FINAL RESTING PLACE

Finland is set to open the world's first permanent repository for high-level nuclear waste. How did it succeed when other countries stumbled?

By **Sedeer El-Showk**

After passing through a security gate, the van descends into a tunnel that burrows under the forests of Olkiluoto, an island off Finland's west coast. The wheels crunch on crushed stone as a gray, wet October day gives way to darkness. "Welcome to Onkalo," deadpans Antti Mustonen, a geologist here. Onkalo—"cavity" or "pit" in Finnish—will be the world's first permanent disposal site for high-level nuclear waste, and a triumph for Finland.

Safety lights guide the van down through switchback turns that lead to a cavernous chamber, its walls reinforced with spray-on concrete. In just a few years, spent reactor fuel rods, encased in giant copper casks as tall as giraffes, will arrive here via elevator before robotic vehicles take them to one of the dozens of dead-end disposal tunnels that will form an ant's nest in the bedrock. In a freshly excavated disposal tunnel, Mustonen explains over the roar of ventilator fans that the peculiar smell comes from rock dust mixed with a trace of explosives. It is muddy underfoot—not what you want to see in a place that shouldn't have leaks, but Mustonen says the water is only from the excavation effort.

In the blackness, bare bedrock glints in the meager light from the van. After 30 to 40 of the copper casks are buried in the tunnel floor, the holes will be plugged with bentonite, a water-absorbing clay. Each tunnel will be backfilled with more bentonite and sealed with concrete. The casks will then begin their long vigil. They must remain undisturbed for 100,000 years, even as the warming climate of coming centuries gives way to the next ice age. "It's final disposal," Mustonen says. "Right here, in stable Finnish bedrock, 430 meters belowground, 420 meters below sea level."

Although nuclear power is declining in many nations, Finland has embraced the carbon-free energy source, lobbying the European Union to label it as sustainable. Two of the country's four reactors are on Olkiluoto. After a new Olkiluoto reactor is connected to the grid later this year, nuclear power will account for more than 40% of Finland's electricity.

The emissions-free electricity comes with a downside: hot and highly radioactive spent uranium fuel rods. In Finland, the rods cool for decades in pools of water; other nations park them in concrete and steel "dry storage" casks. Either way, surface storage is vulnerable to accidents, leaks, or neglect during the thousands of years the waste remains dangerous, says Budhi Sagar, a nuclear expert formerly at the Southwest Research Institute. "It's not safe—some disaster will occur," he says, citing the groundwater contaminated by leaky waste tanks at the U.S. Department of Energy's (DOE's) Hanford Site in Washington state, where reactors produced plutonium for the first nuclear weapons.

Without a long-term solution, the waste is piling up. Finland had about 2300 tons of waste in 2019, and about 263,000 tons of spent fuel sit in interim storage facilities worldwide, a report this year from the International Atomic Energy Agency estimates. "In my view, that's an unacceptable legacy to leave to future generations," says Tom Isaacs, a strategic adviser for Canada's Nuclear Waste Management Organization (NWMO) and Southern California Edison. "We generated this electricity. We benefited from that."

Many experts view permanent deep repositories like Onkalo as the best solution, but getting community buy-in is often a deal breaker. Street protests have slowed down plans for a disposal site in France, and in 2009, after years of debate, then-President Barack Obama's administration gave up on plans to develop Nevada's Yucca Mountain as the U.S. national repository. "The U.S. approach didn't pay sufficient attention to community acceptance or engagement," says Isaacs, who was the lead adviser on a 2012 blue-ribbon report commissioned by DOE to chart a way forward. "The original approach led to conflict rather than cooperation."

Finland, however, has run into remarkably few problems with Onkalo, which the government approved as a site in 2000. It helped that the residents of Eurajoki, the town closest to Onkalo and the nearby reactors, were comfortable with nuclear power. "Almost everyone in Eurajoki has a friend or relative who has worked in the nuclear power plants, so they know how we operate," says Janne Mokka, CEO of Posiva, the nuclear waste company set up by two nuclear power utilities to develop and manage Onkalo.

But experts say the success of Onkalo also reflects unique cultural and political conditions in Finland: high trust in institutions, community engagement, a lack of state-level power centers, and a balance of power between industry and stakeholders. "If you tried to implement the same thing in a country with much lower levels of trust, it would probably fail," says Matti Kojo, a political science researcher at Tampere University in Finland.

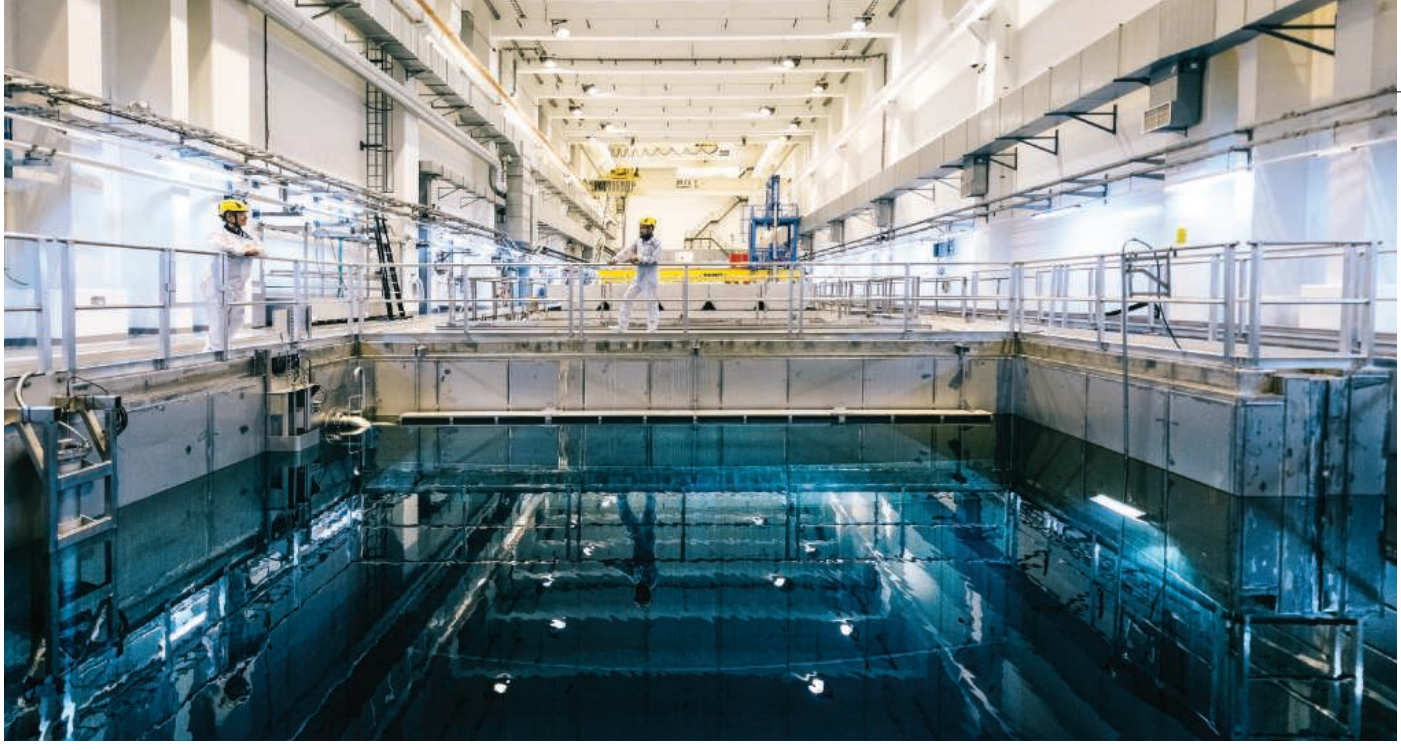
"The Finns have been able to articulate a consistent message about what they're doing, why they believe this facility will be safe, and why it will be a major benefit to the well-being of certain communities," Isaacs says. In late December 2021, Posiva applied for a license to begin operations in 2024.

POSIVA BEGAN its search in the 1990s, with dozens of candidate sites, before narrowing the list to four with different geological characteristics. The final choice was

Spent uranium fuel rods will be sealed within thousands of tall, corrosion-resistant copper canisters.

About 100 nuclear waste disposal tunnels are being dug 430 meters underground at Onkalo.

PHOTOS: LEHTIKUVA/EMMI KORHONEN/VIA REUTERS; (OPPOSITE PAGE) TAPANI KARJANLAHTI/TVO



Spent fuel rods from Olkiluoto's nuclear power plants will cool off for several decades in interim storage pools before final burial at Onkalo.

PHOTO: TAPANI KARJALAINEN/LVO

between Olkiluoto and the area around the town of Loviisa, which houses the country's other nuclear power plants. In 1999, Posiva put forward the site that would become Onkalo.

The bedrock at Onkalo has been mostly stable for the past billion years, geologists say, although there is evidence of earthquakes during the past 10,000 years as massive glaciers retreated at the end of the last ice age and the bedrock rebounded. Posiva scientists don't expect significant earthquakes in the region until after the next ice age. Mustonen says Onkalo was purposefully situated between two parallel fault zones about 800 meters apart. If an earthquake were to occur, it would preferentially happen along those existing fault lines, he says. "They absorb the movement and nothing happens here in the area in between."

But earthquakes aren't the main threat. "The only way for things to move from the repository out to the surface and to impact people is to be carried by water," says Sarah Hirschorn, director of geoscience at NWMO. That means deep repositories are best situated in certain types of clay, salt, or hard crystalline rock, because they have small, disconnected pore spaces and are almost impermeable to water. At Onkalo, the nearly 2-billion-year-old bedrock is mostly gneiss, a hard rock formed at high temperatures and pressures.

Although decidedly nonporous, these rocks can still contain cracks, and Posiva had to map and avoid them as workers dug deeper. "It's these fractures which control the movement of water," says Neil Chapman, a geologist who has served as an independent consultant for Finland's nuclear regulator, the Radiation and Nuclear Safety Authority (STUK). If any significant fractures are discovered when drilling individual cask pits, he says, those holes won't be used.

If water were somehow able to seep into the repository, it would still have to get past the bentonite and copper to reach the spent fuel. "You're never relying on a single barrier," says Emily Stein, who researches deep geologic disposal at DOE's Sandia National Laboratories. "If one barrier fails, you have other barriers that can minimize or prevent radionuclide release."

After arriving at Onkalo, spent fuel will be unpacked in an encapsulation plant. In a stainless steel room surrounded by 1.3-meter-thick concrete walls, robots will vacuum away any water left on the fuel rods from their time in the storage pools, and seal them within a cast-iron canister nested inside a copper canister. Argon will be injected between the two canisters to provide an inert atmosphere, and the copper cask will be welded shut.

Copper is slow to corrode, and by the time any groundwater does reach Onkalo's depths, chemical or microbial reactions would have consumed all of its dissolved oxygen, making it less reactive. But Peter Szakálos, a chemist at the KTH Royal Institute of Technology in Stockholm, has concerns. In a 2007 study, he and colleagues found signs that copper can corrode even in pure, oxygen-free water. When the metal is exposed to water, Szakálos and his colleagues found it releases a whiff of hydrogen gas. He suspects the water reacts with the copper to form a "distorted" copper oxide crystal along with free hydrogen, which is either released or absorbed into the copper. Szakálos says any absorbed hydrogen would make the copper brittle and prone to cracking, and bronze would have been a safer choice. "It's just a matter of time—between decades and centuries—before unalloyed copper canisters start to crack at Onkalo."

Posiva and SKB, Sweden's nuclear waste management company, say Szakálos's experimental conditions are not relevant for the planned repositories. Even so, SKB contracted Uppsala University and the University of Toronto to try to replicate the findings. The Uppsala tests did not find evidence of any reaction with pure water, whereas the Toronto group observed one but said it was too slow to matter. "Making a measurement that tells you nothing happened is impossible," says David Shoesmith of the University of Western Ontario, a corrosion chemist who has consulted for SKB. "Based on what's been published, the answer to this question is that minimal things will happen."

Those concerns nevertheless delayed plans for what would be the world's second deep repository, near the Swedish coastal town of Forsmark. In 2018, Sweden's Land and Environment Court called for SKB to provide more evidence that copper corrosion would not undermine long-term safety. SKB submitted additional documentation to the Swedish Radiation Safety Authority, and in January, the Swedish government approved the facility based on the regulator's assessment that the other barriers would keep the repository safe.

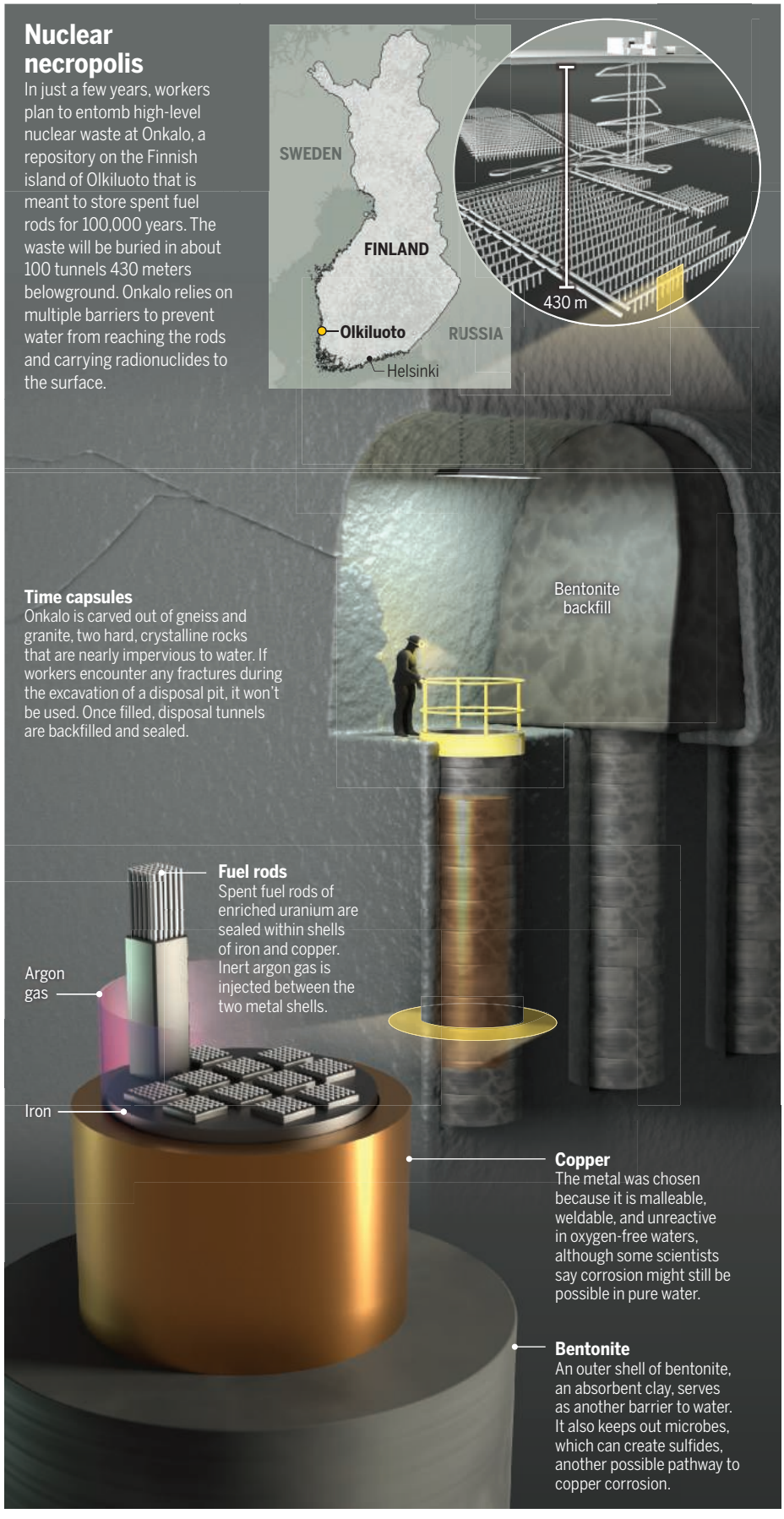
In addition to the casks themselves, the bentonite surrounding them will also prevent radionuclide escape, regulators say. The mineral not only keeps water away, but also prevents microbes from reaching the canister surface. Microbes can pose a threat, says Karsten Pedersen, CEO of Microbial Analytics Sweden, a company that researches their effect on deep repositories, because they can metabolize sulfates in groundwater and turn them into sulfides, which can slowly corrode copper. Posiva acknowledges that possibility, but the company's calculations suggest that even at elevated sulfide levels, the canisters would have a lifetime of more than 100,000 years.

Should all these barriers fail, escaping waste would face one last impediment: the decades it would take to migrate to the surface, with radioactivity levels dropping all the while. Sagar, who reviewed the long-term scenarios that were a part of STUK's overall safety assessment, says that even under worst-case assumptions the impact of leaking radionuclides would be minimal. For people living near the repository and drinking contaminated water from deep wells, the assessment found, the annual exposure would be well below the allowable limit set by STUK, which is about the same as the average background radiation exposure a person in Finland experiences today. "That's the point of a multibarrier system," Sagar says. "Even if some containers fail or a systematic construction error means they all have defects, the geology and other barriers are good enough that you're still within limits."

YET THE TRUE SECRET to Finland's success with Onkalo lies not so much in geology and engineering, but in the site selection process, the structure of government, and a culture of trust in institutions and expertise.

Finland's 1987 Nuclear Energy Act set up a nuclear waste management fund, financed by the nuclear operators, which incentivizes companies to develop waste disposal solutions. It also insulates the process from politics. Isaacs notes how this differs starkly from the situation in the United States, where DOE—which answers to the White House—runs the waste disposal program. "No matter how competent and well-intentioned people are, presidential and congressional elections are held regularly," he says. Important decisions can end up subject to political expedience, crippling a project that takes decades to build.

Another important difference, according to Isaacs, is the absence of strong state-level government in Finland. State governments, often far from disposal sites, see repositories more in terms of perceived



GRAPHIC: V. ALTOUNIAN/*SCIENCE*

Onkalo's encapsulation plant (white) sits atop an ant's nest of underground tunnels in this August 2021 photo. Olkiluoto's nuclear power plants can be seen in the distance.

PHOTO: TVO

costs rather than benefits, Isaacs says. Nevada officials—governors, senators, and others—have consistently opposed the development of the Yucca Mountain facility, blocking funding and throwing up other hurdles. More recently, state politicians in New Mexico have opposed a proposed temporary storage facility for nuclear waste in the state.

In Finland, without comparable power centers to play spoiler, Posiva and the national government could deal directly with communities like Eurajoki. Community acceptance was forged in the back and forth between Eurajoki and Posiva, Kojo says. "In the 1990s, the power companies knew that they really needed approval at the local level," he explains. Finnish law gave Eurajoki the right to veto disposal in the area. But Eurajoki officials were tempted by the tax revenue that would come from the third nuclear power plant if Posiva's parent company, TVO, decided to build it there. Posiva also funded the construction of a new senior center in town.

This approach—continual engagement with potential host communities—is rare in many other countries, including the United States. Even in Finland it is new. In the mid-1980s, Finland had a technical, top-down approach with no public participation that experts like Kojo and Isaacs call "decide-announce-defend." In 1986, TVO announced it would investigate the municipality of Ikaalinen as a final disposal site. However, local resistance, particularly in the wake of the catastrophic nuclear accident at Chernobyl in the former Soviet Union, foiled the plans. The company realized it would have to engage more and build local political support using an approach Kojo calls "mitigate-understand-mediate."

Once an agreement was reached, Eurajoki residents were largely willing to leave technical matters and safety questions to expert bodies. "In Finland, there is a very high level of trust in science and in the authorities," Kojo says. "If the national authority says the repository is safe, they don't need to worry about it." The process became a purely technocratic affair in the hands of Posiva and STUK.

Not everyone's concerns have been allayed. The Finnish Association for Nature Conservation (FANC) says it is worried about long-term ecotoxicity and bioaccumulation of the radioisotopes. It also cites concerns raised by retired geologist Matti Saarnisto, former director of research for the Geological Survey of Finland. In 2010, Saarnisto told Finland's national broadcaster that as the next ice age arrives, freezing soil and rock could create pressures that would damage the repository. In any case, Saarnisto argued, it is impossible to make predictions on the scale of 100,000 years.

Jari Natunen, a scientist with FANC, says the relationship between industry and regulators in Finland is far too cozy—a form of "structural corruption." "The authorities are biased to think that the industry's position is correct and valuable, and the concerns of civil society are not," says Natunen, who is also a member of Nuclear Transparency Watch, an antinuclear advocacy organization.

Natunen adds that the Finnish media's coverage of Onkalo has been too compliant. By contrast, in the United States, France, and Sweden, safety concerns remain a central part of the public debate. A 2020 study by Kojo and his colleagues, for example, found that France's *Le Monde* newspaper played a more critical role in debates about repositories, acting as a watchdog that challenged authorities, whereas Finland's leading daily, the *Helsingin Sanomat*, generally took a more positive approach that reflected the framing and confidence of the government and industry.

If getting the operating license goes smoothly, Posiva is on track to begin to bury nuclear waste deep in the Finnish bedrock in 2024 or 2025. Excavation will continue over the next century as new disposal tunnels are added. When the repository is filled to capacity, sometime around 2120, the entrance tunnel will be sealed shut. The encapsulation plant and other surface structures will be demolished. Nothing above will remain, not even a warning sign. Deep below the dismantled site, 6500 tons of spent fuel rods will lie in their tombs, quiet but still warm from radioactive decay.

"What we are doing really has meaning and is really important," Mustonen says. "For me, this is the reasonable thing to do with nuclear waste, and we need to make it as good as possible. The sense of responsibility to the next generation doesn't keep me awake at night, but it's there. It just is." ■

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Final resting place

Sedeer El-Showk

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