Heavy Duty

New nuclear reactors require pressure vessels that are several stories tall and weigh hundreds of tons. What would it take to make one in the U.S.?

By Bridget Mintz Testa

ELLWOOD CITY FORGE

In the public imagination, nuclear power revolves around uncommon isotopes of uranium undergoing a controlled chain reaction, releasing energy. And it does involve that, to be sure. But at its heart, nuclear power relies on old-fashioned steel. Lots of it.

Indeed, the reactor vessels that contain the nuclear fuel rods and the steam generated by their heat weigh in at several hundred tons and demand observance of exacting standards. To make them requires the kind of industrial facilities that recall an earlier century, when molten steel and heavy machinery were the centerpiece of the economy.

The newest nuclear reactors are even bigger than the ones that were built in the United States in the 1970s and 1980s. And the companies that are looking at building

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Red-hot ingots (above and left) are being turned into high-quality steel in the 5,000-ton press at Ellwood City Forge's 100,000-square-foot facility in New Castle, Pa.

new reactors want the critical components of the reactor vessels to be built from as few pieces as possible.

The reactor vessels, which stand around five stories in height, are assembled from forged steel components known as RV sets. Each RV set includes two end caps and a series of cylindrical rings that are stacked and welded together. RV sets are forged from ingots that weigh approximately 550 tons to 660 tons.

Working with ingots of that size requires an "ultra-heavy" forge. And it is work that by necessity will be done outside the United States, because the U.S. has never had its own ultra-heavy forge and likely never will.

There hasn't been much call for making reactor vessels in the United States for decades. Even in the 1970s, the peak decade for building nuclear power plants in the U.S., only around a dozen reactor vessels were installed in the best years. And the rate has been zero per year for most of the past 20 years.

The pace will pick up. Even in an industry still shaken by the Fukushima accident, nuclear power is taking some halting steps forward in the United States. In February, the U.S. Nuclear Regulatory Commission approved licenses to build two new nuclear reactors at the Alvin W. Vogtle Electric Generating Plant in Waynesboro, Ga. Another reactor is under construction at Watts Bar in Tennessee and others are being planned in South Carolina and Alabama.

Although no U.S. company has ever owned a modern ultra-heavy forge, U.S. forgemasters were able to make some components for the "nuclear island"—which includes both the reactor vessel and the steam generators that heat water into steam—and all the components of the "turbine island"—which include the turbine and generator rotor forgings—for the country's current 104 operating Generation 2 nuclear reactors. To see why, it's important to understand the nature of forging as well as the capabilities of U.S. forgemasters when Gen 2 plants were being built.

Making a reactor vessel or any large steel structure starts with an ingot, which "is a casting, where you pour molten steel into a giant bucket, and it shrinks from the bottom and sides inward," said Mike Kamnikar, senior vice president of marketing and business development at heavy forgemaster Ellwood Group in Ellwood City, Pa. "In the solidifying of steel, you get micro-voids. These voids have deleterious effects on product performance."

Those microscopic holes in the castings weaken the steel and make it prone to cracks and fissures. Forging is a way to strengthen the steel by destroying those holes.

"Forging closes all the pores, densifying the steel," Kamnikar said. "It also aligns the steel crystals, creating a grain flow that helps improve the performance. Forging can densify the steel in all three directions."

Forging turns a cast steel ingot, with all of its defects, into a component that is much stronger and tougher than steel made by any other process. Those characteristics are mandatory for brutal environments like those found in a nuclear reactor and its surroundings.

"In an open-die forge, the metal is free to move in one of three directions," said Kamnikar. "If you put your hands six inches apart, parallel to each other, they are like the dies of the press. Your hands can move up and down together, as if pressing modeling clay between them. You can make simple geometric shapes like a rolling pin." A press squeezes hot metal into the overall desired shape via a process that is repeated several times over a period of days or even weeks.

After rough shaping in the forge, the metal is "heat treated to get the balance between strength and ductility," Kamnikar said. "Then it's rough-machined for non-destructive testing, shipped to the customer for more testing, then it undergoes final machining."

Today's heavy forgemasters in the U.S. operate presses that exert force in the neighborhood of 5,000 tons to 10,000 tons on ingots weighing between 70 tons and 300 tons, squeezing the metal into the overall desired shape.

"Press size varies, especially in the distance between the dies," said Al Robertson, vice president of marketing and sales at Lehigh Heavy Forge in Bethlehem, Pa. LHF can work ingots of up to 300 tons with its 10,000-ton press, making it the largest forgemaster in the United States today. "Our press can forge pieces up to 200 inches in diameter," Robertson said. "But with that, there is a limitation on length of the finished product. Some presses can go wider and longer. It's a matter of press design."

LHF and Ellwood Group are the only heavy forgemasters in the United States. Neither of them, however, can match the ability that U.S. Steel and Bethlehem Steel once had. Those steel giants could cast and then forge ingots of nearly 400 tons, at least until they shut down their largest forges in the early 1980s.

They were impressive, but they pale in comparison to the output of the ultra-heavy forges that have been built in other countries over the past few decades. Typically, an ultra-heavy forge is about the height of a three-story building, with all the equipment—such as the press and the manipulators that handle the ingot while it's in the press—sized appropriately. And an ultra-heavy press exerts between 15,000 and 17,600 tons of force on ingots weighing as much as 600 tons.

Even so, the U.S. Steel and Bethlehem Steel forges were plenty big enough to make some forgings for Gen 2 plant nuclear islands and all of the ones for the turbine island, although the rest of the critical nuclear island components were imported, according to Kamnikar.

Capacity wasn't the only factor that made forging nuclear reactor vessels in the U.S. possible. Gen 2 RVs were physically smaller than their 21st-century descendants. Gen 2 and Gen 3 RVs are about the same height—roughly 40 feet—but Gen 2 RVs are slimmer, around 15 feet across, while some Gen 3 RV diameters are more than 23 feet. In addition, whereas Gen 2 RVs required about 2,200 tons of forgings, RVs for reactors such as the AP1000s that will be built at Vogtle require about twice that amount.

Finally, older components were made somewhat differently from the way their counterparts are today. They were forged as multiple pieces with split reactor ring segments, which were welded together when the RV was fabricated.

The mostly-made-in-the-U.S.A. Gen 2 nuclear plants have done very well. Many of the ones that have already operated for their design lifetimes of 40 years are being licensed for 20 more years. Why, then, do the critical components of Gen 3 plants require ultra-heavy forging?

Although Gen 2 reactor vessels are smaller in diameter than Gen 3 RVs, size really isn't the issue. Even with ultra-large forgings, the Gen 3 critical components are still made in multiple pieces. Regarding the AP-1000 reactor, of which four are currently under construction in China, "The reactor vessel comes in many pieces," said Jack Lanzoni, vice president of nuclear power plants supply chain management at Westinghouse, the reactor's designer. "It takes eight to 10 different forgings to configure it. The two steam generators require about 20 forgings in total.

"From a technical perspective," Lanzoni added, "it is possible for us to use heavy forgings known as split forging, where two pieces are used instead of one." That would, of course, double the number of pieces that have to be welded together.

At Babcock & Wilcox, which has been in the nuclear business for 40 years, the vice president of nuclear manufacturing, Craig Hansen, said, "Any reactor vessel or steam generator manufactured in the world can be made in North American facilities." Hansen added that "those facilities may have to import 15 percent of the ultra-heavy forgings used in the vessel" from an ultra-heavy forgemaster such as Japan Steel Works.

But in spite of the technical feasibility of forging the reactor vessels in U.S. facilities, Lanzoni said that customers specifically request that reactor vessels be made from fewer, larger pieces that require fewer welds. That preference is the primary reason that customers turn to ultra-heavy forging.

"RV welds degrade under high energy neutron bombardment," said Rick Johnston, an engineer with the engineering consulting firm MPR Associates Inc., which in 2010 investigated the viability of building ultra-heavy forges in the United States for the Department of Energy. "Horizontal welds hold

up fairly well, but when the vertical welds degrade, the circumferential stresses of the RV try to pull them apart," Johnston said. "Vertical welds are unavoidable in RVs fabricated from split forgings."

No one knew that welds would be an issue in the 1970s and 1980s when most of the Gen 2 plants were built. Once the vulnerability of welds was discovered, however, it meant intense and repeated scrutiny of all welds by licensing and inspection bodies like the Nuclear Regulatory Commission. That increases maintenance and upgrade costs for owners of today's nuclear power plants. It would do that for new Gen 3 plants, too, but Johnston said the real drawback for a new plant's having more than the minimum possible number of welds is regulatory. According to Johnston, it's very hard "for an RV design incorporating an increased susceptibility to a known failure mechanism to get through all the licensing requirements."

It is possible that U.S. forgemasters could make critical components for the so-called small modular reactors, which would have RVs with smaller diameters than currently operating reactors. As yet, none of the small modular reactor designs has been approved by the U.S. Nuclear Regulatory Commission.

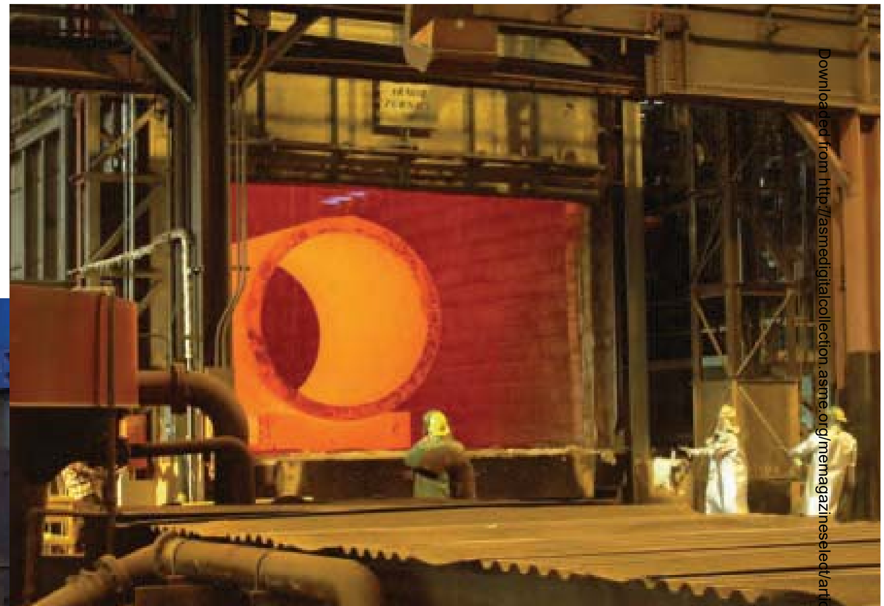
But is the lack of ultra-heavy forging capability hindering the growth of nuclear power in the U.S.?

"When we first started our research in the fall of 2009, we initially thought there was going to be a big bottleneck to the nuclear renaissance," Johnston said. "At the time, there was only one source for ultra-heavy forgings, in Japan, and they were way backed up for years at a time."

Since then, that supplier, Japan Steel Works, quadrupled its capabilities, Doosan Heavy Industries & Construction in Korea and several Chinese ultra-heavy forging facilities came online, and the Areva Creusot Forge is doubling its capability from production of one to slightly more than two RV sets per year. Other ultra-heavy forgemasters are starting up, too.

"It turned out that the demand might not be as high as we originally thought, and the manufacturing capacity was increasing," Johnston said.

Upgrading existing American forges to produce ultra-heavy products isn't an option: Entirely new forging facilities would have to be built. MPR estimates that one new ultra-heavy forging facility would cost $1.5 billion to $2.5 billion, and it would take five to seven years to build. That's a good fraction, in terms of both money and time, of the estimated $6 billion to $9 billion and seven to ten years needed to build a nuclear power plant.



The ingot at left is being worked at the 10,000-ton press at Lehigh Heavy Forge. Above, a large shell is coming out of a heat-treatment furnace at LHF.

LEHIGH HEAVY FORGE CORPORATION

Assuming that a company could raise the money and accept the risk of constructing such a facility, there are other obstacles. Forging four RV sets each year for Gen 3 nuclear construction would use about 100,000 tons of ingot, but a new plant designed to produce ultra-heavy components would "be able to make one million tons of steel a year, so what do you do with the rest of that steel and the plant?" Kamnikar said.

Large forges can't just be turned on and off, either. "They degrade," Johnston said. "So you can't shut down without consequences when there's no business."

Then there is the problem of making a profit. "Take a look at the nuclear market worldwide," Hansen said. "North America is the only place where the market is completely open. The rest of the world is not a level playing field."

Changing these conditions to favor building domestic ultra-heavy forging capability would take a coherent "energy policy for the United States regarding nuclear power, making it much more important in our energy capabilities," Kamnikar said. "It should be a consortium, and the government could provide funds up-front."

Until that happens, though, he said, "We don't need this capacity in the U.S. for what's needed right now. We have enough allies to provide the forgings." ■