

its chances of getting funding. Sharing data is a sticking point, says Sesana. "When you share, you open the database of interesting physics to everybody. You might have students working on projects on specific pulsars, and you want to protect your students." Still, with scientists circulating among the projects and closer collaborations in the works for future facilities, says Verbiest, "the pulsar timing arrays are slowly growing to accept a more global approach."

Uncharted territory

The primary targets of the pulsar timing arrays are supermassive black hole binaries. "We think they form when galaxies merge," Sesana says. "We have circum-

stantial evidence and predictions, but the way to nail them and to understand them is by observing their gravitational waves." Scientists hope to learn how frequently they form, how many they are, how they evolve, and more.

The pulsar timing array experiments may also detect "exotic" sources such as erratic gravitational waves from when the universe was undergoing inflation and from superstrings—topological defects in the universe with huge concentrations of energy that could shake up spacetime with relativistic oscillations. In any case, Sesana says, "By looking at longer wavelengths than have previously been probed, we will unveil completely different phenomena."

Many in the community expect that the first detection won't be from a single event but from the stochastic background created by thousands of black hole mergers. "It would look like a long-period rumble," says McLaughlin.

The collaborations have not yet plucked a gravitational wave from their data. "But even nondetections place stringent constraints on the theory," says Verbiest. "The data have already been useful." There are a host of sources that might be detectable, he says. "The difficulty is that we don't know what to expect. We have to be careful as we get sensitive to things we are not aware of. We are probing uncharted territory."

Toni Feder

Cleanup of Cold War nuclear waste drags on

Despite billions of dollars spent preparing to treat and stabilize liquid radioactive wastes, cleaning out leaking tanks at the former nuclear production site in Hanford, Washington, will take decades more.

A quarter century after US nuclear weapons production ceased and cleanup of the sprawling Cold War weapons complex began, the US Department of Energy has achieved some notable successes. The Rocky Flats Plant in Colorado, for example, where plutonium pits for tens of thousands of nuclear weapons were manufactured, has been restored as a wildlife refuge. (See the article by David Clark, David Janecky, and Leonard Lane, *PHYSICS TODAY*, September 2006, page 34.) But stabilizing and safely disposing of the tens of millions of gallons of highly radioactive and toxic liquid wastes produced in making that plutonium remains a distant goal.

Although two DOE installations with liquid wastes have turned some of them into stable solids, the one with the largest inventory, the Hanford site in Washington State, has yet to treat any of the 212 million liters stored in its 177 underground tanks, some of which are about 16 kilometers from the Columbia River. Some of the waste dates to the 1950s, and leaks from at least 62 tanks have dumped an estimated 3.8 million liters into the soil.

Since the Hanford cleanup effort began in the early 1990s, DOE has spent

\$19 billion on several waste-treatment strategies, according to the Government Accountability Office (GAO). The target date for processing and disposing of all the waste by pouring it into canisters and converting it to a glassified state is now set for 2047, more than a century after the Fat Man bomb was dropped on Nagasaki. But even that timetable isn't definitive, since DOE has yet to specify how more than half the waste will be treated and disposed of.

Designed to turn the waste into glass logs—a process known as vitrification (see the article by Ian Pegg, *PHYSICS TODAY*, February 2015, page 33)—Hanford's waste treatment plant (WTP) has been under construction since 2002. It was originally planned as a pilot plant to process 10% of the waste, and was estimated to cost \$4.3 billion. DOE later decided to expand the project into a full-scale facility, and its cost to treat only a fraction of the waste has now ballooned to nearly \$17 billion.

At the WTP, the tank waste is to be separated into a high-level waste (HLW) stream, roughly 10% of the tank volume containing more than 90% of the radioactivity; the remaining volume will be low-activity waste (LAW). A pretreat-

ment plant will remove soluble fission products and return them to the tanks for treatment as HLW. Each waste stream will be mixed with borosilicate material to form a molten glass, which will be poured into stainless steel canisters. The HLW will be stored in an onsite vault for eventual disposal at a nuclear waste repository that doesn't yet exist. The LAW canisters will be permanently stored at Hanford.

Under a 2012 court order that was amended just last year, DOE must begin vitrifying LAW by the end of 2023. But the order doesn't require HLW glass-log production to begin until 2036.

Under pressure to meet the 2023 deadline, DOE elected in 2015 to build yet another WTP component that will bypass the main pretreatment facility for 76 million liters of LAW, filter out the solids and cesium-137, and feed the treated material to the vitrification plant. Completion is set for 2021. The current WTP cost estimate of \$16.8 billion includes construction of the new facility and the LAW vitrification plant, plus the work that has been done so far on the pretreatment and HLW vitrification plants. It does not include completion of the pretreatment and HLW facilities, and

THE HANFORD WASTE TREATMENT PLANT, shown in this aerial view taken in January, is designed to turn liquid radioactive wastes from 177 underground tanks into a glass material for safe long-term disposal. The plant is due to begin operating in 2023.



DOE has not provided a cost estimate for the entire WTP.

A different approach

As the Hanford cleanup languishes, the Savannah River Site (SRS), DOE's other major Cold War plutonium production facility, has been vitrifying HLW since 1996. The sprawling South Carolina installation has 140 million liters of waste kept in 51 tanks. Tom Clements, director of SRS Watch, the site's citizen watchdog group, notes that the site's wastes contain more total curies of radioactivity than Hanford's. But the SRS has already filled about 4000 2-m-tall, 61-cm-diameter stainless steel canisters with vitrified HLW at its Defense Waste Processing Facility. That's about halfway toward emptying the tanks, which DOE has agreed to do by 2028. Unlike at Hanford, new reprocessing wastes being added to the SRS tanks are delaying the cleanout, says Clements.

The South Carolina site has been pretreating the wastes to separate cesium and transuranics, which are then combined with HLW for vitrification. But instead of vitrifying the LAW, the SRS mixes it with cement, ash, and furnace slag to form a grout, called saltstone.

About 15 million liters of saltstone has been poured into above-ground cylindrical vaults to solidify. The newest vault will hold 113 million liters—10 times the capacity of each of the existing five tanks.

A new salt waste processing facility has been built at the South Carolina site to accelerate the cesium and transuranic removal process, which has been slowing the rate of saltstone production. The new facility is due to come on line in 2018.

Some experts and DOE blame the Hanford delays on the more complex and heterogeneous contents of its tanks, some of which still haven't been adequately characterized. Savannah River used one chemical process throughout. But several different chemical processes were used to separate plutonium over Hanford's production lifetime, says Arjun Makhijani, president of the Institute for Energy and Environmental Research, an environmental think tank in Takoma Park, Maryland. At Hanford, "wastes were transferred from tank to tank, and wastes of different chemistries and consistencies started getting mixed up and reacting," Makhijani says. "Eventually you had a whole set of problems: The consistency of the waste ranged

from cement-like to peanut-butter-like to liquid."

According to David Trimble of the GAO, there is more to the story. An expert panel the GAO convened a year ago noted that waste complexity alone does not explain the situation. He said that similar heterogeneous wastes have been vitrified at other reprocessing plants, including the UK's Sellafield facility. A Hanford spokesperson disagrees, saying the wastes are far more complex than Sellafield's.

Trimble says the current approach taken at Hanford is rooted in the cleanup agreement DOE negotiated with Washington State. The state contended that glass would permanently immobilize the wastes, so it insisted DOE vitrify both LAW and HLW. South Carolina, wanting to get the job done before tanks leaked into groundwater, elected to accept grout as a treatment solution for LAW.

In the 1990s DOE pursued an approach in which the contractor would bear the cost of building a vitrification plant and charge the agency a fixed price per canister of waste. But the complexity and uncertainties associated with the wastes led DOE to abandon that approach. Instead, DOE instructed the

current contractor, Bechtel National, to begin constructing the full-scale plant before the design was complete and before all systems had been fully qualified. The contractor, says Trimble, has been "building systems on top of systems and having to go back after realizing the system furthest upstream is inherently flawed." As a result, major reworks have been needed, he says. But Bechtel spokesperson Fred deSousa says no major reworks have been required.

DOE declined to make an official available for an interview for this article. In written responses, a spokesperson from the Environmental Management Office said that DOE halted work on the WTP's pretreatment and high-level vitrification components in 2012 due to unresolved technical issues. Since then, Environmental Management has focused on getting LAW vitrified as early as 2022.

Ensuring the safe operation of the waste pretreatment process has been the primary technical challenge at Hanford, according to a May report by the GAO. The Defense Nuclear Facilities Safety Board, an agency that audits safety at DOE nuclear facilities, warned in 2010 of the potential that a mixing vessel could explode from the buildup of waste-generated hydrogen. The board further warned that plutonium particles could settle in the vessels and cause a runaway chain reaction. Further complicating matters, the vessels were built to be "black"—sealed shut before operations begin, with no maintenance or repair possible throughout the plant's lifetime.

In January DOE told the safety board



THE DEFENSE WASTE PROCESSING FACILITY at the Department of Energy's Savannah River Site has filled around 4000 of these stainless steel canisters with solidified high-level radioactive wastes from underground tanks for permanent storage.

DOE SAVANNAH RIVER SITE (CC BY 2.0)

that sufficient progress had been made in addressing the safety concerns to allow resumption of some design activities that were suspended in 2012. In its written responses to PHYSICS TODAY, DOE said three of eight pretreatment issues have been resolved, a fourth is close to resolution, and "significant progress" has been made on the others.

DOE said that the declining number of US firms capable of providing parts and equipment that can meet nuclear quality control standards has also contributed to delays, as did reconfiguring the WTP design to incorporate changes made in the mid 2000s to seismic protection criteria.

In 2014 a review team of 37 experts



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identified hundreds of significant design vulnerabilities at the LAW vitrification facility. Their findings, detailed in a leaked DOE report, ranked dozens of the vulnerabilities as of high concern, meaning they have a cost impact of \$50 million to \$100 million and potential schedule delay of 6–12 months. Some of them, the team said, “could potentially extend to [personnel] safety and health, secondary waste handling, and operations and maintenance, if action is not taken.” Bechtel disputed many of the review team’s findings, and deSousa says that 338 of the 362 vulnerabilities have been resolved to DOE’s satisfaction. The DOE site office ultimately released a report with 10 recommendations covering ventilation, maintenance, fire safety, control system software, and other issues; it concluded that all the issues were manageable.

But the GAO has advised DOE to suspend work. “We have said several times that the design-build approach being used at Hanford is part of the problem and DOE needs to apply its recent project management reforms to make sure you don’t pour any more concrete or bend any more steel without knowing whether your designs are 100%,” Trimble says.

Tom Carpenter, executive director of Hanford Challenge, a watchdog organization, claims the WTP flaws are so severe that the project should be scrapped and done over from scratch. Even if completed, the plant will be unlikely to pass an operational readiness review, the DOE equivalent of Nuclear Regulatory Commission licensing, he says, because nuclear quality assurance and quality control protocols weren’t followed during construction. He points to a False Claims Act lawsuit alleging that Bechtel and its subcontractor AECOM billed DOE for materials, services, and testing that failed to meet quality standards. The suit also alleged that Bechtel illegally used federal funds to lobby for continued funding for the WTP. Bechtel and AECOM last year agreed to pay \$125 million to the federal government to settle the suit. Bechtel and AECOM admitted no wrongdoing and the companies continue to manage the project.

Should the WTP problems be resolved, the facility will be capable of treating only 40% of Hanford’s LAW. In its response to PHYSICS TODAY, DOE sim-

ply acknowledged that it hasn’t decided what to do with the remainder. According to a May GAO report, 21 experts convened by the National Academies of Sciences, Engineering, and Medicine said grout will effectively treat the LAW. The panel members said recent research had shown grout will perform better at immobilizing the waste than was assumed when the vitrification decision was made.

But Washington State officials have continued to insist that all the wastes be vitrified. Doing so would be enormously costly: The GAO calculates that grouting at Savannah River costs around \$40 per liter; the price tag for vitrifying the much larger quantity of LAW at Hanford is estimated at about \$290 per liter.

Road-ready wastes

A third DOE site, Idaho National Laboratory, is dealing with sodium-bearing HLW, produced mainly from reprocessing spent fuel from naval reactors. While those operations were under way, the lab converted the waste into a fine powder, using a process known as calcining. But emissions regulations in the 1990s brought calcining to a halt, which left about 3.4 million liters of liquid waste.

A waste treatment unit has been built at the Idaho lab, at a reported cost of \$1 billion, to transform the remaining liquid waste into a granular solid suitable for canister storage. The plant was to begin operating in 2012, but even a second target date for startup was missed last fall. DOE hasn’t committed to a new date, but says that it will commence treatment of the waste as soon as remaining technical issues have been resolved.

The calcined waste at Idaho is soluble in water and won’t meet legal requirements that HLW be vitrified for acceptance in a nuclear waste repository, if one should be built. DOE has said in the past that it will transform the calcined waste into a ceramic-like solid. In its written responses, DOE said only that it plans to have all Idaho HLW, including the calcined material, “road-ready” for disposal outside the state by 2035. Beatrice Brailsford, nuclear program director for the Snake River Alliance, a citizens’ group that monitors the Idaho lab, fears the agency will simply leave the powdered waste in canisters indefinitely.

David Kramer



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