receptor with which they form a heterodimer, but data are currently lacking.

Lotus and medicago have a narrow rhizobial host range, which, at least in part, can be explained by the occurrence of specific ligand recognition motifs in LjNFR1 and MtLYK3. However, several legumes are more promiscuous and can establish root nodules with a wide range of rhizobium species that produce Nod factors with different structures. It should be feasible to model the corresponding Nod factor receptors and identify the structural characteristics of such promiscuity.

An important issue is the evolutionary origin of Nod factor perception in nodulation. Nodulation is not specific to legumes, but occurs in 10 plant lineages in four taxonomic orders. It has been proposed that nodulation has a single evolutionary origin (~110 million years ago), driven by an acylated CO-producing, nitrogen-fixing *Frankia* bacterium (*14*). Among nodulating nonlegumes, *Parasponia* (Cannabaceae) is the only lineage that is nodulated by Nod factor–producing rhizobia, and the corresponding receptors have recently been identified (*13*). Notably, *Parasponia* did not experience a duplication of the *CERK* gene. Instead, a single LysM-type receptor fulfills multiple functions, including CO-induced innate immunity, AM symbiosis, and rhizobium Nod factor–induced nodulation (*13*). These observations suggest that the ancestral gene from which the legume Nod factor receptors evolved already encoded a LysM-type receptor that could perceive COs as well as acylated COs. In legumes, the duplication of this gene may have allowed the evolution of highly specific Nod factor receptors. Subsequent coevolution of Nod factor structure and the receptor ligand–binding site could have resulted in host specificity through a key-lock system, which is considered an important driver in the evolution of efficient symbiotic systems (*2*). ■

REFERENCES AND NOTES

1. C. Zipfel, G. E. D. Oldroyd, *Nature* **543**, 328 (2017).
2. P. Remigi, J. Zhu, J. P. W. Young, C. Masson-Boivin, *Trends Microbiol.* **24**, 63 (2016).
3. Z. Bozsoki *et al.*, *Science* **369**, 663 (2020).
4. F. Maillet *et al.*, *Nature* **469**, 58 (2011).
5. A. Genre *et al.*, *New Phytol.* **198**, 190 (2013).
6. P. Lerouge *et al.*, *Nature* **344**, 781 (1990).
7. T. V. Nguyen *et al.*, *BMC Genomics* **17**, 796 (2016).
8. K. R. Cope *et al.*, *Plant Cell* **31**, 2386 (2019).
9. S. De Mita, A. Streng, T. Bisseling, R. Geurts, *New Phytol.* **201**, 961 (2014).
10. Z. Bozsoki *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **114**, E8118 (2017).
11. C. Gibelin-Viala *et al.*, *New Phytol.* **223**, 1516 (2019).
12. F. Feng *et al.*, *Nat. Commun.* **10**, 5047 (2019).
13. L. Rutten *et al.*, *Plant Physiol.* 10.1104/pp.19.01420 (2020),
14. R. van Velzen, J. J. Doyle, R. Geurts, *Trends Plant Sci.* **24**, 49 (2019).

10.1126/science.abd3857

NUCLEAR WASTE

Opening the floodgates at Fukushima

Tritium is not the only radioisotope of concern for stored contaminated water

By **Ken O. Buesseler**

In the time since Japan's triple earthquake, tsunami, and nuclear disaster in 2011, much has improved in the ocean offshore from the Fukushima Daiichi Nuclear Power Plant (FDNPP). Concentrations of cesium isotopes, some of the most abundant and long-lived contaminants released, are hundreds of thousands of times lower than at their peak in April 2011. Since mid-2015, none of the fish caught nearby exceed Japan's strict limit for cesium of 100 Bq/kg (*1*, *2*). Yet, enormous challenges remain in decommissioning the reactors and clean-up on land. Small, and sometimes unexpected, sources of contaminants still continue to enter the ocean to this day (*3*). Two of the biggest unresolved issues are what to do with the more than 1000 tanks at the site that contain contaminated water and the impact of releasing more than 1 million tons of this water into the ocean.

The tank water is a combination of recovered groundwater and deliberately injected cooling waters, both of which became contaminated when interacting with the highly radioactive nuclear reactor cores. From the first months after the earthquake and tsunami, these waters were contained in tanks to prevent further radioisotope releases and remediated by using several systems, most notably the Advanced Liquid Processing System (ALPS). ALPS was designed to efficiently remove more than 62 different contaminants. The installation in an ice dam and other groundwater barriers, as well as the diversion of groundwater flow around the site, also assisted in reducing the daily accumulation of water from more than 400 to less than 200 metric tons per day.

Despite this effort, no decontamination system can remove 100% of all radioactive contaminants. Tritium, ^{3}H, is notoriously difficult to remove because it is a radioactive form of hydrogen that is part of the water molecule itself. Fortunately, tritium is relatively harmless because it emits a low-energy β particle that does little damage to living cells. As a result, tritium has the lowest dose coefficient for those radioactive isotopes reported in the tanks (*4*) and higher allowable release limits (see the table). These properties do not detract from the potential for large amounts of tritium to have harmful effects, and debates remain about the potential health effects.

The total amount of tritium contained in the tanks also matters, which is reported to be around 1 PBq (PBq = 10^{15} Bq) (*5*). That total is far less than the 8000 PBq of tritium still remaining from global atmospheric nuclear testing in the 1960s or the 2000 PBq from natural interactions between cosmogenic particles and nitrogen that form tritium in the atmosphere. In addition, all nuclear power facilities emit tritium that, depending on plant design, can be several PBq per year, or even higher, as in the case of nuclear fuel reprocessing plans such as at Cap de La Hague (*6*).

However, this story is not only about tritium but what else is in the tanks. It was not until mid-2018 when TEPCO, the operator at FDNPP, released data detailing the

Release limits and risk

Different isotopes pose different environmental and health challenges.

ISOTOPE	MAX RELEASE (BQ/LITER)[1]	FOOD LIMIT (BQ/KG)[2]	HALF-LIFE (YEARS)[3]
^{3}H	60,000	10,000	12.35
^{14}C	2000	10,000	5730
^{99}Tc	1000	10,000	211,000
^{125}Sb	800	1000	2.77
^{60}Co	200	1000	5.27
^{106}Ru	100	100	1.01
^{137}Cs	90	100	30.0
^{134}Cs	60	100	2.06
^{90}Sr	30	100	29.1
^{129}I	9	100	16,000,000

[1]Maximum levels allowed in Japan for waters released from nuclear reactor operations. [2]Limits allowed for food safety (CODEX standard based upon adult consumer and annual consumption limit). [3]Half-life is a physical property indicating the time it takes for 50% of an isotope to decay. A shorter value means a quicker loss.

Woods Hole Oceanographic Institution, Woods Hole, MA, USA. Email: kbuesseler@whoi.edu

Corrected 7 August 2020. See full text.

amounts of more dangerous isotopes, such as ruthenium-106, cobalt-60, and strontium-90 (*7*). The concentrations of these radioactive isotopes are orders of magnitude lower than tritium but highly variable from tank to tank (see the figure). By TEPCO's own assessments, more than 70% of the tanks would need secondary treatment to reduce concentrations below that required by law for their release (*7*).

However, there are other important factors to consider. These radioactive isotopes behave differently than tritium in the ocean and are more readily incorporated into marine biota or seafloor sediments (see the figure). For example, the biological concentration factors in fish are up to 50,000 higher for carbon-14 than tritium (*8*). Also, isotopes such as cobalt-60 are up to 300,000 times more likely to end up associated with seafloor sediments (*8*). As a result, models of the behavior of tritium in the ocean, with tritium's rapid dispersion and dilution, cannot be used to assess the fate of these other potential contaminants.

To assess the consequences of the tank releases, a full accounting after any secondary treatments of what isotopes are left in each tank is needed. This includes the volume, not just for the nine isotopes currently reported but for a larger suite of possible contaminants, such as plutonium. Plutonium may be present in FDNPP cooling waters but was not released in large amounts to the atmosphere in 2011.

The public has been told that there are few options other than ocean discharge. However, given the short half-lives of the isotopes known in the tanks, time would help. With a 12.3-year half-life, in 60 years, 97% of all of the tritium would decay, along with several of the other shorter lived isotopes. In those intervening years of cleanup on site, about four times the current volume would be generated. The risk of tank leaks—even if stored in earthquake-resistant tanks, similar to what Japan already does for petroleum or liquefied natural gas—needs to be weighed against the greatly reduced amount of radioactivity after decay. The lack of space, the reason for the urgency in ocean release, could be alleviated if tanks were stored just outside the boundaries of the current FDNPP.

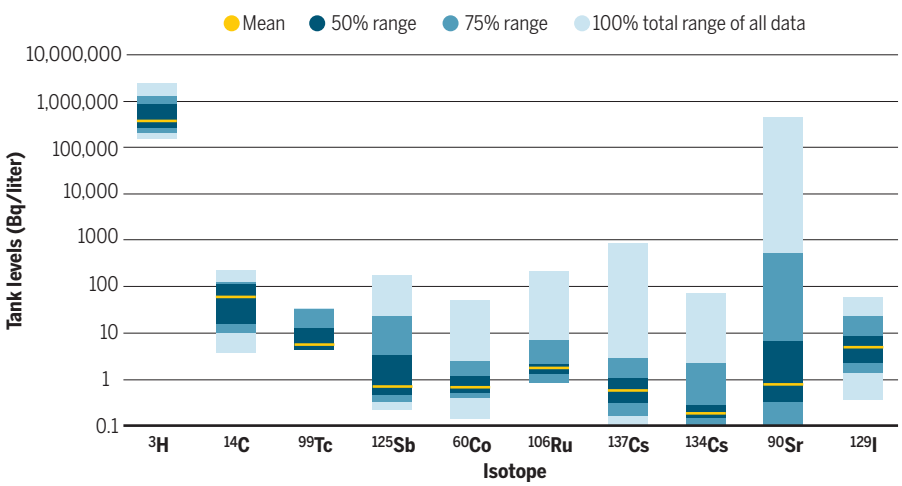
Last, public fears should not be dismissed because these decisions may have negative impacts on local fisheries that are just now rebuilding. Making data available is a good start (*9*) but not enough. Seafood and ocean monitoring should continue to involve local fisherman, and studies that involve public participation in sampling would be an effective tool to improve public education and build confidence in the results (*10*).

The current focus on tritium in the wastewater holding tanks ignores the other radioactive isotopes but presents a solvable issue. A solution includes reducing the concentrations of non-tritium contaminants, reporting after secondary treatment independently verifies concentrations for all contaminants in each tank, and reconsidering other storage options. If there is a release, supporting independent ocean study of multiple contaminants in seawater, marine biota, and seafloor sediments should occur before, during, and after. Although the operators have promised some of this, actions will matter more than words. What needs to be added to the discussion is that the non-tritium isotopes in those tanks have vastly different toxicities and fates in the ocean. ■

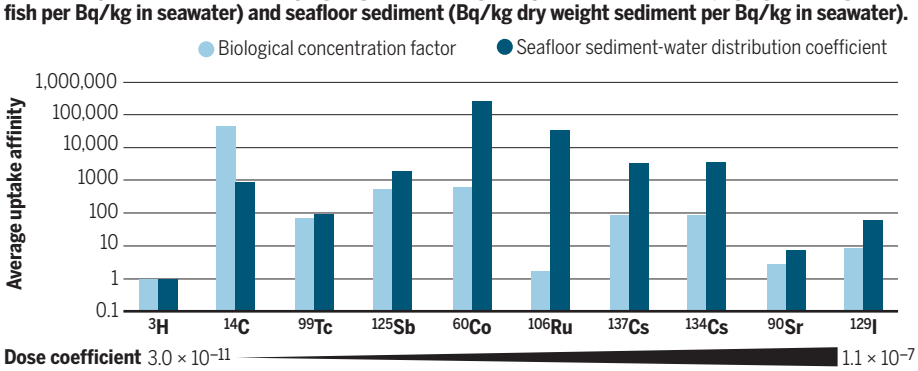
Sorting out what is in the tanks

One legacy of the Fukushima Daiichi nuclear disaster after the 2011 Tohoku-oki earthquake and tsunami is the accumulation of water with a variety of radioisotopes in tanks. Assessing the risk of discharging water from these tanks back into the ocean requires knowing radioisotope amounts and their ability to concentrate in seafloor sediments and biological tissues.

Radioisotope concentration ranges for more than 200 tanks reported on 31 Dec 2019 by TEPCO (*9*) organized by their effective dose (dose coefficient).



Radioisotopes concentrate to varying degrees in biological systems such as fish (Bq/kg wet weight fish per Bq/kg in seawater) and seafloor sediment (Bq/kg dry weight sediment per Bq/kg in seawater).



GRAPHIC: N. CARY/*SCIENCE*

REFERENCES AND NOTES

1. K. Buesseler *et al.*, *Annu. Rev. Mar. Sci.* **9**, 173 (2017).
2. Radioactivity levels are measured in becquerels (Bq) per unit volume or mass, with 1 Bq = one decay event per second.
3. V. Sanial, K. O. Buesseler, M. A. Charette, S. Nagao, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11092 (2017).
4. International Commission on Radiological Protection (ICRP) publication 119, "Compendium of dose coefficients based upon ICRP publication 60" (ICRP, 2010).
5. TEPCO, Draft study responding to the subcommittee report on handling ALPS treated water, 24 March 2020.
6. P.-E. Oms *et al.*, *Sci. Total Environ.* **656**, 1289 (2019).
7. T. E. P. C. O. Treated Water Portal Site, www4.tepco.co.jp/en/decommission/progress/watertreatment/index-e.html.
8. International Atomic Energy Agency (IAEA), Technical report series No. 422, "Sediment distribution coefficients and concentration factors for biota in the marine environment" (IAEA, 2004).
9. TEPCO, "Radiation concentration estimates for each tank area (as of March 31, 2020)" (TEPCO 31 December 2019); https://www4.tepco.co.jp/en/sp/decommission/progress/watertreatment/images/tankarea_en.pdf.
10. Our Radioactive Ocean, www.ourradioactiveocean.org.

ACKNOWLEDGMENTS

This work was supported by the Deerbrook Charitable Trust and the Center for Marine and Environmental Radioactivity. Writing assistance by K. Kostel is also appreciated.

10.1126/science.abc1507

Opening the floodgates at Fukushima

Ken O. Buesseler

Science **369** (6504), 621-622.
DOI: 10.1126/science.abc1507