AMM Newsletter
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Bruce Landrey Joins AMM Team


Bruce Landrey
AMM Advisor

After serving as the Advanced Methods for Manufacturing (AMM) program's national technical director since 2012, Jack Lance is passing the baton to Bruce Landrey. Bruce is a veteran of the nuclear industry. His work in nuclear began with the Trojan Nuclear Plant in Oregon. He later joined the Tennessee Valley Authority as a vice president. In 2008, Bruce helped launch NuScale Power—the developer of a 50-MWe light-water, small modular reactor (SMR). In January, NuScale announced that it had filed the first application with the Nuclear Regulatory Commission for the Design Certification of an SMR. Alison Hahn continues to direct the program as the program manager.

Bruce has supported the Department of Energy (DOE) in other roles. In 2016, he completed a study for DOE into the feasibility of using SMRs to provide clean, secure power to Department of Defense installations. Bruce and Jack Lance also co-facilitated a workshop in 2016 for DOE to gather stakeholder input into opportunities for DOE to support the accelerated commercialization of SMRs. Bruce also planned and organized two nuclear supply chain conferences sponsored by ATI Metals. He served three terms on the Secretary of Commerce's Civil Nuclear Trade Advisory Committee, and chaired its subcommittee on International Advocacy for the United States (U.S.) nuclear industry. Bruce has been active in both the Nuclear Energy Institute and the Nuclear Infrastructure Council.

One of the areas of interest that is important to Bruce is to broaden the outreach and stakeholder engagement for the AMM program. Bruce believes "The PIs and research teams at the universities, laboratories, institutes, and companies involved in the AMM program are delivering findings that can make a fundamental difference in the competitiveness of the U.S. nuclear industry. If our goal is to reduce the cost and schedule for new nuclear construction, and restore the U.S as the leading nuclear manufacturer, we need to share the findings of the AMM research programs so the results can be put into application."

Bruce welcomes ideas and recommendations on how to broaden the outreach of the AMM program. He can be contacted at brucel@landreyco.com.

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Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

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Additive manufacturing (AM) technologies have the potential to significantly impact many industrial sectors, including the nuclear energy industry. These technologies manufacture parts through a variety of techniques that add material to a developing part in a controlled and reproducible fashion. Parts can be produced in nearly any shape or configuration, including many that cannot be made using conventional manufacturing techniques. While cost typically scales with complexity in conventionally manufactured parts, there is often little-to-no penalty for complexity in additively manufactured parts. AM can thus be used to produce unique heat exchanger geometries, or difficult-to-assemble piping unions. AM also offers the potential for quickly and affordably producing one-of-a-kind replacement parts, which can be extremely important in maintaining 40+ year-old nuclear power facilities. Finally, AM also offers the potential to allow quick development and production of custom irradiation capsules and experimental rigs, such as those needed to support the Advanced Test Reactor.

The deployment of additive manufacturing technologies to support the nuclear energy industry is limited by a lack of characterization and property data for parts produced by different additive manufacturing techniques, which limits the ability to meet nuclear quality assurance requirements. Also, it is limited by a lack of data related to the irradiation and thermal performance of AM parts, which limits confidence that these parts can survive in the challenging environments needed for nuclear energy applications.

The project will collect some of the first irradiation performance data for stainless steel and Inconel specimens. Tensile bar and thermo-physical property test specimens will be harvested from test articles produced by a representative range of currently available additive manufacturing techniques. The Colorado School of Mines will conduct pre-irradiation thermo-mechanical testing (tensile strength,

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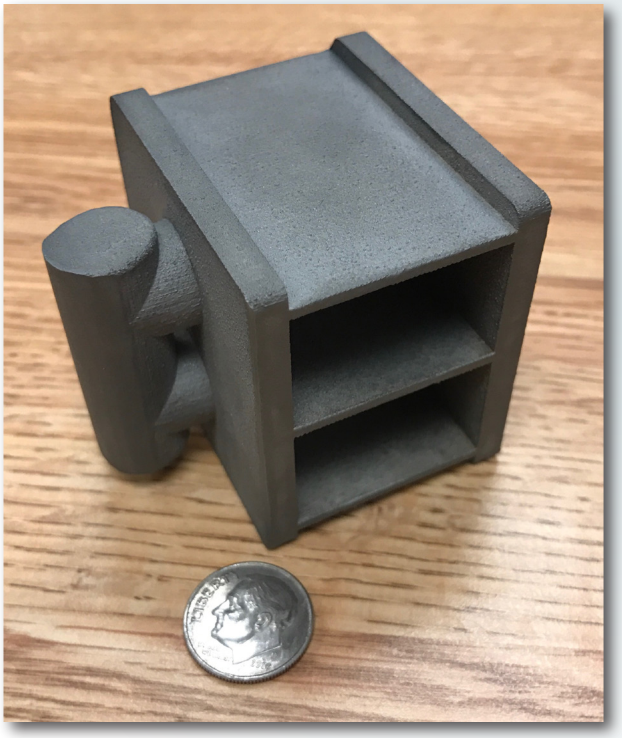

Figure 1: Prototype Inconel 718 test article produced using the powder bed laser sintering process.

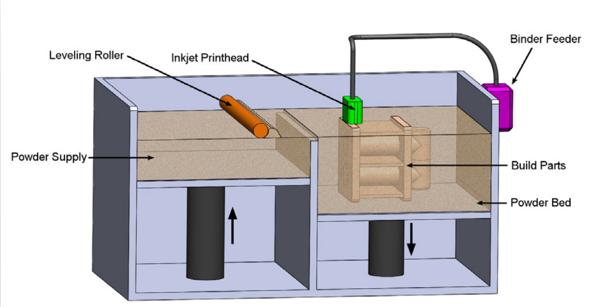

Figure 2: Schematic of the powder bed binder jet process.

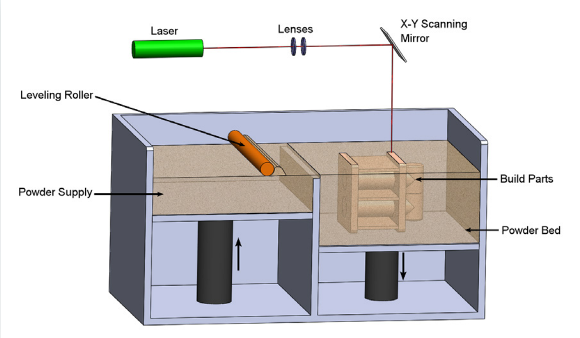

Figure 3. Schematic of the powder bed laser sintering process.

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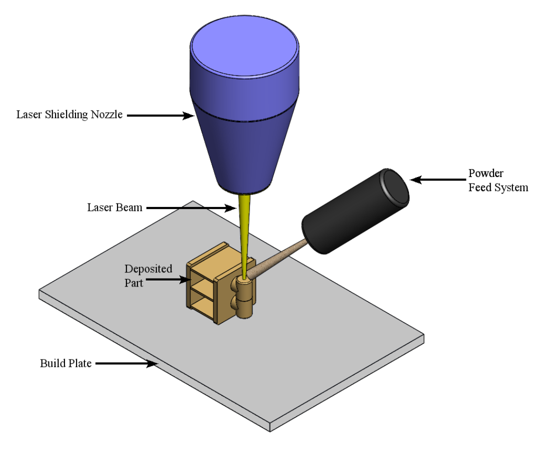


Figure 4. Schematic of the laser powder fabrication process.

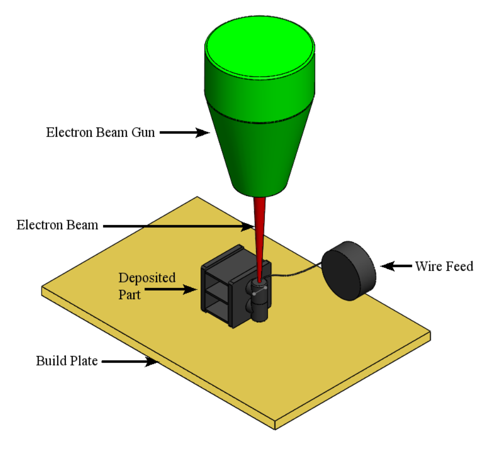


Figure 5. Schematic of the electron beam free-form fabrication process.

yield strength, elastic modulus, ductility, thermal conductivity, and thermal diffusivity) and micro-structural characterization of the specimens. A subset of the specimens will be irradiated to a range of fast neutron fluences at typical light water reactor temperatures (~600 K) in the Advanced Test Reactor (ATR). Thermo-mechanical testing and micro-structural characterization of the irradiated specimens will be conducted at the Nuclear Science User Facilities (NSUF) post-irradiation examination facilities. The remaining un-irradiated specimens will be thermally aged at the Colorado School of Mines and subjected to post-aging thermo-mechanical testing and micro-structural characterization. A comparison of the physical properties and microstructure of the irradiated specimens to those of the as-fabricated and thermally aged specimens will provide insight into the viability of additively manufactured parts for nuclear reactor applications, identify key areas of concerns for further technology development efforts, and provide data for future computational model development.

Current Status

The Colorado School of Mines is currently developing the test article (Figure 1) to be produced by commercial vendors using the four technologies of interest: powder bed binder jet (Figure 2), powder bed laser sintering (Figure 3), laser powder fabrication (Figure 4), and electron beam free-form fabrication (Figure 5). A range of test specimens will be produced from the test article (Figure 6). Engineers from the NSUF are currently designing the test capsule. Insertion of the test items into the ATR is scheduled for June 2017.

Conclusion

This project will provide first-of-a-kind data in each of these areas, for parts produced using powder bed binder jetting, powder bed laser sintering, electron beam freeform fabrication, and laser powder forming. This data will provide direction for future technology development and testing to meet the quality assurance and performance needs of the nuclear energy industry, and will provide input and benchmark data for future computational modeling efforts related to additively manufactured components. Successful completion of the project will provide data for the qualification of additively manufactured parts for nuclear applications and may enable the development of tailored microstructures that provide enhanced resistance to radiation damage.

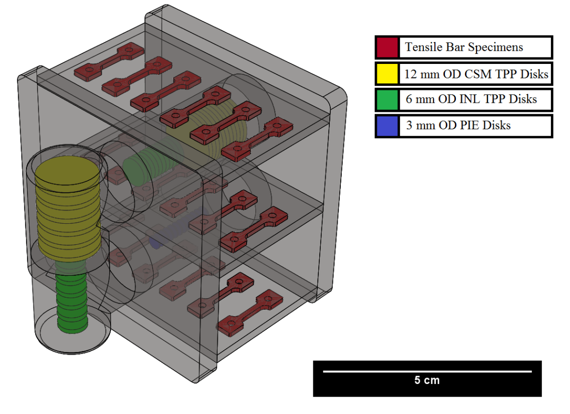
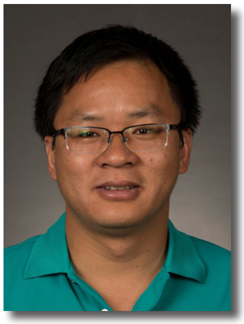


Figure 6. Test specimens to be harvested from the test article.

Enhancing irradiation tolerance of steels via nanostructuring by innovative manufacturing techniques



Haiming Wen
Idaho State University

This project involves neutron irradiation and post-irradiation examination of bulk nanostructured austenitic and ferritic/martensitic (F/M) steels that were expected to have enhanced irradiation tolerance. The steels are produced by two innovative, low-cost manufacturing techniques: equal-channel angular pressing (ECAP) and high-pressure torsion (HPT). The objective is to enhance the fundamental understanding of irradiation effects in ultrafine-grained (UFG, 100 nm < grain diameter < 1 µm) or nanocrystalline (NC, grain diameter < 100 nm) steels produced by ECAP or HPT. It also will assess the potential use of ECAP and HPT to fabricate materials for current and advanced reactors. Improving the performance of currently used austenitic and F/M steels through microstructural engineering via advanced manufacturing techniques holds the potential to improve radiation tolerance at a relatively low cost compared to the development of new alloys.

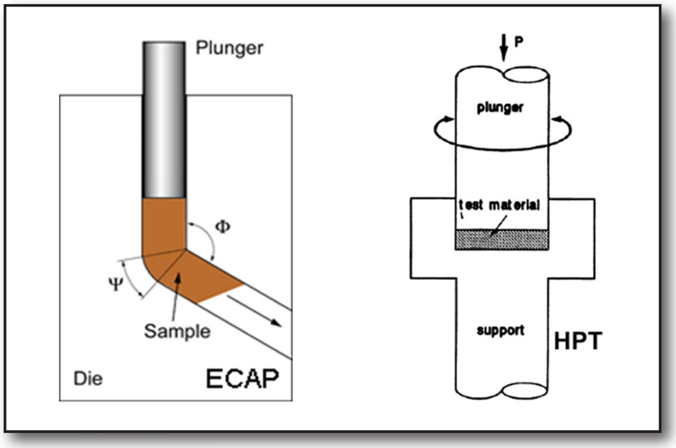


Figure 1. Schematic of equal-channel angular pressing (ECAP) and high-pressure torsion (HPT).

ECAP and HPT produce ultrafine or NC grain sizes in metals and alloys through the application of severe plastic deformation. It is relatively simple to perform ECAP and HPT at relatively low cost. Figure 1 shows schematics of ECAP and HPT. Alloys produced by ECAP or HPT possess dramatically higher strength than

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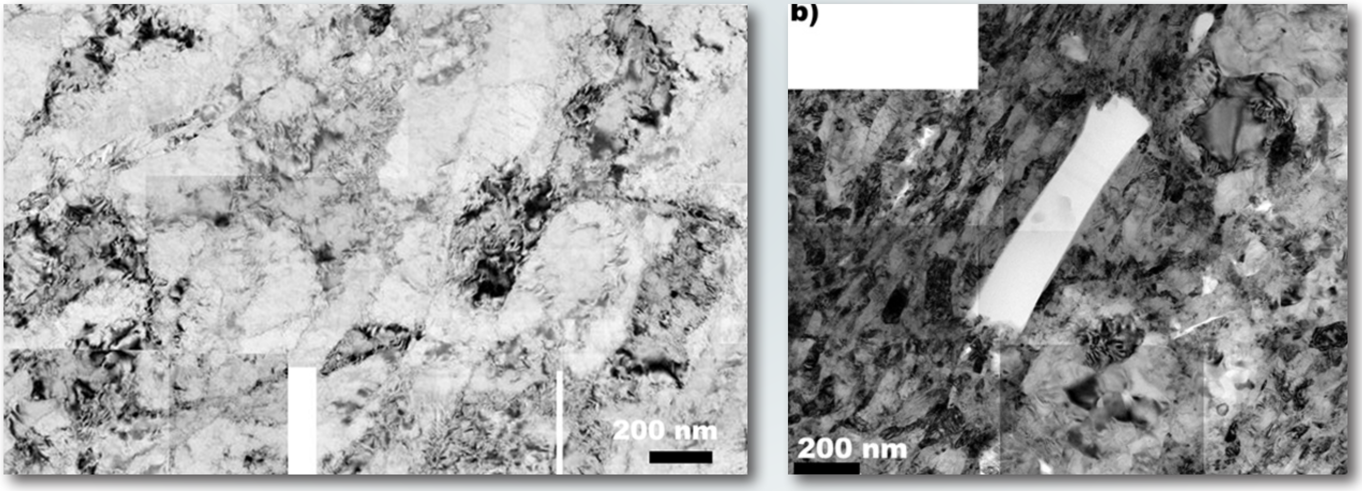

Figure 2. TEM images of stainless steel 316 processed by (a) ECAP and (b) HPT demonstrating the ultrafine-grained and nanocrystalline microstructure, respectively.

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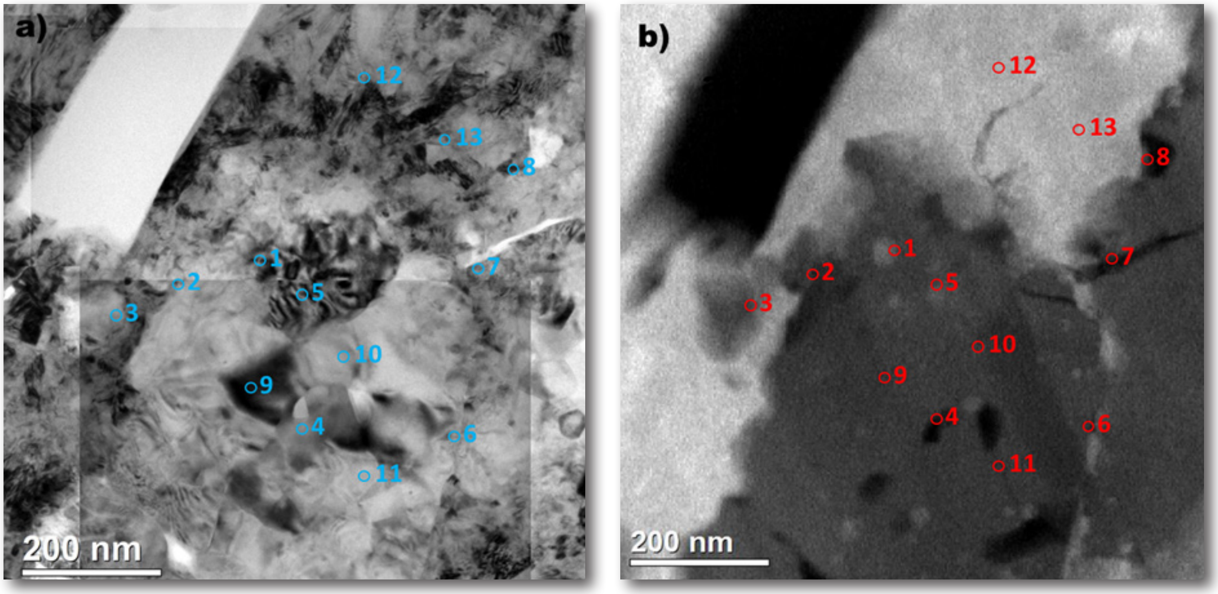

c)

	Atomic %										
#	Fe	Cr	Ni	Mo	Si	Mn	Cu	V	W		Phase Composition
1	31.95	61.47				4.83	2.98				Cr(Fe)
2	65.74	19.44	11.86				2.98				Fe(Cr, Ni)
3	10.94	78.02	1.67		0.96	3.19	3.63	0.89		0.06	Cr(Fe)
4	2	69.91			0.73	25.1	2.24				Cr
5	4	92.51	0.25		0.4		2.59		0.09		Cr
6	66.32	29.15	1.3				2.94	0.56			Fe(Cr)
7	77.5	17.8			0.88	0.26	3.13				Fe(Cr)
8	16.94	3.09	0.24		79.22					0.42	Si(Fe)
9	3.38	93.22			0.45		2.92				Cr
10	3.21	93.47	0.13				3	0.02			Cr
11	3.22	93.26					2.97	0.36			Cr
12	73.62	16.01	7.46	0.72	0.4		1.58				Fe(Cr, Ni)
13	69.89	14.42	12.16		0.32		3.18				Fe(Cr, Ni)

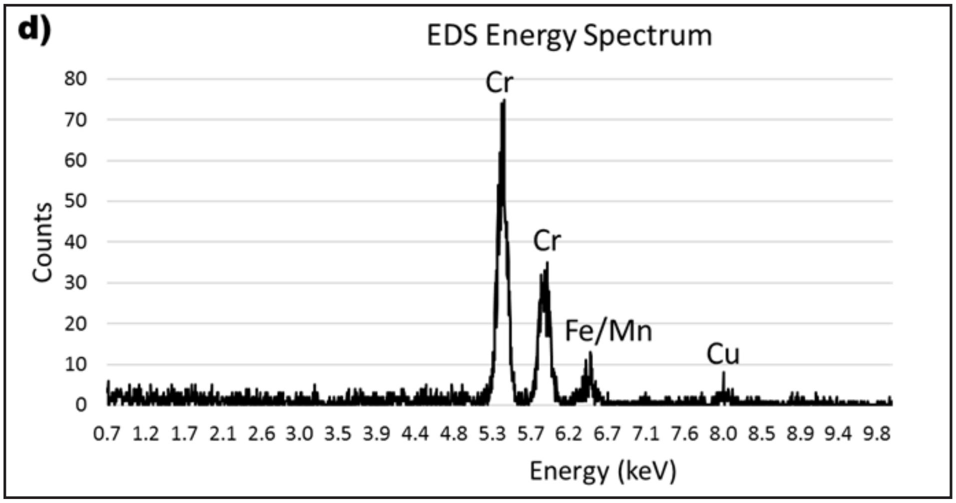

Figure 3. (a) TEM and (b) STEM images of stainless steel 316 sample prepared using HPT with the locations of the EDS point scans marked. (c) Table showing composition results obtained via EDS in STEM. (d) EDS spectrum corresponding to point Scan 4 in (b).

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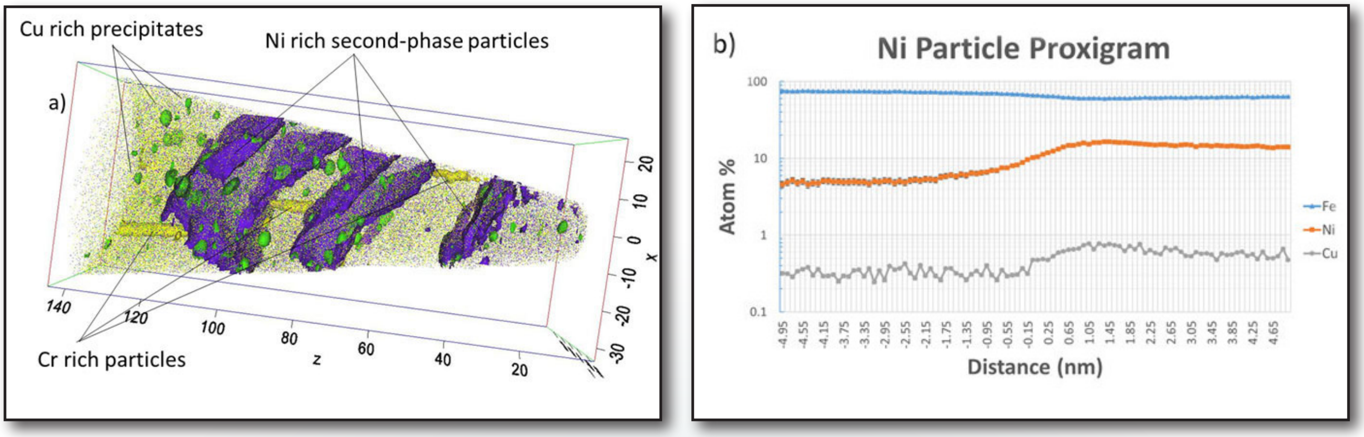

Figure 4. (a) Atom probe data for stainless steel 304 processed by high pressure torsion. Ni is represented in violet, Cr in yellow, and Cu in green. Some of the Cu rich precipitates are formed on the surfaces of the Ni rich particles. (b) Proximity histogram concentration profile of the Ni rich particle on the left of (a). The increase in Cu concentration is most likely due to the formation of Cu rich precipitate on the surface of the Ni rich particle.

their conventionally processed counterparts, owing to significant strengthening by the grain boundaries (GBs), and have enhanced irradiation tolerance due to the GBs' role as sinks or recombination centers for radiation-induced defects. Austenitic steels are important core-internal materials for light-water reactors (LWRs). F/M steels are the leading fuel cladding and structural materials for advanced fast reactors. Life extension of LWRs and development of fast reactors requires steels with enhanced irradiation tolerance and higher strength. This work will establish, for the first time, the performance of UFG and NC variants of reactor structural and cladding steels produced by ECAP or HPT, under neutron irradiation at relevant reactor operating temperatures. Our project is focused on pre-irradiation characterization, neutron irradiation, and post-irradiation examination.

Current status

Major activities since the start of the project in October 2016 include pre-irradiation characterization, neutron irradiation design, and design of specific geometry and dimensions for specimens to be neutron irradiated. The research team performed the preliminary pre-irradiation characterization of bulk nanostructured austenitic steels (304 and 316 steels) manufactured by ECAP and HPT, including mechanical testing (via microhardness measurement) and microstructural examination. Microhardness measurements indicated that these steels have significantly higher hardness/strength compared to their conventional coarse-grained counterparts. Limited transmission electron microscopy (TEM) studies were performed. Figure 2 shows TEM images of stainless steel 316 processed by ECAP and HPT. The grain size of the ECAP sample was found to be in the UFG range, and that of the HPT sample in the NC regime, verifying that ECAP and HPT

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can produce UFG or NC structures in these austenitic steels. Second-phase particles were found in these UFG or NC austenitic steels, although these steels are nominally single-phase materials. The researchers used scanning transmission electron microscopy (STEM) coupled with energy-dispersive x-ray spectroscopy (EDS) to study the distribution and composition of these second-phase particles. Figure 3 displays representative second-phase particles identified in HPT 316 sample. Cr-rich and Si-rich second-phase particles are observed. Atom probe tomography (APT) was used to further investigate these second-phase particles and possible GB solute segregation. Figure 4 shows some APT data obtained on HPT 304 steel. The results indicate the presence of Ni-rich, Cr-rich, and Cu-rich second-phase particles in the material. Also, it is possible that some of the Cu-rich precipitates have nucleated on the surface of the Ni-rich particles.

The researchers performed limited electron backscatter diffraction to study the grain orientation and phases in these steels. Preliminary x-ray diffraction was performed to study the phase compositions in these UFG or NC austenitic steels. Analysis of the results is underway. A preliminary understanding of the microstructure of the UFG or NC austenitic steels has been accomplished. Preliminary neutron irradiation design was performed, including mechanical design, neutronics/physics calculations, and thermal and structural analyses. Although the NSUF researchers primarily performed this part of the work, the Idaho State University team also provided input. The design parts/aspects were made ready for conceptual design review. Specific geometry and dimensions for specimens to be neutron irradiated were designed and determined.

More pre-irradiation characterization of the UFG or NC austenitic steels is ongoing, including mechanical testing and microstructural characterization, to be followed by detailed analyses of the results. Mechanical testing and microstructural characterization are also being performed on UFG or NC F/M Grade 91 steel. Materials to be neutron irradiated are being machined into specific geometry and dimensions, including tensile, hardness, and TEM specimens. More detailed design is being carried out for neutron irradiation.

Conclusions

UFG and NC steels manufactured by ECAP and HPT are expected to have significantly enhanced irradiation resistance and strength compared to their conventionally processed coarse-grained counterparts. The team obtained a preliminary understanding of the microstructure of the UFG or NC austenitic steels during this study. Preliminary neutron irradiation design has been performed. More detailed pre-irradiation characterization is ongoing, and detailed design is being carried out for neutron irradiation. Neutron irradiation and post-irradiation examination will be performed on UFG and NC steels manufactured by ECAP and HPT to assess their irradiation performance. ECAP and HPT will be assessed for fabricating materials with improved performance for current and advanced reactors, resulting in an established/enhanced understanding of the irradiation effects in UFG and NC steels.

SMR Reactor Vessel Manufacture/Fabrication/Demonstration Project




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Many of the same manufacturing/fabrication technologies that were employed for light water reactor (LWR) plants built 30 to 50 years ago are also being employed today to build advanced light water reactors (ALWRs). Manufacturing technologies have not changed dramatically for the nuclear industry even though higher quality production processes are available that could significantly reduce the overall cost of components. New technologies that can accelerate production and reduce costs are vital for the next generation of plants, small modular reactors (SMR), and Advanced GEN IV plants to ensure they can be competitive in the current and future market.

The current project will demonstrate and test several new technologies with the goal of producing critical assemblies for a two-thirds scale demonstration SMR reactor pressure vessel (RPV). Through use of electron beam welding, powder metallurgy-hot isostatic pressing (PM-HIP), diode laser cladding, bulk additive manufacturing, and advanced machining, the Electric Power Research Institute (EPRI) and the United Kingdom (U.K.)-based Nuclear Advanced Manufacturing Research Centre (Nuclear-AMRC), together with a number of other industrial team members, seek to demonstrate that critical sections of an SMR RPV can be manufactured and fabricated in less than 12 months and at a cost savings of more than 40% compared to today's technologies. The project aims to demonstrate and test the impact that each of these technologies can have on future production of SMRs, and explore the relevance of the technologies to the production of ALWRs, SMRs, GEN-IV, ultra-supercritical fossil, and supercritical CO_2 plants. The project, if successful, may accelerate deployment of SMRs in both the United States (U.S.) and U.K., and ultimately throughout the world.

Tasks

The project consists of eight individual tasks. The first two focus on demonstrating technologies to manufacture and fabricate the lower and upper assemblies of the NuScale Power SMR (Figure 1). The lower section (Figure 2a) will include a lower RPV head, a lower RPV flange shell, and an upper RPV transition shell. The upper section (Figure 2b) will include an RPV top head, a pressurizer (PZR) shell, an integral steam plenum, and a steam plenum access assembly.

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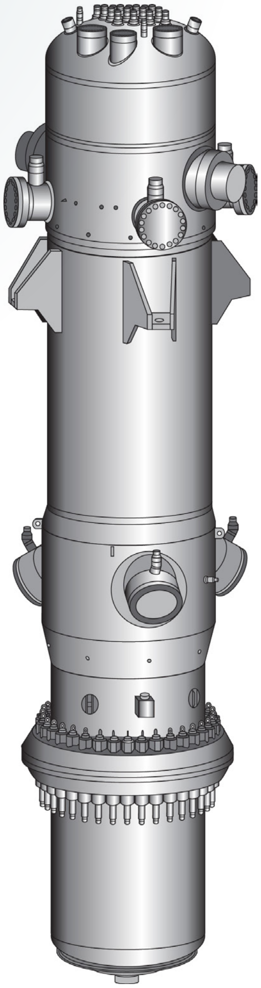

Figure 1. Representative model of the NuScale Reactor Pressure Vessel (courtesy of NuScale Power).

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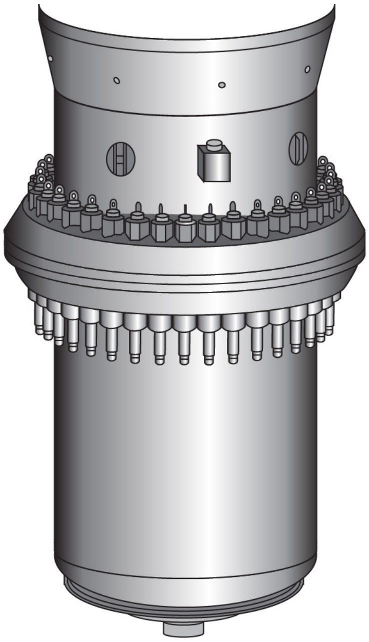

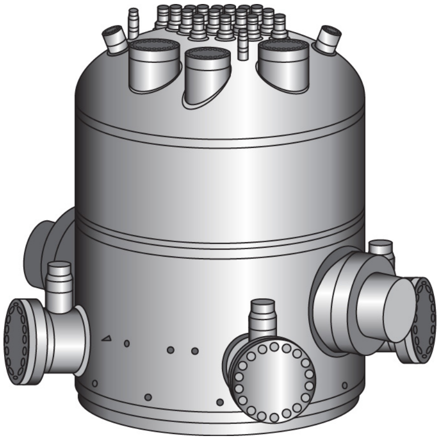

Figure 2a. Lower Assembly, including the lower head, lower RPV flange shell, and upper RPV transition shell.

Figure 2b. Upper Assembly, including the upper head, PZR shell, integral steam plenum, and steam plenum access ports. The two schematics provide a representative model (courtesy of NuScale Power).

The middle section was omitted because it will use many of the same technologies as the other sections. Additional tasks that support the production steps include development steps for thick section electron beam welding, diode laser cladding, elimination of DMWs, potential elimination of in-service inspection via solution heat treatment, ASME Code, and mechanical testing at Oak Ridge National Laboratory to support the ASME Code activities.

Current Status

The jointly funded project was initiated in Q3-2016 , with the effort thus far focused on:

- Creating multiple SOLIDWORKs drawings for two-thirds scale components (performed by NuScale Power)
- Significant planning/scheduling to allow manufacture and fabrication of the lower and upper reactor assemblies.
- Atomizing A508 powder for production of the lower assembly components.
- Establishing several subcontracts
- Detailed planning of the lower reactor head manufacture and fabrication—the first task in the project.

In the coming weeks, the investigators plan to complete the design of the lower reactor head and then begin fabricating the cans (capsules) to produce halves of the head. The lower reactor head will be produced using PM-HIP, a technology previously demonstrated in the DOE Nuclear Energy Enabling Technologies (NEET) program. The lower head will be assembled using two tori-spherical halves that are joined together via electron beam welding (EBW) (Figure 3) and then heat-treated to remove evidence of the weldment. Investigators opted to produce two halves of the lower head and then join them together since the largest HIP furnace in the U.S. today is only 60-inches in diameter. EPRI is currently working with industry to bring a 140-inch diameter by 160-inch long (3.5 m × 4 m) HIP unit to the U.S. to produce large components.

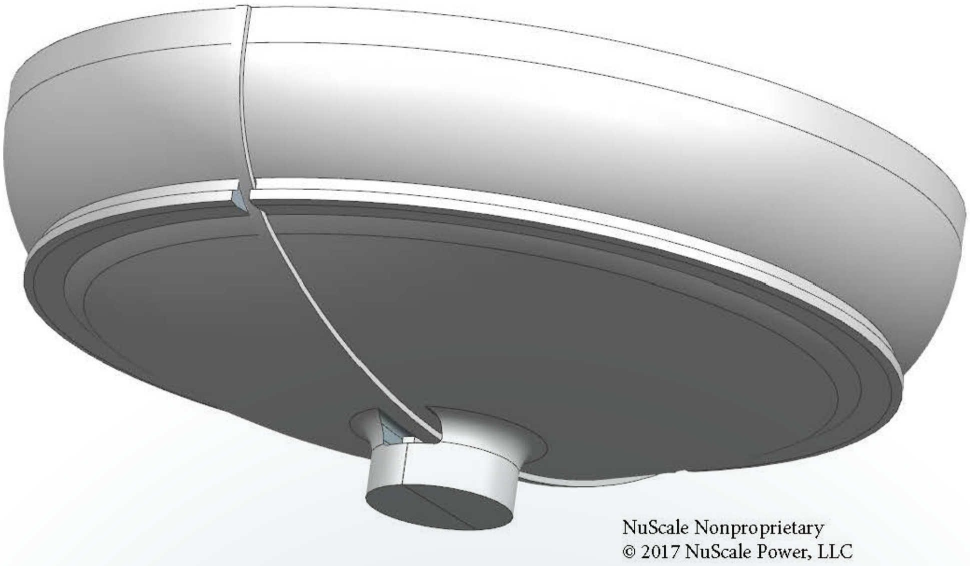

Figure 3. The lower head will be produced using PM-HIP and then joined together using electron beam welding. **The representative model is courtesy of NuScale Power.**

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Impact, Value, and Implications

If successful, the impact of the current SMR manufacturing/fabrication project will be dramatic in terms of cost reduction, quality, and schedule. Below are a few of the projected outcomes from the project:

- Demonstrate an advanced welding technology, EBW, and reduced pressure EBW for fabrication of reactor sections, which can reduce welding time by 90% over conventional welding processes and methods.
- Demonstrate PM HIP methods to manufacture difficult-to-produce sections of the SMR (upper and lower reactor heads, plenum, access covers, etc.) in less than 6 months each.
- Potential to eliminate in-service inspection requirements for no fewer than five (out of seven) full-diameter circumferential welds through the use of the EBW process and solution annealing.
- Develop/demonstrate diode laser cladding (DLC) technologies that can apply thin (1 mm) layers of cladding using robotics. The overall volume of material required for cladding will be reduced by 75% resulting in a substantial cost savings across the entire vessel inner diameter (ID) and outer diameter (OD).

Acknowledgements

The principal investigator would like to recognize Vern Pence (NuScale Power) and Victor Samarov (Synertech-PM) who will be instrumental in production of major components in this project.

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3. Gandy, D., Siefert, J., Lherbier, L., and Novotnak, D., PM-HIP Research for Pressure Retaining Applications Within the Electric Power Industry, ASME 2014 Small Modular Reactors Symposium, Paper No. SMR2014-3305, Washington, DC, USA, April 15–17, 2014.

To submit information or suggestions, contact
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