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The end of the cold war left uranium fuel stranded at research reactors around the world, including the Maria reactor in Poland.

A NUCLEAR EXCHANGE

More than 100 cold-war era research reactors run on uranium pure enough to be used in a nuclear weapon. But switching to safer fuel isn't easy.

BY GEOFF BRUMFIEL

It is a warm day in early autumn, and speckled sunlight shines through spruce and linden trees onto a crumbling road. Ahead stands a dilapidated brick building encircled by a chain-link fence. It seems peaceful enough. But attached to the fence is a sign that says *Teren Nadzorowany* — ‘supervised area’ — topped by the faded remains of a red trefoil: the symbol used world-over to denote a radiation hazard. The sign is the only visible hint of what once lay inside the building: enough highly enriched uranium reactor fuel to make more than 18 nuclear bombs.

A group of visiting journalists and US officials files into the building and looks down into pools of ultrapure water in which the fuel once lay. The water is still and clear, the fuel basins empty. Here at the Polish Institute of Atomic Energy in Otwock-Świerk, 30 kilometres southeast of Warsaw, fuel-removal operations have been under way for a year. They end today: the last shipment has been pulled out of the pools and packed away in seven bright-blue shipping containers, which are now sitting on trucks back at the gate. Soon, the containers will begin a high-security journey to a reprocessing plant in Russia, east of the Ural Mountains,

where the fuel's uranium will be converted into a safer form for use in power reactors.

The trip will be a homecoming of sorts: this fuel originally came to Poland from Russia more than 30 years ago. But officials of the US National Nuclear Security Administration (NNSA), sensitized by the attacks of 11 September 2001, feared that this kind of highly enriched fuel posed too tempting a target for terrorists seeking to build a nuclear weapon. So a year ago, after much negotiation with the Polish government, they began clearing out the dangerous uranium and converting the reactor to run on safer fuel. For this last day of removal, *Nature* was granted a rare chance to watch the American programme in action.

The reactor at the Polish institute is hardly unique: globally, roughly 130 research reactors in state laboratories and university campuses continue to run on bomb-grade fuel (see map). US President Barack Obama did not explicitly mention these reactors in April 2009, when he announced a substantial acceleration of established non-proliferation efforts and made a commitment to ensure the security of all vulnerable nuclear material within just four years. But many of the facilities clearly do fall into that 'vulnerable' category.

Research-reactor operators are not always enthusiastic about cooperating with the American initiative. Safer alternative fuels are available, but converting the reactors to use them is difficult, time-consuming and costly. "We are not so happy to convert our reactor," says Grzegorz Krzysztoszek, the director of the Polish facility. But the NNSA is winning the operators over by offering to remove old uranium, help with the conversion process and pay for new fuel — a US\$70-million proposition in this case. The US agency's Global Threat Reduction Initiative has already helped to convert or shut down 72 vulnerable research reactors worldwide. Working on Obama's accelerated timetable, the NNSA is now hoping to spend nearly US\$3 billion over the next four years to secure or convert as many reactors as possible and clear out uranium from ten countries. "It's an aggressive schedule," says Andrew Bieniawski, the head of the operation. "But I do think we can make it."

LEFT BEHIND

Poland's research reactor was built during the cold war, and is one of many that the United States and the former Soviet Union helped to construct during that period. Named Maria after the Polish-born scientist Marie Curie, the 30-megawatt behemoth was actually one of two large research reactors that the Soviets helped to build at the institute starting in the 1950s. An important part of the deal was that the Soviets would also keep the reactors supplied with highly enriched uranium fuel.

But the fall of the Soviet Union in 1991 led to hard times. Plans for a Polish commercial power reactor in the north of the country fell

GLOBAL REACTION

Around the world, some 130 nuclear research reactors run on bomb-grade highly enriched uranium (HEU); others have been shut down or converted to safer fuel, or are being converted.

through, and the older of the institute's reactors was shut down in 1995. That left only Maria — which has become something of a relic. Trail-blazing nuclear physics is now done at particle accelerators, not research reactors.

Yet Maria hums on, Poland's last remaining tie to the nuclear age. Even if Maria is no longer at the cutting edge, Krzysztoszek says that the reactor has found its niche in more utilitarian research — primarily the use of neutrons from the core for imaging, and the production of medical isotopes. About 60% of Maria's US\$5-million annual budget comes from industrial clients, including a US company that hopes to use it to produce molybdenum-99, a short-lived isotope used in medical imaging. Outages in reactors in Canada and the Netherlands have created a dire worldwide shortage of this isotope (see *Nature* 460, 312–313; 2009), and the Polish institute hopes to profit from it. Domestically, the reactor also features in plans

for a new nuclear age of energy independence. The Polish government wants to move away from using dirty coal or Russian-supplied gas, says Krzysztoszek. By 2021–22, it hopes to have two nuclear power plants in operation. But that will require training Polish scientists and engineers in the nuclear arts, and this reactor is the only domestic facility available.

Similar stories can be heard at other research facilities around the world: they still do worthwhile work. "We're not running a reactor just to run a reactor. We do things with it," says David Moncton, director of the research reactor at the Massachusetts Institute of Technology (MIT) in Cambridge, one of a handful on US soil that continues to operate with bomb-grade fuel. The MIT reactor is used to test new nuclear fuels and components, but it also serves less-obvious functions: for example, doping silicon semiconductors by transmuting some of the silicon into phosphorus. The semiconductor wafers

are used as high-performance electronic components in hybrid vehicles.

Whether a reactor is useful or not, the fuel is still a security nightmare. The concern is that a terrorist group might somehow get hold of it and extract enough of the fissile isotope uranium-235 to construct a crude bomb. When atoms of uranium-235 split, they produce energy and neutrons. The neutrons strike nearby uranium-235 nuclei, causing them to split and creating a self-perpetuating chain reaction, which, if uncontrolled, leads to an explosion. To prevent just anyone from gaining a nuclear weapon, fuel for commercial power reactors is diluted with copious amounts of uranium-238 — a more common isotope that does not split. Because the two isotopes are chemically identical, they are impossible to separate without highly specialized equipment.

Most research reactors, however, run on up to 93% pure uranium-235, mixed with elements such as aluminium. This lets the reactors operate for longer and produce more neutrons with less fuel. But the uranium can easily be separated from other elements in the fuel, so extracting enough for a nuclear bomb is comparatively easy — and within the means of a sophisticated terrorist group.

VULNERABLE TO ATTACK

Compounding the problem of fuel security, research reactors are often housed in dilapidated state laboratories or the basements of university research buildings. “Many of these places have very minimal security,” says Matthew Bunn, an expert in nuclear terrorism at Harvard University in Cambridge, Massachusetts. The threat is more than academic: in 2007, two teams of armed men assaulted the Pelindaba reactor near Pretoria, South Africa. While one team engaged the site’s security forces, who fled, the other men penetrated an electrified fence and made their way to an emergency control centre inside the facility. There, they shot a worker in the chest before fleeing. They were never apprehended. No uranium-235 fuel was reported missing — indeed, no one knows what the assailants were after — but the incident underscores the vulnerability of civilian nuclear facilities.

Security was much on the mind of the NNSA negotiators as they worked out a deal with the Polish institute, where 454.9 kilograms of fresh and used highly enriched uranium fuel were left stranded by the collapse of the Soviet Union. And security remains very much on the minds of the US and Polish team members today.

By mid-afternoon, police cars have gathered at a gate near the reactor building. Officers in black T-shirts cluster in small groups near an adjacent yard where seven trucks are parked, each carrying one of the blue containers of the

Grzegorz Krzysztozek is overseeing the reactor's conversion.

last remaining spent fuel. A military helicopter suddenly roars over the treetops and begins to circle overhead; the airborne escort has arrived, and the convoy quickly lurches into action. One by one, the trucks file out of the gate towards the railway yard — the first stop on the long journey to Russia.

With their departure, the only highly enriched uranium remaining on site lies inside the reactor itself. As in other research reactors covered by the NNSA programme, that fuel will systematically be replaced with a safer one.

This is not as easy as it sounds. Researchers in the United States and elsewhere had to go to great lengths to develop safe blends of around 20% uranium-235 that will work in the cores of research reactors but can't be fashioned into a bomb. Because the reactors are designed for highly enriched uranium, they can run only on a very high density of uranium-235 atoms, which can make the fuel less stable. So to keep it from breaking down in the intense environment at the reactor's core, researchers have had to come up with exotic mixtures of uranium and elements such as silicon and molybdenum.

That development effort was a success, and the fuel is now available for many research reactors, including Maria. But most institutions with research reactors don't have the millions of dollars needed to buy the new fuel — or to convert the core to use it. “It's a hell of a lot of work,” says Michael Corradini, a mechanical and nuclear engineer at the University of Wisconsin–Madison, which last year made the switch to the safer fuel.

At Maria, even the most mundane-seeming issues can be a challenge. For example, the cooling water that helps to regulate the fission reaction doesn't circulate as well through the new blended fuel, Krzysztozek says, so

the pumps must be upgraded. Moreover, the core will have to be converted little by little in a laborious operation that will take nearly two years.

FINAL DESTINATION

By dusk, the convoy has reached a railway yard on the outskirts of Warsaw. Shipping containers are stacked around the train, part of an effort to shield the shipment from view during loading. The watchful helicopter peels off as a heavy loader lifts the containers onto flatbed cars. As darkness falls, the train begins to roll towards the Baltic port of Gdynia, some 400 kilometres to the north.

In the end, the promise of ridding the facility of the old fuel helped to convince the Poles to convert Maria to the blended fuel. Like most countries,

Poland has no long-term facility for storing spent nuclear material, and the prospect of US aid to take it back to Russia was simply too tempting to pass up. It is hoped that the expansion of the US repatriation programme, and the development of new fuels for research reactors, will convince many countries to surrender their uranium. Over the next four years, the NNSA hopes to make a similar switch

“MANY OF THESE PLACES HAVE VERY MINIMAL SECURITY.”

over in about ten countries around the world, and to complete most of its work worldwide by 2020.

Right now, the US teams are stretched thin, frantically trying to accelerate the repatriation of fuel. American-supplied fuel will go to the United States, and Soviet material will go to Russia. Meanwhile, scientists at the US Department of Energy's laboratories are close to certifying another kind of even-higher density fuel that will work in reactors that cannot take the current mixtures available.

The biggest problem, says Bunn, is that Russia itself continues to operate 60-odd reactors on bomb-grade material. “They've been very resistant” to changing, he says. The NNSA still hopes to win the Russians over, and says that it already has some six reactors in the country considering conversion.

The next morning finds Bieniawski and the rest of the American team standing on the deck of a Russian cargo ship that has been specially outfitted to carry the fuel. Bieniawski watches the containers being lowered slowly into the hold. “This is the last we'll physically see of it,” he says. He and his team are already mustering for a trip to another reactor site, which holds more fuel that could be fashioned into a weapon. When asked where it is, he demurs: “Let's talk about that later.” ■

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NNSA