Forward fusion:

BUILDING A NUCLEAR FUTURE IN WISCONSIN

By Tim Gregoire

SHINE's isotope production building, called the Chrysalis, under construction in October 2022.

In a former farm field just outside the historic town of Janesville in south-central Wisconsin, a large concrete-and-steel building is taking shape. Dubbed the Chrysalis, the building will eventually house eight accelerator-based neutron generators, which start-up company SHINE Technologies will use to produce molybdenum-99. As the precursor to the medical radioisotope technetium-99m, Mo-99 is used in tens of millions of diagnostic procedures every year, primarily as a radioactive tracer.

Greg Piefer

At the heart of the Chrysalis will be the high-flux neutron generators, being supplied by SHINE's sister company, Phoenix. The compact accelerators use a deuterium-tritium fusion process to produce neutrons, which in turn induce a subcritical fission reaction in an aqueous low-enriched uranium target (19.75 percent uranium-235) to produce Mo-99.

"As far as I know, this will be the biggest beneficial use of fusion ever made by human beings," said Greg Piefer, SHINE's founder and chief executive officer. "And that is exciting for us."

When operational, the Chrysalis will produce annually about 2 grams of Mo-99, Piefer said, enough to treat around 20 million patients. In 2017, the cost of Tc-99m in North America was about $20 to $25 per dose, according to a report by *Scientific American* that year.

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The building

SHINE received the construction permit for the Chrysalis building from the Nuclear Regulatory Commission in February 2016, and the company broke ground on the 43,000-square-foot facility in May 2019. The NRC is currently reviewing SHINE's application to operate the production facility under 10 CFR 50, *Domestic Licensing of Production and Utilization Facilities*. Piefer expects the license will be issued later in 2023.

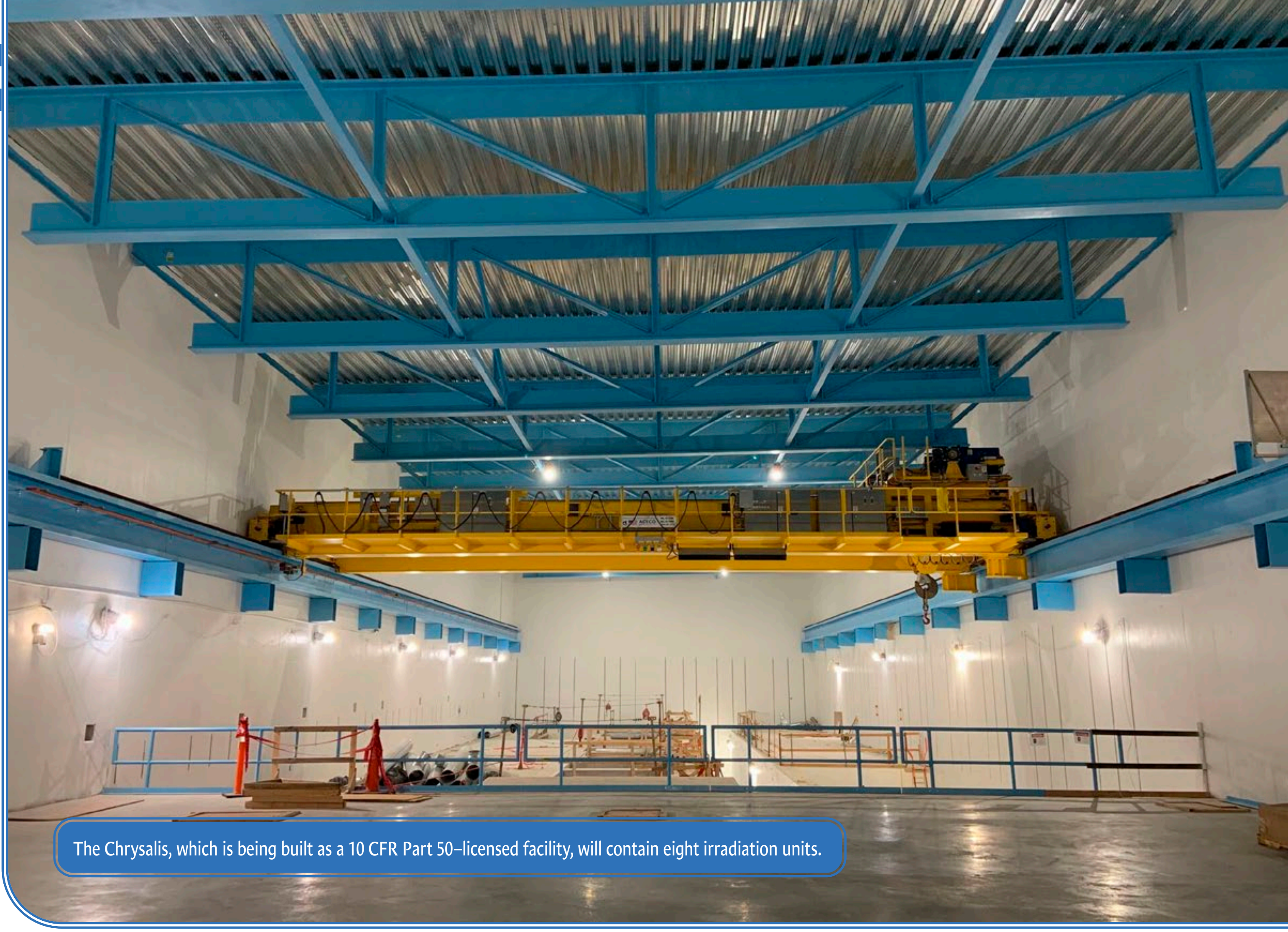
The 30-year operating license will allow SHINE to produce up to 8,200 6-day curies of Mo-99 per week. A 6-day curie is the measurement of the remaining radioactivity of Mo-99 six days after it leaves the processor's facility. Mo-99 beta decays with a 66-hour half-life, and so it must be continually produced to meet demand. Piefer said SHINE expects to produce about half that amount, which he said will still meet approximately 40–50 percent of global demand for the isotope. The operating license also allows SHINE to produce up to 2,000 Ci of both xenon-133 and iodine-131 a week.

SHINE is using a four-phased approach to ramping up operations of the Chrysalis, with the first three phases seeing the eight neutron generators, referred to as irradiation units, being sequentially brought on line to produce Mo-99. The fourth phase will add xenon and iodine production. The phased approach, according to Piefer, will allow the company to minimize startup complexities and begin operations prior to installation of all units. "It is not super rational to install all eight [irradiation units] and then start operations; you would like to learn," he said, adding that the company will move quickly through the phases, with all units installed within about one year.

Inside the Chrysalis processing canyon, still under construction.

When SHINE submitted its Part 50 operating license application to the NRC in 2019, it expected to start bringing the irradiation units on line in 2021, with commercial Mo-99 production starting in 2022. That schedule, however, has been pushed back by as much as three years. And while the company still expects first-phase construction to be substantially complete by May, it asked the NRC in April 2022 to extend the building's construction deadline from December 2022 to December 2025 out of an "abundance of caution and conservatism." In requesting the extension, SHINE noted the challenges of designing and building a first-of-its-kind isotope production facility.

Piefer also attributes the schedule delay to the COVID-19 health emergency. In particular, having non-construction personnel working from home and unable to connect in real time caused difficulties, he noted. "When you have



The Chrysalis, which is being built as a 10 CFR Part 50–licensed facility, will contain eight irradiation units.

a really broad team working on a very complex project, they need to be in the same place," Piefer said.

And as with many other industries, SHINE has been encumbered by issues surrounding supply chains. "In terms of both cost and schedule on key supply chains, for even simple things like electrical panels, wiring, and piping, all have been affected," Piefer said. "And that has pushed things backward and made them more expensive."

The Mo-99 marketplace

The challenges of meeting patient demand for Mo-99 have been widely reported. Previously, most of the U.S. supply of Mo-99 was produced by Canada's National Research Universal reactor, which produced about 40 percent of the world's supply of the isotope until it ceased operations in 2016.

Since then, the majority of Mo-99 has been produced by research reactors in Australia (OPAL), Belgium (BR-2), Poland (MARIA), the Czech Republic (LVR-15), the Netherlands (HFR), and South Africa (SAFARI-I), many of which have been in use since the 1960s. That has put the supply at risk of disruption from unanticipated events.

In January 2022, the HFR, which produces about 60 percent of the global supply of Mo-99, was shut down after a water leak was detected in the reactor beam tube cooling system, impacting the production of Mo-99 and lutetium-177. And in October 2022, a mechanical failure delayed the planned restart of Belgium's BR-2, also causing shortages of Mo-99 and I-131.

To ensure a reliable domestic supply of Mo-99 while also reducing proliferation concerns surrounding the use of high-enriched uranium, Congress passed in 2012 the American Medical Isotopes Production Act, which resulted in the National Nuclear Security Administration entering into 50/50 cost-shared cooperative agreements with private companies to support the production of Mo-99 using LEU.

The NNSA currently has a cooperative agreement with SHINE as well as with NorthStar Medical Radioisotopes, located in Beloit, Wis., and Lansing, Mich.–based Niowave. NorthStar currently produces Mo-99 without the use of uranium by irradiating and processing Mo-98 targets (neutron capture) at the University of Missouri Research Reactor. This past November, the

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company completed construction on a new facility that will employ electron-beam accelerators to induce photo transmutation (neutron knockout) of enriched Mo-100. Niowave, meanwhile, uses the LEU-modified Cintichem process to harvest and purify Mo-99 from fission uranium targets.

Outside the United States, BWX Technologies subsidiary BWXT Medical is working with Ontario Power Generation to produce Mo-99 at the Darlington nuclear power plant in Ontario, Canada. When operational, it will be the only Mo-99 source from a commercial power reactor in the world. Instead of using uranium as a starting material, BWXT's approach is to irradiate natural molybdenum targets, producing Mo-99 through neutron capture. The Mo-99 will be used in the company's proprietary Tc-99m generator, which is currently under review by the U.S. Food and Drug Administration.

For Piefer, SHINE's fusion-fission approach to producing Mo-99 from LEU is preferrable to those that use transmutation. "It was clear from talking to our customers that the specific activity of the molybdenum generated matters," he said. "And when you start with Mo-98, you turn very little of your starting material into your end product." Because uranium is chemically distinct from molybdenum, Piefer said it is easier to strip all the source material away and isolate the fission-produced Mo-99, rather than try to pull Mo-99 from the chemically identical Mo-98. According to Piefer, transmutation produces a dilute finished product with specific activities 10,000 times less than that compared to fission-produced Mo-99.

Likewise, Piefer said that by using its neutron generators, the company avoids the high costs associated with building a conventional fission reactor. "Versus new reactors, our capital cost is way lower as a result of the fusion-based engine," he said. "And we believe our operating cost is proportionately lower. We have yet to prove that. But based on our models, the operating cost should be proportionately lower than reactors." Piefer added that SHINE's system is expected to produce less radioactive waste than a conventional reactor.

Ross Radel (right), SHINE's chief technology officer, talks to (from left) John Fabian and Craig Piercy of ANS and Grace Stanke, UW–Madison nuclear engineering student and Miss Wisconsin 2022, during a tour of the Chrysalis.

SHINE's Greg Piefer talks with construction crew members.

The next phases

For Piefer, who was named one of 2022's most exceptional entrepreneurs by Goldman Sachs, SHINE's future is not tied just to the production of Mo-99 and other medical radioisotopes. The company has embarked on a four-phase journey to generate fusion energy. Reflecting the expanded scope of its business, the company changed its name last year from SHINE Medical Technologies to simply SHINE Technologies.

SHINE has already accomplished the first phase of its goal: the commercial use of Phoenix's fusion neutron generators in nondestructive neutron radiography, and the company is well on its way to achieving the second phase of scaling up the production of medical isotopes.

The third phase involves adapting SHINE's chemical separation capabilities to the large-scale recycling of high-level radioactive waste. Piefer, who prefers the term recycling to reprocessing, said that as a facility licensed under 10 CFR Part 50, the Chrysalis will be equipped to handle the separation and recycling of used nuclear fuel.

As SHINE's technology advances, the company plans to move to the large-scale transmutation of nuclear waste through the fusion process, reducing the burden of long-lived isotopes. "We believe, based on the business model we have created, that we can expand into [nuclear] waste and make it a profitable venture," Piefer said.

The final phase is to generate nuclear fusion energy by building on the commercial successes of the previous phases. However, Piefer admits that the reality of fusion power may still be a long way off. "When I look at, not the next 100 years of humanity, but when I think about the next 1,000 or 10,000 years, it is clear to me that fusion will play the dominant role over those time frames. And I wanted to do my part to help bring it to the table now," he said.

Piefer came to understand the challenges facing commercial fusion power while studying under Professor Gerald Kulcinski at the University of Wisconsin–Madison. It was Kulcinski, Piefer said, that got him thinking about the practical uses of fusion other than power generation. "Gerry had this idea that you might be able to do some more near-term things with fusion, and that really resonated with me," he said. "The thought was that if you could capitalize on some of these nearer-term uses of fusion, you would provide value to society but also get better at fusion. And maybe in doing that move toward power."

The goal of SHINE, Piefer noted, is to continue to decrease the cost of the neutrons it generates while increasing the uses of those neutrons in the marketplace. He compares it to the business model exemplified by Tesla, which began by making the expensive Model S before working to increase its proficiency in producing electric vehicles, then expanded its share of the market by offering the more affordable Model 3. "As you get better at it and make it cheaper, more people can access it and it gets bigger. That is what we are trying to do," he said.

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