^{235}U . But Centrus has built just 16 centrifuges. A commercial enrichment plant has thousands.

In his Senate testimony, Constellation's Dominguez plugged laser enrichment technology in development by North Carolina-based Global Laser Enrichment. Part-owned by Cameco, GLE is preparing a commercial-scale pilot demonstration of technology developed in Australia. With DOE providing timely and modest cost-share support, Dominguez said, GLE could accelerate to 2028 the commercialization of its technology at a proposed site in Paducah, Kentucky.

David Kramer

Hybrid scientific conferences: An ongoing experiment

Duplicating or replacing serendipitous encounters in virtual environments is a challenge.

"I've seen you on Zoom, but we've never met." Mark Neubauer, a high-energy physicist at the University of Illinois at Urbana-Champaign, has heard such comments repeatedly since in-person scientific conferences began making a comeback. In 2020, when COVID-19 was declared a pandemic, Neubauer, like most researchers, started spending a lot of time on Zoom for conferences and other activities. He organized a May 2021 workshop on the future of meetings (a summary is available at <https://arxiv.org/abs/2106.15783>).

By late 2021, many conferences were offered in hybrid formats, with some people participating in person and others logging in from afar. Before the pandemic, remote participation in conferences was often frowned on, Neubauer says. But now "the genie is out of the bottle" for remote participation in meet-

ings, which can have the advantage of accessibility and sustainability. Hybrid formats are here to stay, he says, even as "there is a lot of pressure to get back to how we held meetings prepandemic."

The purposes of scientific conferences include sharing knowledge, providing visibility for early-career scientists, and maintaining and extending networks. Hybrid options could improve some traditional conferences, which may not always deliver what scientists want from them. "Sessions are held back-to-back, and there is little time for discussion," says Astrid Eichhorn, a University of Southern Denmark professor whose research is in quantum gravity. And, she adds, often conference goers sit in a presentation checking their phones and working rather than paying attention to the talk. "Overall, we do not have the ideal format yet."

"Conferences need to change"

Julia Marks Peterson says that until recently, she "only knew online conferences." She began her PhD studies at

Oregon State University in 2020, during the lockdown phase of the pandemic. Last October she went to an ice-core science conference in Crans-Montana, Switzerland, with about 500 attendees. "When I went to my first in-person conference, I realized what I had missed out on," she says. "I hadn't realized how productive a conference could be." The informal feeling of the gathering gave her confidence to approach leaders in her field. Besides forming connections with people, Marks Peterson says she was more likely to attend sessions that did not sound relevant to her own research than she would have been online. "When it's all in the same place, why not?"

Marks Peterson also appreciates the hybrid aspect of conferences. Last December, for example, she couldn't attend the fall meeting of the American Geophysical Union because she was doing fieldwork in Antarctica. So she prerecorded a talk, which was presented as part of an otherwise live session. "It was a nice way for me to get my work out there," she says.