SPECIAL REPORT

France digs deep for nuclear waste

Geological storage of long-lived radioactive material is moving closer to reality in Europe, says **Declan Butler**.

"It'll be about 8 minutes before we reach the 490-metre lab level," shouts an official, barely audible above the roar of machinery, as we slam shut the heavy doors of the small lift and trundle slowly towards the depths of the Earth.

Here, half a kilometre beneath rolling wheat fields outside the small town of Bure in north-east France, the country is preparing to dispose of its radioactive waste. In a €1-billion (US$1.3 billion) underground laboratory, the French National Radioactive Waste Management Agency (ANDRA) is testing the soundness of the rock and the technologies to contain the waste. ANDRA scientists are convinced that the rock formations can safely house highly radioactive waste, and plan an industrial-scale facility that would open deep below a 30-square-kilometre site nearby in 2025. It would be among the world's first geological repositories for high- and medium-level long-lived nuclear waste — and the largest.

B. TINOCO/ANDRA

The tunnels of the Bure laboratory are still being carved out of the 150 million-year-old rock.

The warren of tunnels under Bure is at the vanguard of several parallel efforts across Europe to come up with a permanent home for the long-lived waste that is accumulating at temporary storage sites. Projects that started decades ago are finally coming to fruition. Finland and Sweden plan to open deep geological repositories in about 2020–2025, whereas Germany hopes to open its own long-term repository in 2035. Several smaller European countries have banded together to form a European Repository Development Organisation to work on the concept of a shared facility.

By contrast, development of the United States' only proposed long-term repository, at Nevada's Yucca Mountain site, has stalled again and looks set to be abandoned after two decades of work and more than $10 billion in investment (see *Nature* **458,** 1086–1087; 2009). The Obama administration wants to scrap the Yucca Mountain site, and has created a commission to explore alternatives. One of the main problems is that the selection of Yucca Mountain by the US Congress in 1987 was, from the outset, a political rather than a scientific choice. "There are far better geological sites in the US than Yucca Mountain," says Patrick Landais, a geologist and scientific director of ANDRA, as we tour the lab in hard hats and fluorescent overalls. Like many experts, he questions Yucca's geological suitability: "When I went to the top of Yucca Mountain and saw the volcanoes below, that worried me."

Efforts by the US federal government to find a site have been stymied by opposition from individual states, where people are uneasy about having a nuclear dump in their backyard. European countries have taken a more scientific and stepwise approach to locating sites, which has engendered greater public confidence — in typical Scandinavian tradition, Sweden and Finland involved local communities in decisions from the outset, which has increased acceptability.

"The idea of a geological safe does not exist."

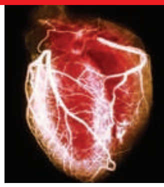
France generates about 80% of its electricity from its 58 nuclear power plants, and is a world leader in the technology. Nuclear power enjoys staunch cross-party support in the country, and the economic incentives that the storage facility offers to the Bure region have been welcomed by local officials. Anti-nuclear groups also have little clout. Perhaps unsurprisingly, there has been little effective resistance to the Bure facility. Mobilizing public opinion to oppose the repository is difficult because the majority of the French are "indifferent" to nuclear power issues, says Sophia Majnoni, head of Greenpeace France's nuclear campaign. The group does not oppose geological storage research, but is concerned that plans to seal the repository after a century of use would make it almost impossible to deal with a subsequent problem in the facility.

The Bure lab, created in 1999, has largely established the geological suitability of the area, with its findings endorsed by international experts. Now, it is shifting into high gear, spending €100 million a year on research to pin down exactly how waste would be stored at the planned repository. ANDRA must present a blueprint for the repository to the government in 2014; if approved by the French National Assembly in 2016, construction would begin the following year. The assembly will then consider licensing the facility to open in 2025.

Once completed, the repository would store all of the existing 2,300 cubic metres of high-level and 42,000 cubic metres of medium-level long-lived radioactive waste — most of which has been generated by France's nuclear power stations — as well as new waste created over at least the next 20 years. The existing waste is currently being stored at temporary sites in La Hague, Marcoule and Cadarache.

Test lab

The lab itself contains no radioactive waste, and never will. Instead, researchers at Bure are focusing on testing the rock and prototype waste-containment strategies. Almost all of the research results are analysed remotely. Once scientists have installed their experiments, the output of instruments lining the tunnels is



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E. SUTRE/ANDRA

Sensors in the tunnel walls monitor the rock around the clock.

transmitted via the Internet to ANDRA's own researchers, along with 80 collaborating labs at other research agencies and universities in France and other European countries involved in the project. Jacques Delay, the geologist in charge of coordination and experimental strategies at the lab, shows me the screens of the remote data-access system: a three-dimensional representation of the galleries in which one can zoom in on any tunnel to find an experiment, and pull up its data output and graphs in real time.

But dozens of scientists and engineers must still make the long descent every day, and working at such depths is not without risk. Before we board the lift, I get a crash course in using the chunky 'self-contained self-rescuer' device strapped around my waist. It is a closed-circuit breathing apparatus used in the mining industry, which can provide 20 minutes of chemically generated oxygen should a power outage cut the tunnels' ventilation.

The lift slows at a depth of 445 metres, then creeps to the bottom. A few minutes later, we push open the doors into galleries crammed with scientific instruments. Incessant tannoys, and the din of pneumatic drills and earth borers at work extending the lab, fill the air. The tunnel walls are reinforced with concrete, steel ribs and bolts, but here and there the grey 150-million-year-old Callovo-Oxfordian argillaceous rock that would seal the repository is left bare.

On the pulse

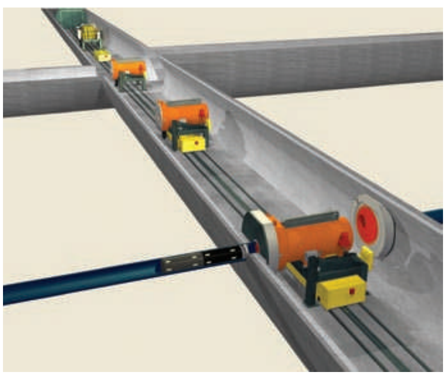
Fine experimental boreholes in the walls carry about 3,500 sensors, which take the pulse of almost every mechanical, chemical and hydrogeological aspect of the rock. The data are fed into models that characterize the rock and also predict its future behaviour over periods from decades to more than a million years. "No other rock lab in the world is as highly equipped as this one," Landais says.

The experiments ultimately aim to answer one key question: can France's most dangerous radioactive wastes be safely contained inside this 150-metre-thick layer of rock? The high-level waste includes the radioactive fission products caesium-134, caesium-137 and strontium-90, and minor actinides such as curium-244 and americium-241. Most nuclear fuel in France is reprocessed to extract useful uranium and plutonium, and to concentrate the waste. Although this high-level material comprises just 0.2% of France's nuclear waste by volume, it accounts for 95% of its total radioactivity.

The waste is immobilized by blending it into glass, in a complex vitrification process pioneered by the French. The molten glass is poured into stainless steel casks, which are then placed inside steel barrels. Robots in the Bure repository will push these barrels into 70-centimetre-diameter boreholes called alveoli, drilled 40 metres horizontally into the walls of the main access tunnels.

The medium-level radioactive waste, meanwhile, which comes from used reactor equipment and reagents, would be compressed into circular cakes and piled into steel canisters, before being encased in concrete and stored in the tunnels.

Scientists at Bure are already testing the stability of the glass that would be used to immobilize the high-level waste, the rates of corrosion of the stainless steel casks, and the fate of the hydrogen gas that this degradation releases. They are also assessing all the interactions between the glass, the layers of steel and the rock in prototype alveoli.



Robots will store high-level waste in boreholes.

The canisters are designed so that heat from radioactive decay inside does not warm their surface beyond 90 °C. Tests using mock-up canisters have shown that prolonged exposure to this temperature does not cause the rock to fissure. Although the volume of high-level waste is much smaller than that of medium-level waste, it will require double the amount of storage space, because the hot casks must be spaced out with empty ones to avoid overheating. The scientists are also investigating ways to reduce the volume of waste to be sent to the facility. "Geological storage is a rare and precious resource," says Landais. Extracting radioactive elements from bulky graphite fuel elements and then concentrating them, for example, could allow much more medium-level waste to be packed into the repository's chambers.

The repository could eventually operate for at least a century, after which it would be sealed. A few thousand years later, the stainless steel would corrode away until it was ruptured by the pressure of the rock, leaving the vitrified waste, and the rock itself, to provide containment.

Rock is not an absolute barrier, says Landais. "The idea of a geological safe does not exist." Radionuclides would slowly diffuse through it. Of most concern at Bure are radioactive iodide and chloride anions, which are the most mobile in this type of rock. But Landais says that it would take hundreds of thousands of years for them to diffuse to the surface. By that time, he says, their low concentrations and lower levels of radioactivity would render any environmental contamination negligible.

A more worrying problem is the possibility of a rock fracture, which could lead to radioactive leaks. But the research at Bure has largely confirmed that the layer of rock that would house the repository is homogenous, highly impermeable to water movement and free from faults and seismic risk.

At the surface, researchers are extensively sampling the air, water and soils in a 250-square-kilometre zone around the site to get a comprehensive baseline of environmental data. An observatory, created jointly in April with France's agricultural research agency, INRA, will monitor this ecosystem for at least a century.

The geologists at Bure are confident that it is a safe place for nuclear waste. The rock is 150 million years old, hasn't budged in the past 20 million years, and won't in the next, they say. With the lab's panoply of sensors, measurements and models "we might make a mistake of a few per cent, but nothing major", says Landais. "The geology is predictable." ■