How do you leave a warning that lasts as long as nuclear waste?

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In January 1997, the crew of a fishing vessel in the Baltic Sea found something unusual in their nets: a greasy yellowish-brown lump of clay-like material. They pulled it out, placed it on deck and returned to

processing their catch. The next day, the crew fell ill with serious skin burns. Four were hospitalized. The greasy lump was a substance called yperite, better known as sulfur mustard or mustard gas, solidified by the temperature on the sea bed.

At the end of the World War II, the US, British, French and Soviet authorities faced a big problem—how to get rid of some 300,000 tonnes of chemical munitions recovered from occupied Germany. Often, they opted for what seemed the safest, cheapest and easiest method: dumping the stuff out at sea.

Estimates are that at least 40,000 tonnes of chemical munitions were disposed of in the Baltic Sea, not all of it in designated dumping areas. Some of these locations are marked on shipping charts but comprehensive records of exactly what was dumped and where do not exist. This increases the likelihood of trawler crews, and others, coming into contact with this dangerous waste.

The problem isn't going to go away, especially with increased use of the sea floor for economic purposes, including pipelines, sea cables and offshore windfarms.

The story of those unlucky fishermen illustrates two points. First, it is difficult to predict how future generations will behave, what they will value and where they will want to go. Second, creating, maintaining and transmitting records of where waste is dumped will be essential in helping future generations protect themselves from the decisions we make today. Decisions that include how to dispose of some of today's most hazardous material: high-level radioactive waste from nuclear power plants.

The red metal lift takes seven juddering minutes to travel nearly 500 metres down. Down, down through creamy limestone to reach a

160-million-year-old layer of clay. Here, deep beneath the sleepy fields and quiet woods along the border of the Meuse and Haute-Marne departments in north-east France, the French National Radioactive Waste Management Agency (Andra) has built its underground research laboratory.

The laboratory's tunnels are brightly lit but mostly deserted, the air dry and dusty and filled with the hum of a ventilation unit. Blue and grey metal boxes house a series of ongoing experiments—measuring, for example, the corrosion rates of steel, the durability of concrete in contact with the clay. Using this information, Andra wants to build an immense network of tunnels here.

It plans to call this place Cigéo, and to fill it with dangerous radioactive waste. It is designed to be able to hold 80,000 cubic meters of waste.

We are exposed to radiation every day. Public Health England estimates that in a typical year someone in the UK might receive an average dose of 2.7 millisieverts (mSv) from natural and artificial radiation sources. A transatlantic flight, for example, exposes you to 0.08 mSv; a dental X-ray to 0.005 mSv; 100 grams of Brazil nuts to 0.01 mSv.

High-level radioactive waste is different. It is, primarily, spent fuel from nuclear reactors or the residues resulting from reprocessing that fuel. This waste is so potent that it must be isolated from humans until its levels of radiation, which decrease over time, are no longer hazardous. The timescale Andra is looking at is up to one million years. (To put this into some sort of context, it's just 4,500 years ago that Stonehenge was constructed. Around 40,000 years ago, modern humans arrived in northern Europe. A million years ago, the continent was in the middle of an Ice Age. Mammoths roamed the frozen landscape.)

Some scientists call this long-lived waste "the Achilles heel of nuclear

power," and it's a problem for all of us—whatever our stance on nuclear. Even if all the world's nuclear plants were to cease operating tomorrow, we would still have more than 240,000 tonnes of dangerously radioactive material to deal with.

Currently, nuclear waste is stored above ground or near the surface, but within the industry this is not considered an acceptable long-term solution. This kind of storage facility requires active monitoring. As well as regular refurbishment it must be protected from all kinds of hazards, including earthquakes, fires, floods and deliberate attacks by terrorists or enemy powers.

This not only places an unfair financial burden on our descendants, who may no longer even use nuclear power, but also assumes that in the future there will always be people with the knowledge and will to monitor the waste. On a million-year timescale this cannot be guaranteed.

So, after considering a range of options, governments and the nuclear industry have come to the view that deep, geological repositories are the best long-term approach. Building one of these is an enormous task that comes with host of complex safety concerns.

Finland has already begun construction of a geological repository (called Onkalo), and Sweden has begun the licensing process for its site. Andra expects to apply for its construction license within the next two years.

If Cigéo goes into operation it will house both the high-level waste and what is known as intermediate-level long-lived waste—such as reactor components. Once the repository has reached capacity, in perhaps 150 years' time, the access tunnels will be backfilled and sealed up. If all goes according to plan, no one will ever enter the repository again.

Stand in front of an unshielded source of radiation and you won't see or feel anything. However, some of that radiation will be passing into your body. Nuclear waste is dangerous because it emits ionizing radiation in the form of alpha and beta particles and gamma rays. While alpha particles are too weak to penetrate the skin, beta particles can cause burns. If ingested, both can damage internal tissues and organs.

It's gamma rays, however, that have the greatest penetrating range, and therefore the potential to cause the most widespread damage to the DNA of your cells. This damage may lead to an increased risk of cancer later in life, and it is largely responsible for the set of symptoms known as radiation sickness.

Some experts estimate that a dose of over 1 sievert is enough to cause radiation sickness. Symptoms include nausea, vomiting, blisters and ulcers; these may begin within minutes of exposure or be delayed for days. Recovery is possible, but the higher the radiation dose, the less likely it is. Typically, death comes from infections and internal bleeding brought about by the destruction of the bone marrow.

For waste buried deep underground, the major threat to public health comes from water contamination. If radioactive material from the waste were to mix with flowing water, it would be able to move relatively swiftly through the bedrock and into the soil and large bodies of water such as lakes and rivers, finally entering the food chain via plants, fish and other animals.

To prevent this, an underground repository such as Cigéo will take great care to shield the waste it stores. Within its walls there will be metal or concrete containers to block the radiation, and liquid waste can be mixed into a molten glass paste that will harden around it to stop leakage.

Beyond those barriers, the planners choose their sites carefully, so they

can exploit the properties of the surrounding rock. At Cigéo, press officer Mathieu Saint-Louis tells me, the clay is stable and has very low permeability, making it hard for any radioactive material reach the surface. After around 100,000 years a few very mobile substances with a long half-life, such as iodine-129, might manage to migrate upwards in extremely small quantities, but at that point, Saint-Louis says, the "potential impact on humans and the environment is much lower than that of radioactivity that is naturally present in the environment."

Deep geological repositories are designed as passive systems, meaning that once Cigéo is closed, no further maintenance or monitoring is required. Much more difficult to plan for is the risk of human intrusion, whether inadvertent or deliberate.

In 1980, the US Department of Energy created the Human Interference Task Force to investigate the problem of human intrusion into waste repositories. What was the best way to prevent people many thousands of years in the future from entering a repository and either coming into direct contact with the waste or damaging the repository, leading to environmental contamination?

Over the next 15 years a wide variety of experts were involved in this and subsequent projects, including materials scientists, anthropologists, architects, archaeologists, philosophers and semioticians—social scientists who study signs, symbols and their use or interpretation.

Science fiction author Stanislaw Lem suggested growing plants with warning messages about the repository encoded in their DNA. Biologist Françoise Bastide and semiotician Paolo Fabbri developed what they called the "ray cat solution"—cats genetically altered to glow when in the presence of radiation.

Quite apart from the technological challenges and ethical issues these

solutions present, both have one major drawback: to be successful they rely on external, uncontrollable factors. How could the knowledge required to interpret these things be guaranteed to last?

Semiotician Thomas Sebeok recommended the creation of a so-called Atomic Priesthood. Members of the priesthood would preserve information about the waste repositories and hand it on to newly initiated members, ensuring a transfer of knowledge through the generations.

Considered one way, this is not too different from our current system of atomic science, where a senior scientist passes on their knowledge to a Ph.D. candidate. But still, putting such knowledge, and therefore power, into the hands of one small, elite group of people is a high-risk strategy easily open to abuse.

Perhaps a better way to warn our descendants about the waste is to talk to them directly, in the form of a message.

At Andra's headquarters outside of Paris, Jean-Noël Dumont, head of Andra's memory program, shows me a box. Inside, fixed in plastic cases, are two transparent discs, each around 20 centimeters in diameter. "These are the sapphire discs," he says. The brainchild of Dumont's predecessor, Patrick Charton, each disc is made of transparent industrial sapphire, inside which information is engraved using platinum.

Costing around 25,000 euros per disc, the sapphire (chosen for its durability and resistance to weathering and scratching) could last for nearly 2 million years—though one disc already has a crack in it, the result of a clumsy visitor on one of Andra's open days.

In the very long term, though, these plans also have a major drawback: how can we know that anyone living one million years in the future will understand any of the languages spoken today?

Think of the differences between modern and Old English. Who of us can understand "Đunor cymð of hætan & of wætan"? That—meaning "Thunder comes from heat and from moisture"—is a mere thousand years old.

Languages also have a habit of disappearing. Around 4,000 years ago in the Indus Valley in what is now Pakistan and north-west India, for example, people were writing in a script that remains completely indecipherable to modern researchers. In one million years it is unlikely that any language spoken today will still exist.

In the early 1990s, architectural theorist Michael Brill sought a way to side-step the issue of language. He imagined deterrent landscapes, "non-natural, ominous, and repulsive," constructed of giant, menacing earthworks in the shape of jagged lightning bolts or other shapes that "suggest danger to the body... wounding forms, like thorns and spikes."

Anyone venturing further into the complex would then discover a series of standing stones with warning information about the radioactive waste written in seven different languages—but even if these proved unreadable, the landscape itself should act as a warning. To help convey a sense of danger there would be carvings of human faces expressing horror and terror. One idea was to base them on Edvard Munch's The Scream.

The drawback is that such a landscape—a strange, disturbing wonder—would probably attract rather than repel visitors. "We are adventurers. We are drawn to conquer forbidding environments," says Florian Blanquer, a semiotician hired by Andra. "Think about Antarctica, Mount Everest."

Or think about the 20th-century European archaeologists, people not noticeably hesitant when it came to opening up the tombs of Egyptian

kings, despite the warnings and curses inscribed on their walls.

As Dumont sees it, a memory program is necessary for three main reasons. First, to avoid the risk of human intrusion by informing future generations about the existence and contents of Cigéo.

Second, to give future generations as much information as possible to allow them to make their own decisions about the waste. They might, for example, want to retrieve the waste because new uses or solutions have arisen. Gerry Thomas, chair in molecular pathology at Imperial College London, believes that much of the waste destined for repositories may one day provide an important new non-carbon fuel source.

Third, cultural heritage: a properly documented geological repository would provide a wealth of information for a future archaeologist. "I have no knowledge of other places or systems where you have at the same time objects from the past and very large, concrete descriptions of how these products were manufactured, where they come from, how we considered them and so on," says Dumont.

One way that memory is transmitted is orally, from generation to generation. To study this, Dumont asked researchers to consider historical examples of oral transmission, using as a case study the 17th-century Canal du Midi between the Mediterranean and Atlantic Ocean. Here, for 300 years, the same families have worked on maintaining the canal, passing down know-how from father to son.

Dumont also talks about the need to ensure that as many people as possible hear about Cigéo. As part of this strategy, Andra has held a series of annual competitions asking artists to suggest ways to mark the site. For example, Les Nouveaux Voisins, winners of the 2016 prize, imagined constructing 80 concrete pillars, 30 metres high, each with an oak tree planted at the top. As the years passed, the pillars would slowly

sink and the oak trees replace them, leaving tangible traces both above and below the repository.

Leaving Andra's visitors' center, I drive through a landscape patchworked with colors, from the russet of the woods to the bright limey green of a wheat field, towards Bure, a tiny village of around 90 inhabitants. The population is aging.

"Young people can't stay here if they want to study and find jobs," Benoît Jaquet tells me. A village that once supported around ten farmers is now home to only two or three. Although not a resident of Bure, Jaquet is the general secretary of CLIS, an organization of local elected officials, representatives from trade unions and professional bodies, and environmental associations. Its purpose is to provide the local community with information about Cigéo, host public meetings, and monitor the work of Andra by, for example, commissioning independent experts to review the agency's work.

If the repository is built, Jaquet says, French law requires that CLIS be transformed into a local commission that will last as long as the repository. "So it's also a way to pass the baton," he says. "If there is a local commission there is a memory—not Andra's memory but an external memory."

At the same time, Andra has set up three regional memory groups, each composed of around 20 interested locals. They meet every six months and make their own suggestions for passing on the memory of the repository. Ideas so far include collecting and preserving oral witness accounts and developing an annual remembrance ceremony to take place on the site, organized by and for the local people. A nuclear beating the bounds, a radioactive summer solstice, an atomic maypole.

This last idea resonates with the work of Claudio Pescatore and Claire

Mays, former employees of the Nuclear Energy Agency, a Paris-based body that supports intergovernmental cooperation on nuclear issues. They wrote in a research paper: "Do not hide these facilities; do not keep them apart, but make them A PART of the community… something that belongs to the local, social fabric." They went on to suggest that a monument celebrating the repository could be created, and argued that if it had "a distinctiveness and aesthetic quality, would this not be one reason for communities to proudly own the site and maintain it?"

Could the repository, I ask Jaquet, one day become a tourist destination? On the contrary, he says, some members of the CLIS say that "every person living here will quit the district because of the risk, because of the image of the repository as a rubbish bin. Of course some also think the repository will create employment and that this will become a new Silicon Valley. Maybe the reality will be somewhere between the two—but a tourist attraction? I'm not sure about that."

Across the road from CLIS and the town hall is a large, ramshackle stone house decorated with a banner. It translates: "Free zone of Bure: house of resistance against nuclear waste." Since 2004, this has been home to a rotating group of international anti-nuclear, anti-repository protesters. By continually campaigning against Cigéo—and, presumably, by passing their beliefs on to future generations—the protesters would necessarily keep the memory of the repository alive and in the public eye, the ramshackle stone house becoming its own sort of monument for Cigéo.

"So in fact the pro-repository groups need the anti-repository groups to stay alive in order to provide a good memory," says Florian Blanquer. "Fortunately, we are in France—in France there are always opponents to something!"

Rely only on the transmission of knowledge between generations and you can never guarantee an unbroken line of succession. Rely only on

direct communication and you risk leaving behind a message that, even if it survives physically, eventually no one will be able to understand. So Andra asked Blanquer to research how to convey a message without written language.

Many visual signs are, like languages, culturally specific. Furthermore, we know that the meanings of signs are not always stable over time.

Still, Blanquer thought that there was one universal sign: an image of a human figure. "And every human being… apprehends its body through space the same way as well. There is an up and down, a left and right, a front and back," he wrote in a conference paper. Pictographs (pictorial symbols for a word or phrase) based on an anthropomorphic figure in movement are likely to be recognized universally, he decided.

Now he had the beginnings of an idea, but it wasn't enough. You might draw a cartoon strip showing a person approaching a piece of radioactive waste, touching it and falling down. But how can you guarantee that the panels will be read in the correct order? Or that touching the waste will be interpreted as a negative action? And how can a pictograph relying on the visual representation of tangible objects convey a message about radioactivity—something that can be neither seen nor touched?

In response to these problems, Blanquer has designed what he calls a "praxeological device." Independent of any verbal language, it works by teaching the person encountering it a brand-new communication system created specially for this purpose.

Blanquer envisages a series of passages built underground, perhaps in the access tunnels of the repository. On the wall of the first passage is a rectangular pictograph showing a person walking along the passage and a line of footprints indicating the direction of movement.

At the end of the corridor is a hole and a ladder and three more pictographs. A circular pictograph shows a person holding on to the ladder; a triangular pictograph shows a person not holding on and consequently falling off. And so it continues.

In this way you begin to establish patterns: you learn first that the figure drawn on the walls relates to a person's actions here, and second that you should copy the actions in the circles and avoid the actions in the triangles. "What is really interesting is the idea of people learning by themselves," Dumont says. "Learning is important in the long term when you cannot just rely on transmission from generation to generation."

There has been one more radical proposal about how to deal with the threat of human intrusion—hide the repository completely from future generations.

Some argue that because the repositories are passive systems, most likely buried far underground in areas with no deep natural resources, the question of memory preservation is moot.

Currently, no one can conceive of a reason why anyone in the future might want to dig down 490 meters to reach the clay formation that Cigéo is planned for. This reduces the chances of inadvertent intrusion. And after around, say, 100,000 years, almost all surface traces and any complex above-ground markers will have vanished. The only things left behind will be some slight indentations, perhaps a gentle protuberance or two. Things that to the untrained eye may appear to be only the natural shape of the land. Eventually it will be as though no one was ever there, as though there is nothing for anyone to remember.

But Blanquer warns that forgetting is not so easy: "You cannot say to yourself, "I will forget about that." It's like trying not to think about pink elephants. If you want to forget about it then first you have to get rid of

any information about it. That would mean shutting down the web and destroying a lot of computers, a lot of newspapers, a lot of books."

In his opinion it is no longer possible that Cigéo could become, as Danish film maker Michael Madsen has said about the Finnish repository, "the place you must always remember to forget."

Last summer I set out with some friends to walk part of the Ridgeway, an ancient long-distance route through the Chiltern Hills and North Wessex Downs in the south of England. On Whiteleaf Hill, the chalky white path passes near the remains of a Neolithic barrow, around 5,000 years old. You can tell immediately that it's not natural, the way the earth has been lumped up on the hillside, but today there is little to see except a low grassy mound with a view over the fields and woods of Buckinghamshire and the small town of Princes Risborough.

We don't know who built the burial chamber or the name of the person interred there, what language they spoke and what they believed the world would be like in 5,000 years. Staring at the barrow, it was not continuity with the past I felt, but distance.

In the 1930s an archaeologist called Lindsay Scott broke open the Whiteleaf Hill barrow and discovered the remains of a human skeleton, around 60 pieces of pottery, flint shards and animal bones. And just as we enter burial chambers in search of answers, so archaeologists of the future may one day find themselves penetrating the concrete passageways and tunnels of the place we call Cigéo.

Peering into the darkness they will ask themselves, who built this place and why? Why did they come here, digging down so far below the surface of the land? What were they running from, or trying to hide?

In the light they carry, the archaeologists will see markings on the

passage walls. Moving closer, they make out a series of footprints stretching away in front of them, down the passageway. In the looming darkness, it becomes clear—someone has left them a message.

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