per kilogram; fish could carry 10,000–100,000 becquerels per kilogram; and algae, some of which are particularly susceptible to iodine uptake, could contain up to 100 million becquerels per kilogram. Japan has legal limits of radioactivity in fish for human consumption of 500 becquerels per kilogram for caesium-137, and 2,000 becquerels per kilogram for iodine-131.

"Doses will decrease very quickly with time and distance from the facility, if no further leaks occur, but there could remain a persistent low-dose component in the local marine environment for many years," says Thomas Hinton, deputy director of the IRSN's Laboratory of Radioecology, Ecotoxicology and Environmental Modelling in Cadarache, France. "The impacts are best addressed through an international long-term assessment."

Ward Whicker, an environmental and radiological health expert at Colorado State University in Fort Collins, agrees that a survey would be worthwhile. "It would require a great deal of sampling effort, near the discharge point as well as at locations farther away," he says. "Concentrations of radionuclides in water, sediments, plankton, molluscs, crustaceans, seaweed and fish would need to be measured, and the health of the ecosystem monitored."

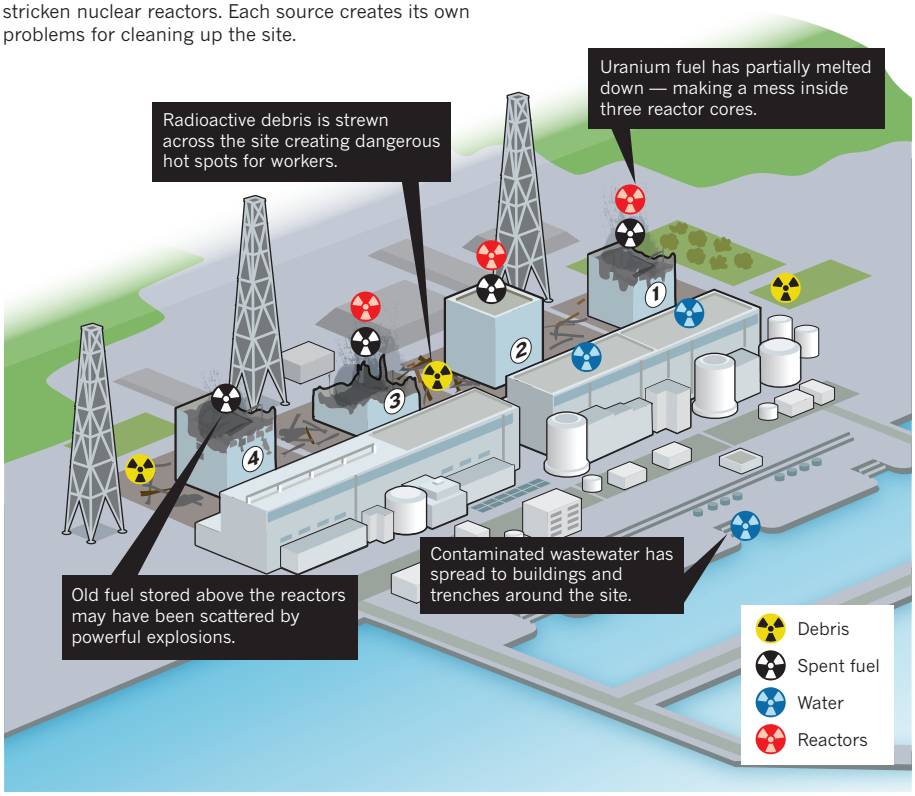
Although radioisotope concentrations in fish, shellfish and seaweed could exceed limits for human consumption for weeks, Whicker thinks that it is unlikely that scientists would be able to detect any genetic effects on marine life. Any affected creatures would probably disperse into the Pacific, or die more quickly, he says. Moreover, teasing out radiological effects from other stresses, such as conventional water pollution and the damage caused by the tsunami, would be extremely difficult.

An alternative approach could be to focus on a suitable proxy species. "In my opinion, brown seaweed should be the number one research priority," says Bruno Fievet, a radioecologist at the IRNS in Cherbourg. The brown seaweed *Laminaria digitata*, ubiquitous in the coastal Pacific waters off Japan, absorbs iodine to help defend itself against environmental stresses such as pollution. It can have iodine concentrations some 10,000 times greater than the surrounding sea water. "This species is the world champion in iodine uptake, and it would be a good indicator of the radioactive labelling of other marine organisms," says Fievet.

But sampling may be hampered by the danger that remains at the Fukushima plant. "Any survey would be welcome," says Ulf Riebesell, a biological oceanographer at the Leibniz Institute of Marine Sciences in Kiel, Germany. "But I certainly wouldn't ask my students to do field work off Japan amid this ongoing crisis." ■

FUKUSHIMA'S RADIOACTIVE WRECKAGE

Radioactive contamination takes many forms at Japan's stricken nuclear reactors. Each source creates its own problems for cleaning up the site.



NUCLEAR ACCIDENT

Fukushima set for epic clean-up

Latest data suggest a Chernobyl-like effort will be needed.

BY GEOFF BRUMFIEL

As the immediate threat from Fukushima Daiichi's damaged nuclear reactors recedes, engineers and scientists are facing up to a clean-up process that could last for many decades, or even a century.

Experts on previous nuclear accidents say that the sheer quantity of nuclear material that needs to be removed from the site, together with the extent of the damage, makes Fukushima a unique challenge. The plant's damaged reactors are home to just under 1,000 tonnes of nuclear fuel and thousands of tonnes of radioactive water (see graphic).

Last week, the Toshiba Corporation floated a rough proposal to clean up the site in a decade. But veterans of clean-up operations at sites such as Three Mile Island in Pennsylvania say that it will probably take much longer. The removal of the radioactive material will require a carefully planned and technologically sophisticated programme, made all the more challenging by the devastation left after partial core meltdowns and explosions.

No clean-up can begin until the reactors are stabilized. Radiation around the plant is beginning to wane, but the threat of further releases has not yet passed. On 7 and 11 April, severe aftershocks struck nearby, raising fears that the three crippled reactors could be damaged further. The Tokyo Electric Power Company (TEPCO), which manages the plant, says that no additional damage has been detected.

A 26 March report from the US Nuclear Regulatory Commission (NRC), leaked to *The New York Times*, says that massive explosions at the plant in March scattered fuel from the reactors' spent-fuel pools around the site. NRC officials also believe that a portion of the uranium fuel inside the unit 2 reactor may have escaped its stainless steel containment

vessel and fallen onto the concrete floor below, although the Japanese government has yet to confirm this. In addition, the document indicates that water is not circulating properly through the cores of the damaged reactors, so it will be necessary to continue to flood them, says Richard Lahey, an emeritus professor of nuclear engineering at Rensselaer Polytechnic Institute in Troy, New York.

This strategy creates its own problems. The reactors' cooling systems are normally a closed circuit. Flooding the cores means that water contaminated with radioisotopes will continue to spill out into the environment. TEPCO has already reported highly radioactive water in buildings and trenches around the site.

Dealing with the water will be a pressing priority for any clean-up operation, according to Jack DeVine, an independent nuclear consultant who spent six years dismantling the unit 2 reactor at Three Mile Island after it partially melted down in 1979. The accident left thousands of tonnes of water laced with radioactive caesium-137 swilling around in the reactor's basement. Over the course of months, the US team built a system that could suck the water out and pass it through radiation-resistant zeolite filters. The zeolite removed the caesium and other radioisotopes, leaving almost pristine water, which was eventually evaporated at a facility on the site. A similar system could work at Fukushima, says DeVine, although the constant leakage from the damaged cores means that any clean-up is a race against time. More than 10,000 tonnes of low-level radioactive water has already had to be dumped from storage tanks into the Pacific Ocean to make way for more-radioactive cooling water (see page 145).

Cleaning up the reactors themselves presents an even greater challenge. Debris and high radiation levels are making it impossible to conduct proper surveys of the damage. In the near term, robots will need to explore the reactor buildings and map the radiation inside, says Red Whittaker, a robotics expert at Carnegie Mellon University in Pittsburgh, Pennsylvania, who has developed systems for other nuclear accidents.

It could be years before anyone can look inside the cores themselves. At Three Mile Island, engineers had to wait three years before radiation levels had fallen sufficiently to allow them to lower a camera through a control rod drive shaft into the heart of the reactor. At Fukushima, it could take longer still. The boiling water reactor (BWR) design used there is sealed with a solid stainless-steel cap that can only be removed by a heavy, fuel-loading crane located above the reactor. Explosions at three of the units with fuel in their cores mean that "their cranes are clearly toast", says DeVine. Plant operators will have to find another way in.

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The reactor's design also presents other problems. "The BWR is just a rat's nest of tight spaces, pipes and valves," says DeVine. To effectively remove the fuel, DeVine thinks that one or more new buildings with dedicated cranes must be built around each reactor. "It's not something that will be up in a month or two," he says. Whittaker adds that robots and humans will need to share the work in a methodical, coordinated way. "The nature of these operations is that they are patient and persistent," he says.

Indeed, the effort required seems likely to be more akin to the clean-up strategy at Chernobyl in the Ukraine than that of Three Mile Island. Engineers at Chernobyl are beginning to lay the foundations for a massive €1-billion (US$1.4-billion) enclosure, complete with automated cranes, that will eventually lift apart the sarcophagus of steel and concrete hastily thrown up around the stricken unit 4 reactor in the months after it exploded in 1986. The new building, which is intended to last a century, was agreed in principle in 2001, but will not be completed until at least 2015. Clean-up of the site is scheduled to last until 2065 — almost 80 years after the accident.

"Bottling it up and leaving it seems to me to be a really bad choice."

TEPCO almost certainly cannot afford a clean-up on this scale. "I think that, ultimately, the government is going to have to pay for it," says Robert Alvarez at the Institute for Policy Studies in Washington DC, who oversaw clean-up of former US nuclear weapons plants during the administration of President Bill Clinton. The government already seems to be mulling whether to take over the utility, shares in which have plunged since the accident.

Given the complexity of the task ahead, some think it may be better to abandon Fukushima entirely — at least for the time being. "My bet would be: you seal it and wait a hundred years," says Alan Johnson, a retired reactor physicist who was head of Britain's Sellafield nuclear processing site in the late 1980s.

Sellafield, once known as Windscale, was in 1957 the site of the United Kingdom's worst nuclear accident, when a reactor's graphite core caught fire. Final decommissioning of the reactor is still at least 20 years away, but the hiatus has allowed radioactive materials to decay and given engineers time to develop the best clean-up strategies possible. "What's the rush in doing it quicker?" asks Johnson.

But natural disasters are rare in England. Given the threat of major earthquakes, tsunamis and typhoons that could strike Japan in the decades to come, DeVine has his doubts about applying the same strategy. "Bottling it up and leaving it seems to me to be a really bad choice," he says. ■