A "Moonshot" for Reactor Vessel Production

Advanced Manufacturing and Fabrication Could Substantially Reduce Time, Costs of Reactor Pressure Vessel Production

By Brent Barker

Imagine being able to build a nuclear plant's reactor pressure vessel in one year instead of four, using metal powders as a starting point instead of massive forgings, and a fabrication process in which welds essentially disappear. This ambitious scenario points to savings in time, money, and materials, far more competitive nuclear power, and a faster path to small modular reactors (SMR). It also describes the central goal of a new four-year, collaborative program spearheaded by EPRI, United Kingdom–based Nuclear Advanced Manufacturing Research Center (Nuclear AMRC), and the U.S. Department of Energy (DOE). Its success could broaden the manufacturing base of reactor pressure vessels beyond Asia.

The team views this program as its "moonshot," with researchers seeking to demonstrate the effectiveness, synergy, and benefits of several advanced manufacturing and fabrication technologies for reactor pressure vessel production. Their immediate focus is on producing large, critical SMR component assemblies at two-thirds scale, using a 50-megawatt unit design from Oregon-based company NuScale Power. They selected this reactor for two reasons: it is small enough to demonstrate many of the technologies with current fabrication facilities, and its design appears closest to commercial deployment. Up to 12 NuScale Power SMRs could be linked at a single site and brought online incrementally as demand grows.

"These advanced manufacturing/fabrication technologies are agnostic," said EPRI Technical Executive David Gandy. "They can be applied to advanced light water reactors, Generation IV nuclear reactors, ultra-supercritical fossil units, and advanced CO_2 supercritical plants. Some of the technologies are already being used at small scale in punishing environments such as aircraft engines and offshore rigs at the bottom of the North Sea."

Why Vessel Production Went Overseas

In the 1960s and 1970s, most full-scale vessels were manufactured at facilities in the United States, France, and United Kingdom, where various sections were joined using conventional welding techniques with filler materials containing tramp (trace) elements such as copper, phosphorus, and sulfur. These weld materials were found to be susceptible to embrittlement as a result of long-term radiation exposure, decreasing their strength.

To reduce the number of welds and inspections, the industry turned to forging the entire vessel in large sections and joining them with fewer, longer welds, such as the one around the vessel's girth. As a result, vessel production moved to Japan, Korea, and China, which had developed the capability for much larger-scale forging operations. Given the limited number of facilities, the global queue for large-scale forgings has lengthened considerably.

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Current reactor pressure vessel production is laborious: Hot ingots are hammered into rough sections, which are machined, rolled, bored, and drilled into the final forms, which are welded together. The forging process can affect the metal's micro-grain structure, making nondestructive inspection more difficult.

Enabling Technologies

Three new technologies show potential for producing vessels from small sections while eliminating previous welding constraints and facilitating inspection.

1. **Powder metallurgy combined with hot isostatic pressing.** In this process, metal alloys are atomized into powder form, inserted into a metal mold (or "can"), and subjected to high temperatures and pressures. This consolidates the powder into a solid metal component.

   "Earlier work by EPRI and others demonstrated that we could use this technology with multiple alloys to produce 'near net-shape' components with a homogeneous microstructure. These require minimal machining to achieve the final geometry of complex parts, and homogeneity means a vastly easier inspection process and good properties," said Gandy.

2. **Electron beam welding** fuses two pieces of metal by focusing a high-intensity energy beam on the junction. Subsequent solution annealing, quenching, and tempering complete the process. Unlike traditional welding, no filler material is used.

   "We've demonstrated that we can remove all evidence of the weld through solution annealing," said Gandy. "Further development and demonstration will be needed to secure ASME Boiler and Pressure Vessel Code approval, but we believe that inspection may only be required immediately after fabrication. This could eliminate the need for in-service inspection because the weld zone no longer exists metallurgically."

   EPRI estimates that these two technologies, when used together on an SMR vessel, could reduce welding time by 70%, overall production time by 60%, and manufacturing costs by 40%, creating new opportunities for how, when, and where reactor pressure vessels are produced. This, in turn, could lead to more suppliers globally.

3. **Diode laser cladding** combines a metal wire or powder with a laser beam at the surface to apply extremely thin layers. This can be used to clad the inside of vessels and their nozzles with stainless steel or nickel-based alloys for corrosion resistance. This technology potentially reduces by 75% the amount of cladding material needed, providing an economic benefit. Nuclear AMRC spearheaded this technology development.

The SMR Reactor Vessel Demonstration Project

The four-year collaborative project dates back to 2009, when EPRI investigated the use of powder metallurgy and hot isostatic pressing to produce nuclear and fossil plant valves. That led to a DOE-funded project with EPRI involving the design, manufacture, and validation of large, near-net-shaped components for multiple alloy systems. The successful project produced several complex sample components, including a 3,600-pound vessel nozzle.

At the same time, DOE began looking for industrial participants to test advanced manufacturing techniques for SMRs. EPRI explored the project vision with Nuclear AMRC, drawing on its capabilities in advanced nuclear manufacturing. With DOE's support and sponsorship, a collaborative project on SMR manufacturing and fabrication emerged, building momentum in 2016.

"We have gathered an ideal combination of expertise on our team," said EPRI Technical Leader Craig Stover, who manages the collaborative with Gandy. Participants include:

- Nuclear AMRC, a co-investigator in the project with EPRI, will lead the fabrication of critical SMR assemblies.
- NuScale will provide the SMR design.
- Pennsylvania-based Carpenter Powder Products will supply the powders.
- UK-based Sheffield Forgemasters will produce several forgings for the SMR.
- Los Angeles–based Synertech-PM will lead the hot isostatic pressing efforts.

The project, which began in late 2016, has two phases. The first will focus on the reactor pressure vessel's lower assembly, which is less complex in design than the upper assembly. Phase two will build on this work to focus on the upper assembly.

The reactor pressure vessel top head assembly is considered the most complex component of the NuScale SMR design, with 16 nozzle penetrations for control rod drive mechanisms as well as 7 additional nozzle penetrations. Conventional manufacturing would require extensive boring, machining, and welding. Because a hot isostatic pressure chamber sufficiently large to produce the entire head assembly in one run is not yet available, the team will produce two halves of the assembly and weld them together with electron beam welding, followed by cladding and solution annealing. Using this approach, EPRI currently estimates that the assembly could be produced at nuclear-grade quality for less than $2 million—just 10% of current manufacturing costs.

Advanced manufacturing and fabrication technologies hold significant promise to improve nuclear power's competitiveness and support commercial operation of smaller, modular reactors. The demonstration project is expected to provide insights on these technologies at a scale sufficient to evaluate their commercialization.

Small Modular Reactors

Small modular reactors (SMRs) offer the potential to produce 300 megawatts of power on a site smaller than 10 acres. Compare that with a 1000-megawatt nuclear plant that typically requires around 800 acres. The SMR's compact architecture enables modular fabrication in the factory as well as passive safety features.

"With modern SMR designs, emergency planning zones could potentially be reduced to the site boundary," said EPRI Technical Leader Craig Stover.

With advanced manufacturing technologies, such as powder metallurgy, hot isostatic pressing, and electron beam welding, SMR capital and operations and maintenance costs "could conceivably be cut to less than one-third the costs of an advanced light water reactor," said EPRI Technical Executive David Gandy.

Additive Manufacturing: Building from the Ground Up

For manufacturing intricate nuclear plant parts weighing less than 100 pounds, additive manufacturing offers a compelling alternative to powder metallurgy—hot isostatic pressing, forging, and casting. Similar to 3-D printing, it involves the layer-by-layer construction of a component by mimicking the contours of an existing object.

"With additive manufacturing, you are essentially laying down weld metal and fusing tiny beads layer-by-layer," said EPRI Technical Executive David Gandy. "The real advantage is that you can replicate obsolete parts and make very detailed, intricate parts." The current limitation is size; most of these parts are produced inside a chamber that is less than 1.3 cubic feet. EPRI is launching a three-year research project with the U.S. Department of Energy, Westinghouse, and Rolls Royce to test the potential application of additive manufacturing for nuclear reactor components. This effort is focused primarily on reactor internals, fuels, and fuel assemblies.

Key EPRI Technical Experts

David Gandy, Craig Stover