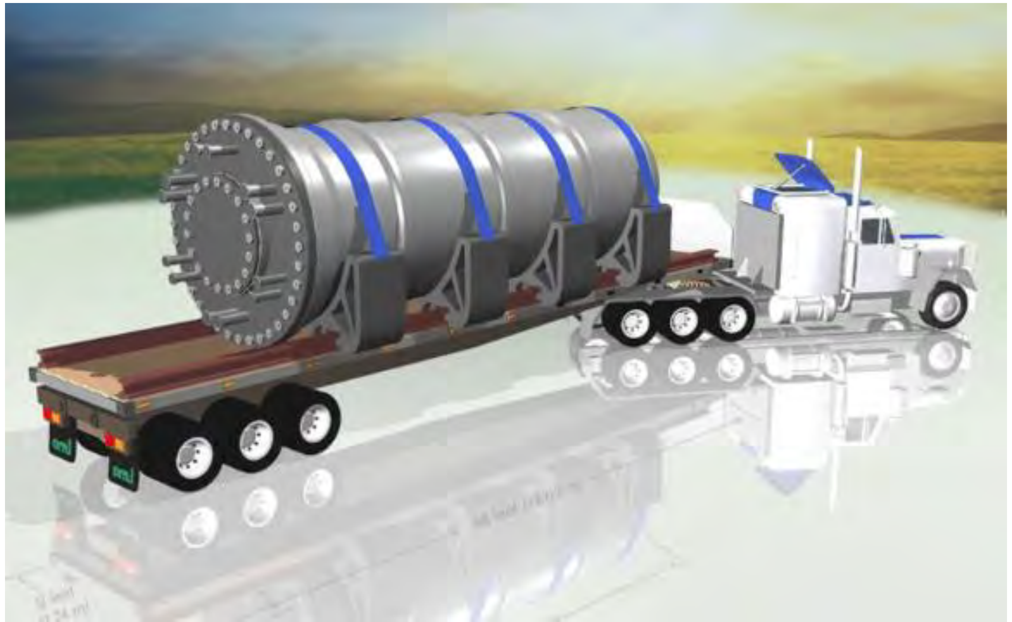
Opportunities and challenges in using additively manufactured materials in modular nuclear reactors



Scott Thompson, Ph.D.

Associate Professor
Mechanical & Aerospace Engineering
University of Missouri Research Reactor (MURR)

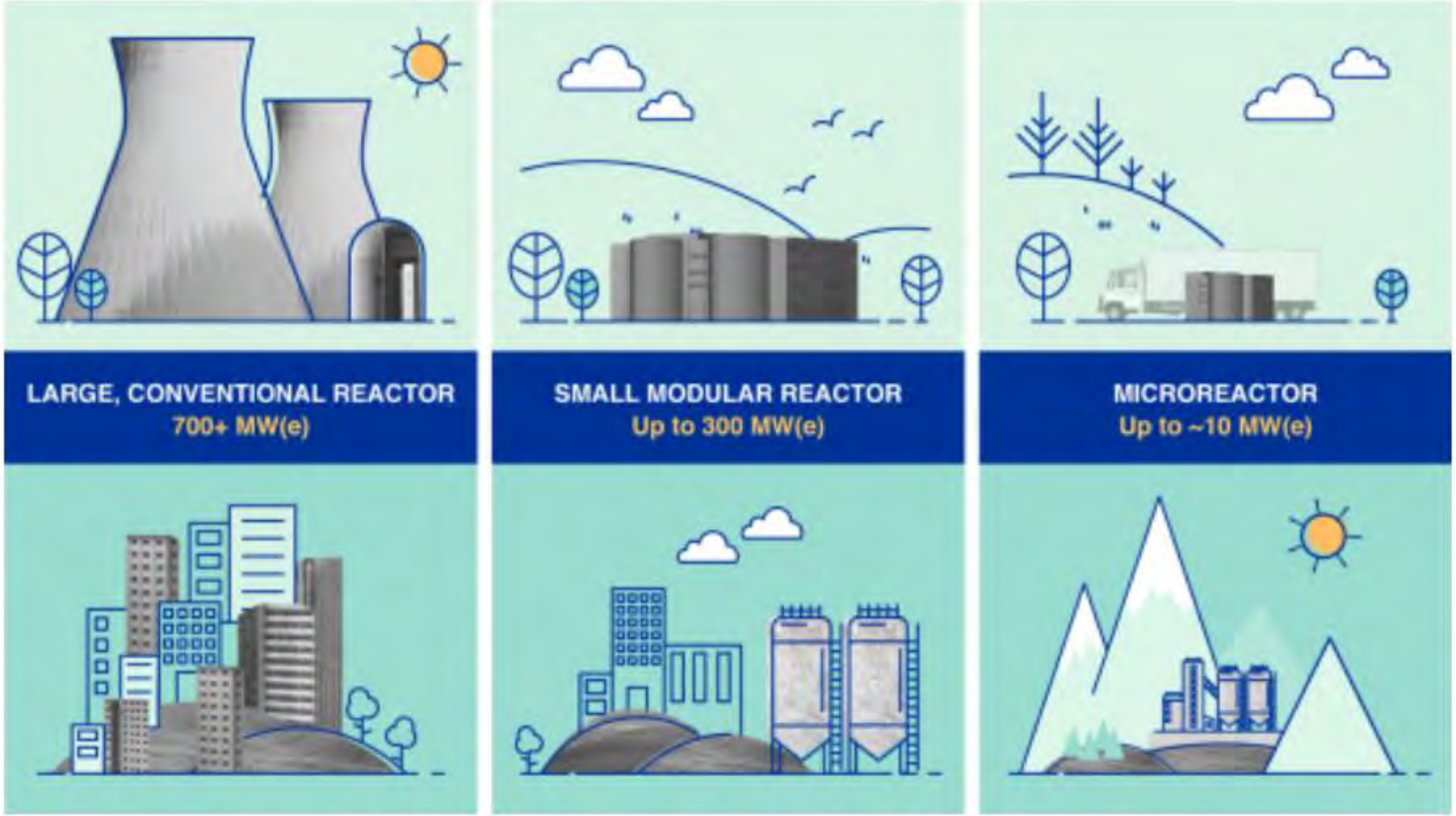
Email: smthompson@missouri.edu

October 3rd, Center for Energy Innovation Symposium

Topics

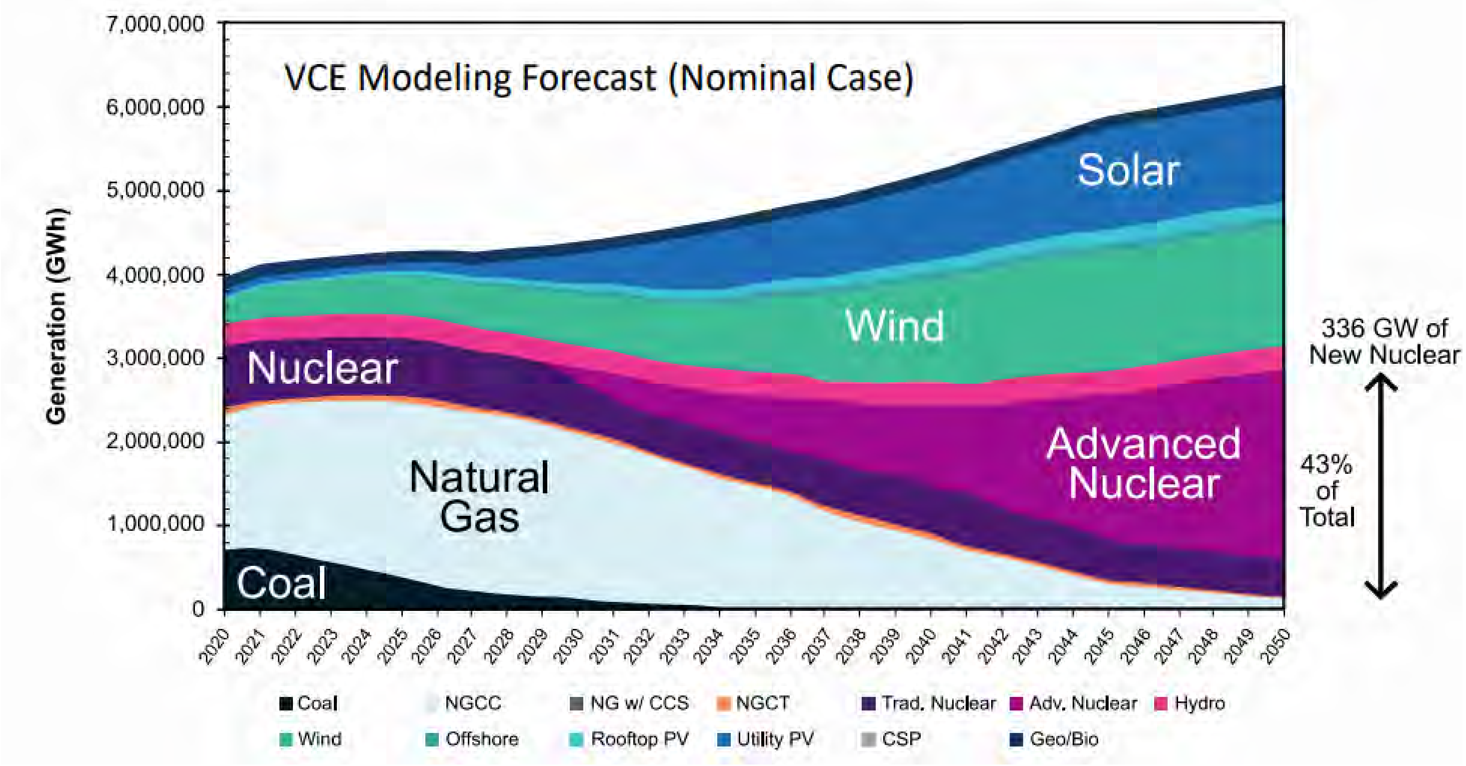
- Micro and small modular nuclear reactors
- Trends in nuclear power
- Metals additive manufacturing (AM)
- Opportunities for AM in nuclear industry
- Challenges in AM
- Ongoing research

Advanced Nuclear Reactors



International Atomic Energy Agency, 2023, “What are Small Modular Reactors (SMRs)?,” **IAEA Office of Public Information and Communication**, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

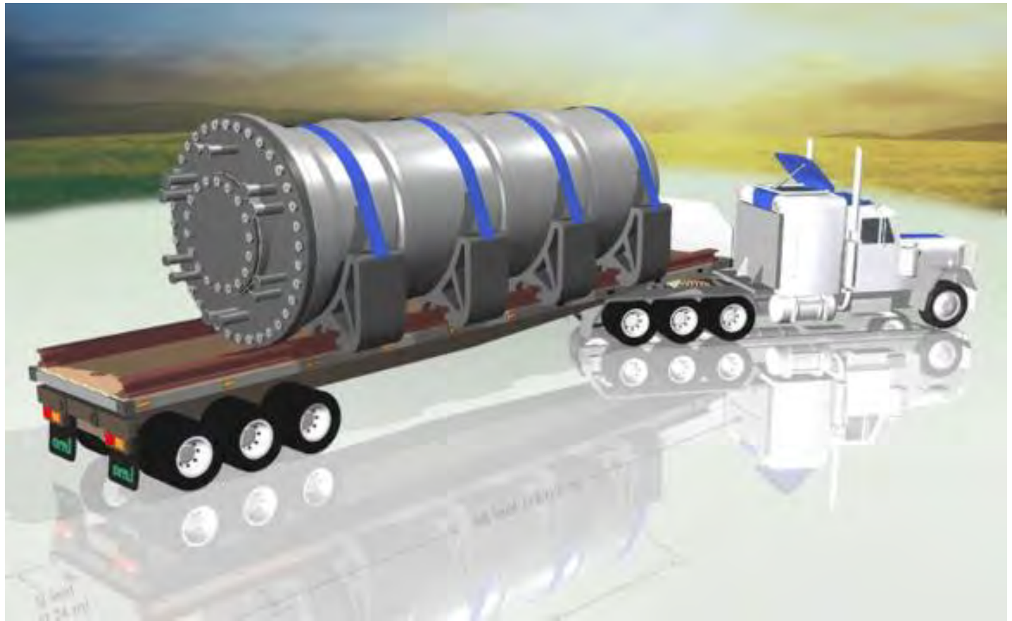
Advanced Nuclear Reactors



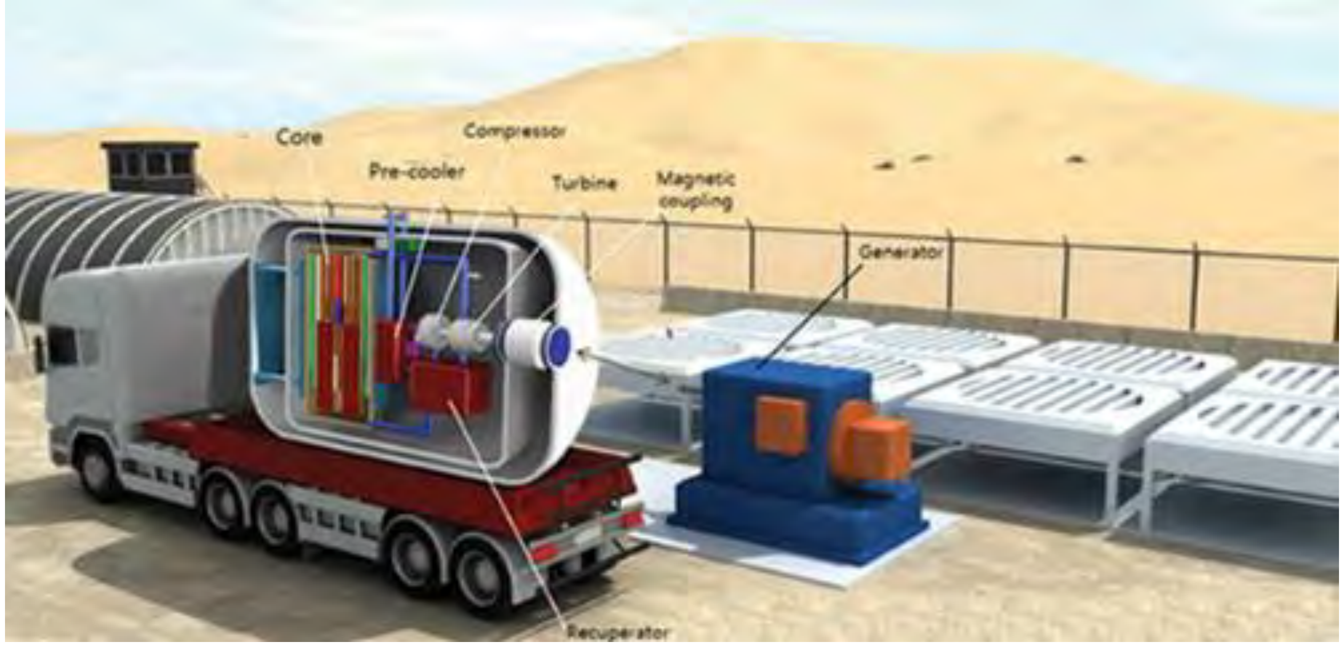
Source: Vibrant Clean Energy, *Role of Electricity Produced by Advanced Nuclear Technologies in Decarbonizing the U.S. Energy System* (June 2022), available at https://www.vibrantcleanenergy.com/media/reports/

Hilary Lane (Nuclear Energy Institute), 2023, "Securing the Future of the Nuclear Industry," **NRC AMT Workshop**, Rockville, MD, USA. https://www.nrc.gov/docs/ML2332/ML23324A239.pdf

Very Small Modular Nuclear Reactors

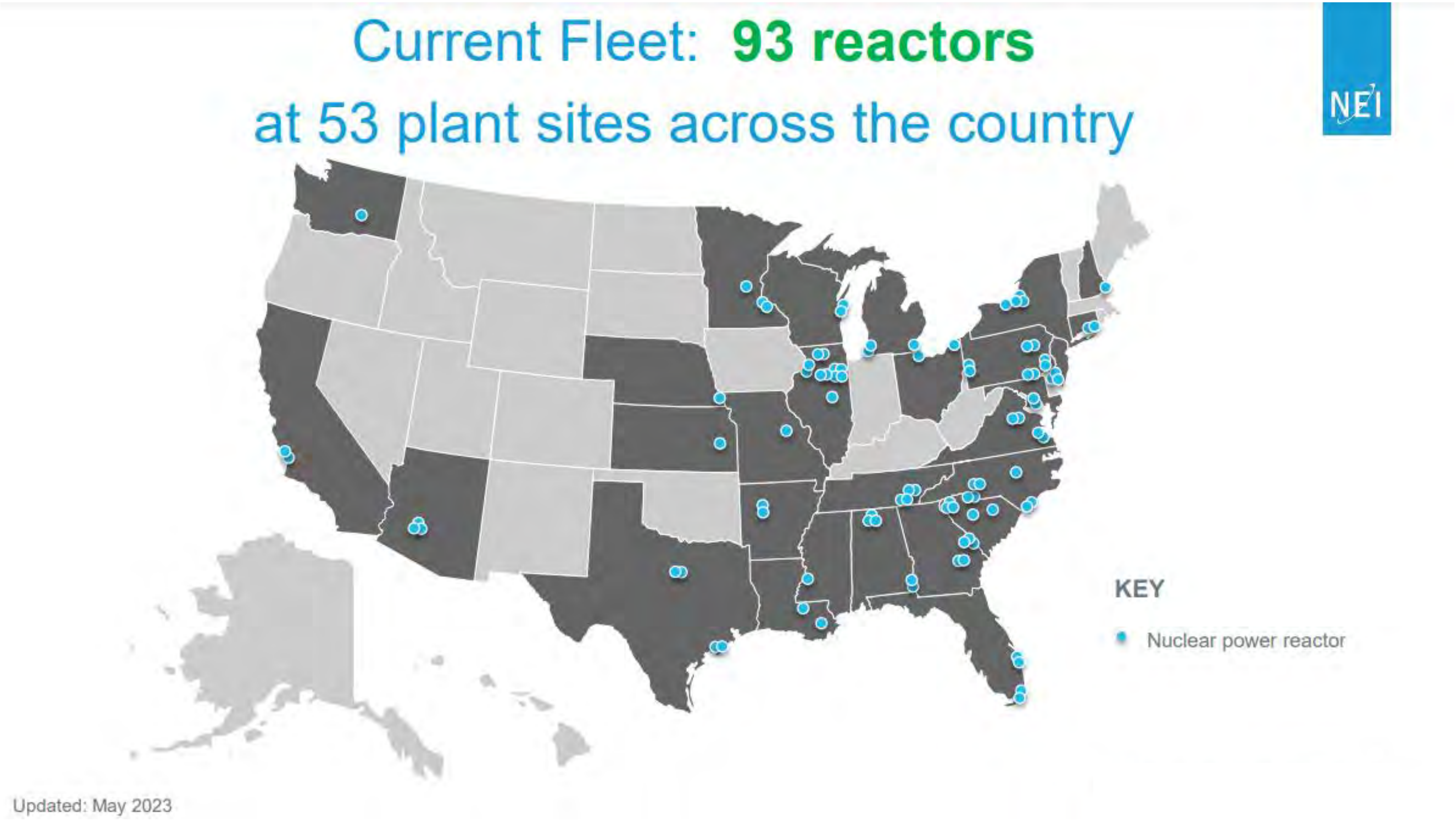


https://www.businessgreen.com/bg/news/3065864/going-nuclear-uk-readies-gbp32m-small-modular-reactor-testing-scheme



https://energypost.eu/small-modular-reactors-for-nuclear-power-hope-or-mirage/

Nuclear Power Resurgence

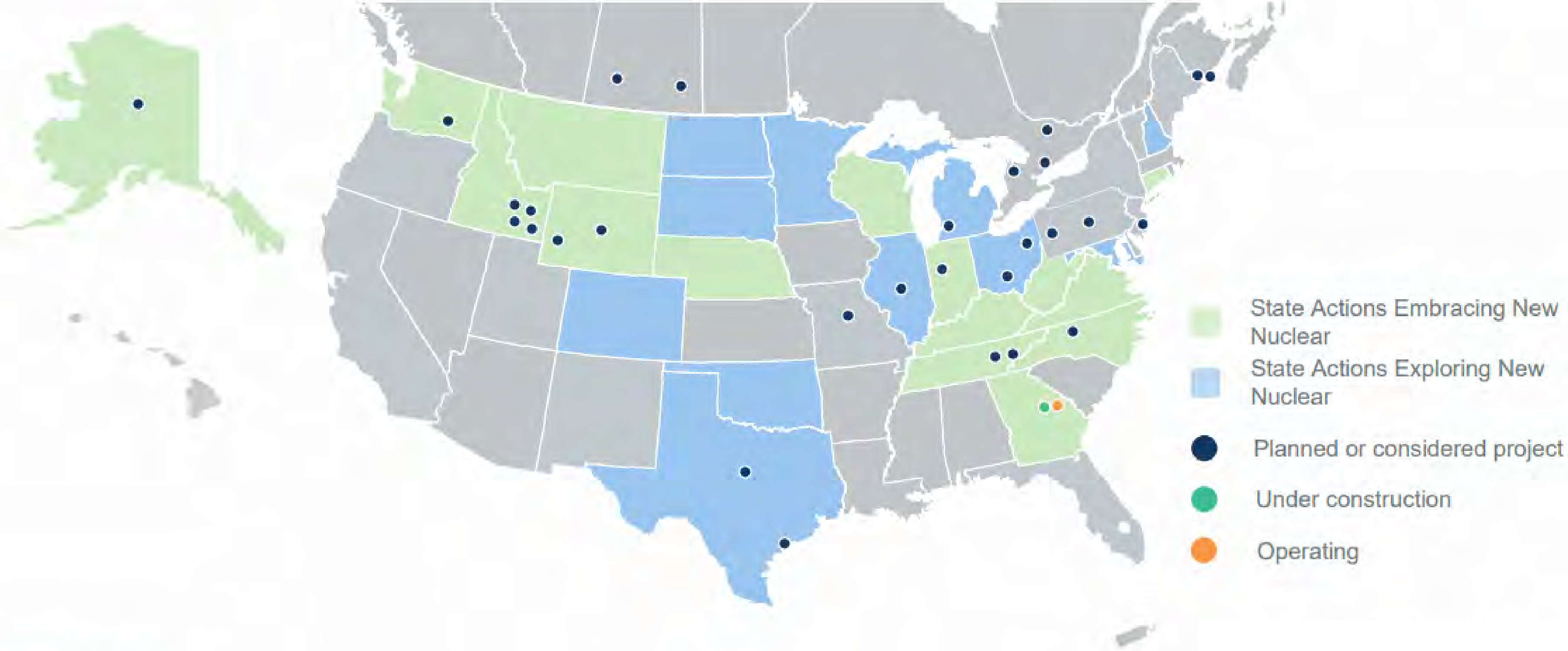


Hilary Lane (Nuclear Energy Institute), 2023, "Securing the Future of the Nuclear Industry," **NRC AMT Workshop**, Rockville, MD, USA. https://www.nrc.gov/docs/ML2332/ML23324A239.pdf

Nuclear Power Resurgence

Advanced Nuclear Deployment Plans

Projects in planning or under consideration in U.S. and Canada for Operation ~2030



Updated 10/09/2023

Hilary Lane (Nuclear Energy Institute), 2023, "Securing the Future of the Nuclear Industry," **NRC AMT Workshop**, Rockville, MD, USA. https://www.nrc.gov/docs/ML2332/ML23324A239.pdf

Advanced Manufacturing for Future Reactors

- Next-generation reactors will conists of hundreds of metallic components packaged together.
- Advanced, non-traditional manufacturing methods can serve this market sector well.
  - High-value, low production number parts
- Metals Additive Manufacturing (AM)
  - Laser-powder bed fusion (L-PBF)
    - Can achieve high resolution (~100 micron) for building complex, conformal parts

- Challenge: Part certification and the claims of legacy material/part equivalency
  - NRC

U.S.NRC

Additive Manufacturing?

"a process of joining materials to make objects from 3D model data, usually layer upon layer…"
- ASTM Standard F2792-12a

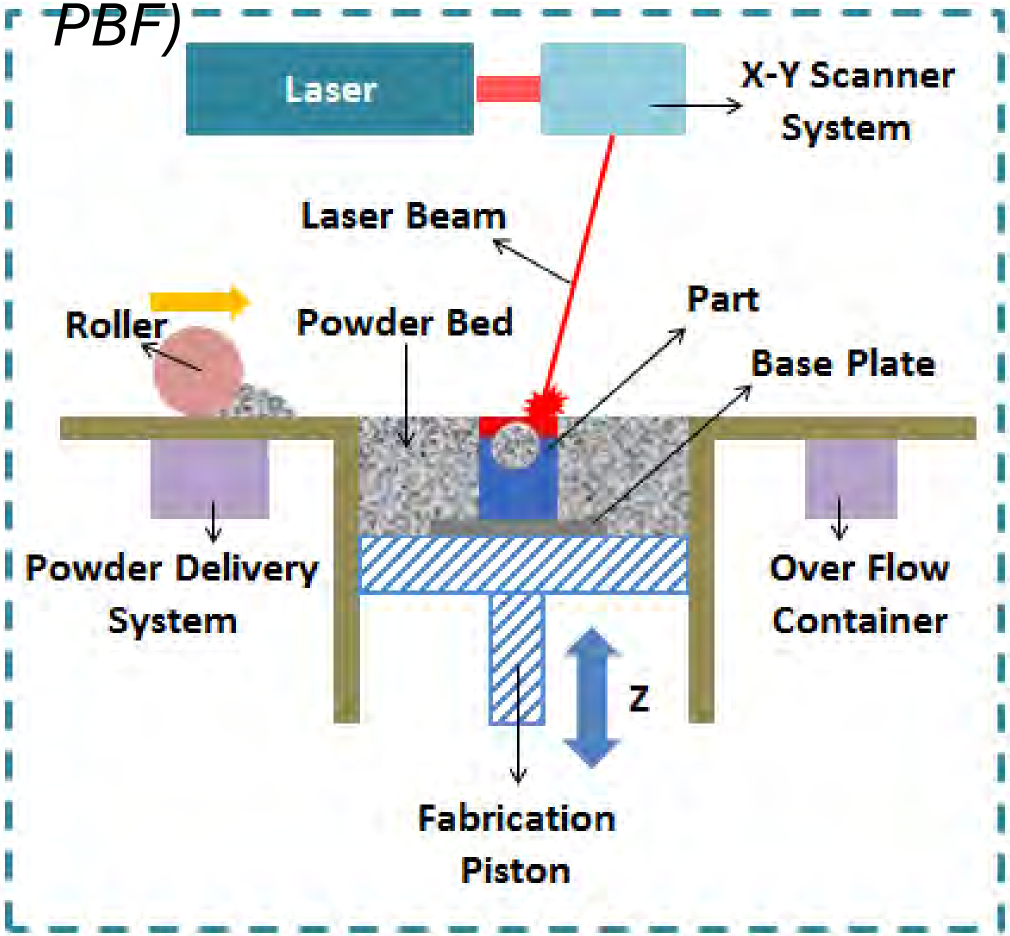
- Material extrusion
- Material jetting
- Binder jetting
- Vat photopolymerisation
- Sheet lamination
- Powder bed fusion (PBF)
- Directed energy deposition (DED)

- What changes among each technique?
  - Feedstock material/preform, feedstock delivery, energy deliver method

dupress.com/articles/additive-manufacturing-3d-opportunity-in-aerospace/

Additive Manufacturing

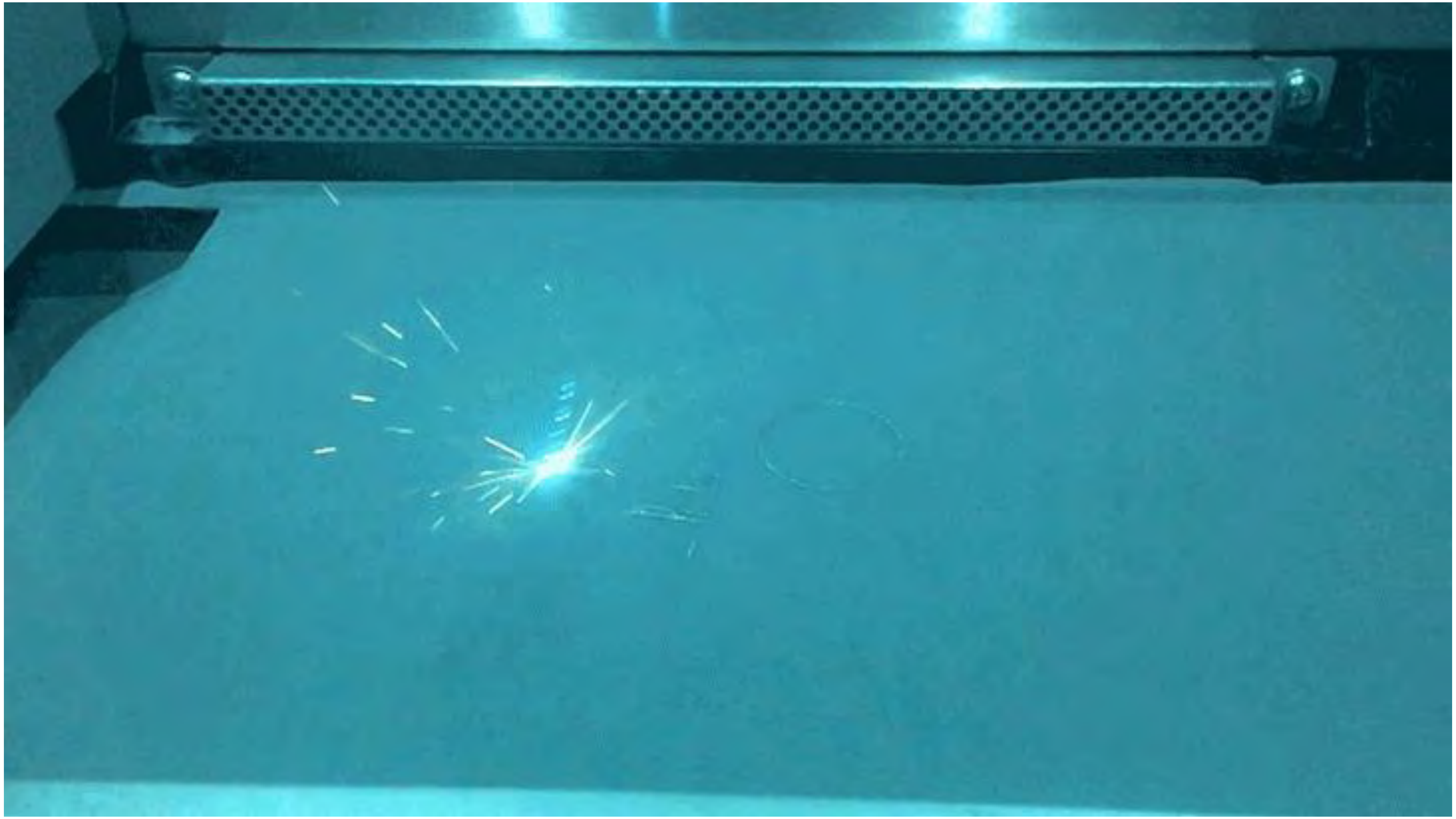
Laser Powder Bed Fusion (L-PBF)



Thompson, S.M., Bian, L, Shamsaei, N., Yadollahi, A., 2015, "An Overview of Direct Laser Deposition for Additive Manufacturing; Part I: Transport Phenomena, Modeling and Diagnostics," Additive Manufacturing, 8, pp. 36-62. DOI: 10.1016/j.addma.2015.07.001.

- Laser Powder Bed Fusion (L-PBF): bed of powder selectively melted by a laser beam
  - Highly adopted metals AM method
  - Complex geometries
  - Unmelted powder = support structure
  - Good surface finishes

Laser-Powder Bed Fusion

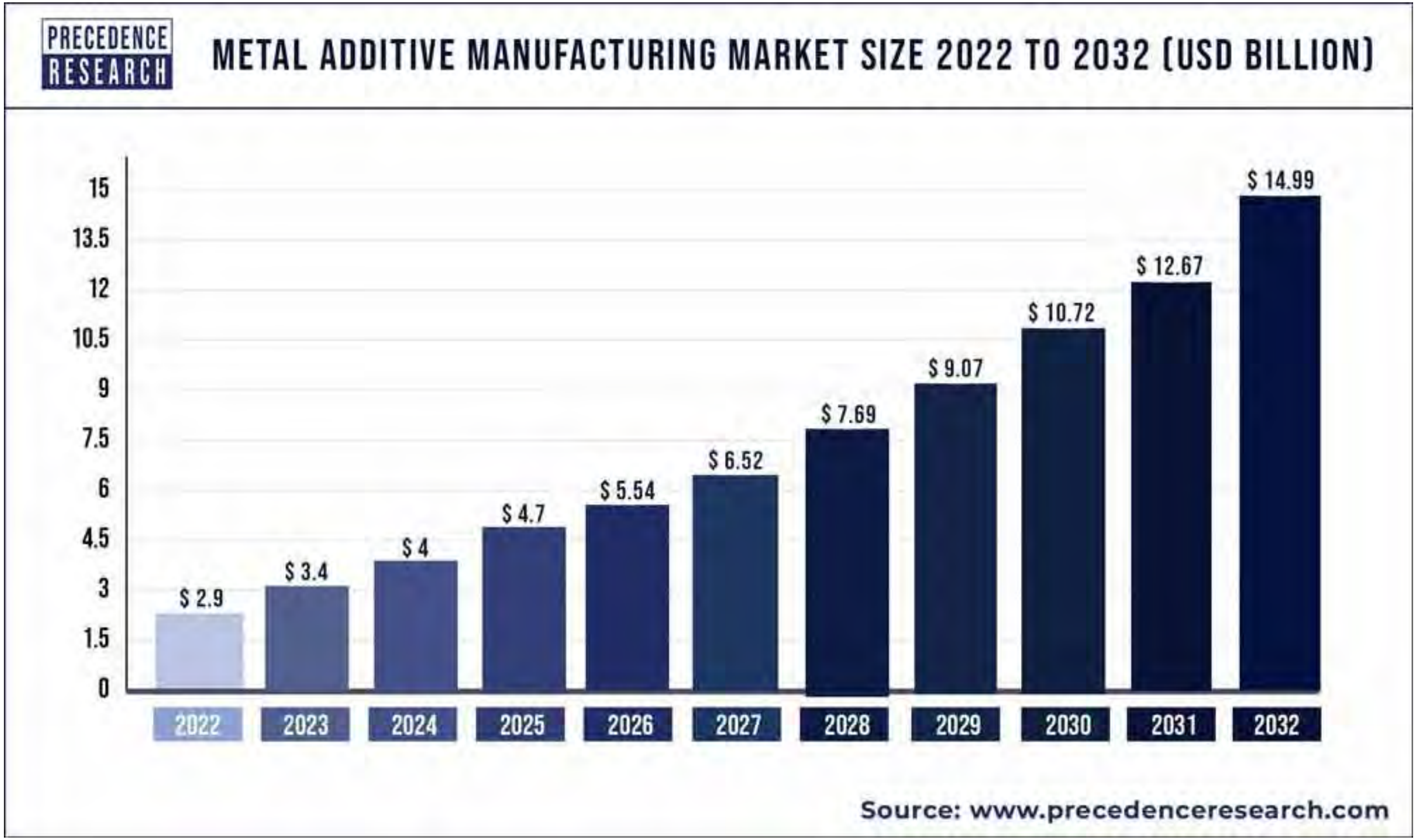


https://3dprintingindustry.com/news/3d-printing-titanium-the-bin-of-broken-dreams-part-1-44130/

Additive Manufacturing Benefits

- Customize parts for specific applications
  - Biomedical, aerospace, automotive
- Create tailored properties
- Wider design space
- Light weighting (mass reduction)
- Manufacture in remote locations
  - Submarines, battlefield, ships, space
- More resilient supply chains and reduced stockpiles
- Consolidate assemblies
- Rebuild legacy, hard-to-find components
- High value, low production parts

Growth in Additive Manufacturing



Additive Manufacturing of Compact Heat Exchangers

- AM enables the design of novel HeXs outside the domains and constraints of typical HeXs in terms of geometry, materials and performance, including:
  - part/joint consolidation,
  - non-uniform cross-sectioned channels,
  - asymmetric core architecture,
  - fully-circular channels (as opposed to semi-circular),
  - reduced wall thicknesses,
  - stream-tailored (cold/hot channel) designs,
  - new levels of tortuosity (in-plane and out-of-plane twisting,
  - distributor-channel transitions,
  - new nozzle/header flow configurations,
  - unconventional header geometries,
  - biomimicry

https://www.metal-am.com/ge-research-launches-project-to-develop-metal-additively-manufactured-heat-exchanger/

www.renishaw.com

Additive Manufacturing in Aerospace

- GE realized a design for a next-generation fuel injection nozzle that could not be successfully casted.
- Rather than 20 pieces welded together, the new tip was a single elegant piece that weighed 25 percent less than its predecessor, and was five times more durable and 30 percent more cost-efficient.

Nuclear Components

- Examples of nuclear components that can be additively manufactured
  - Heat exchangers
  - Flanges
  - Support brackets
  - Containers
  - Manifolds
- Can integrate structural health monitoring sensors more easily into AM'ed parts

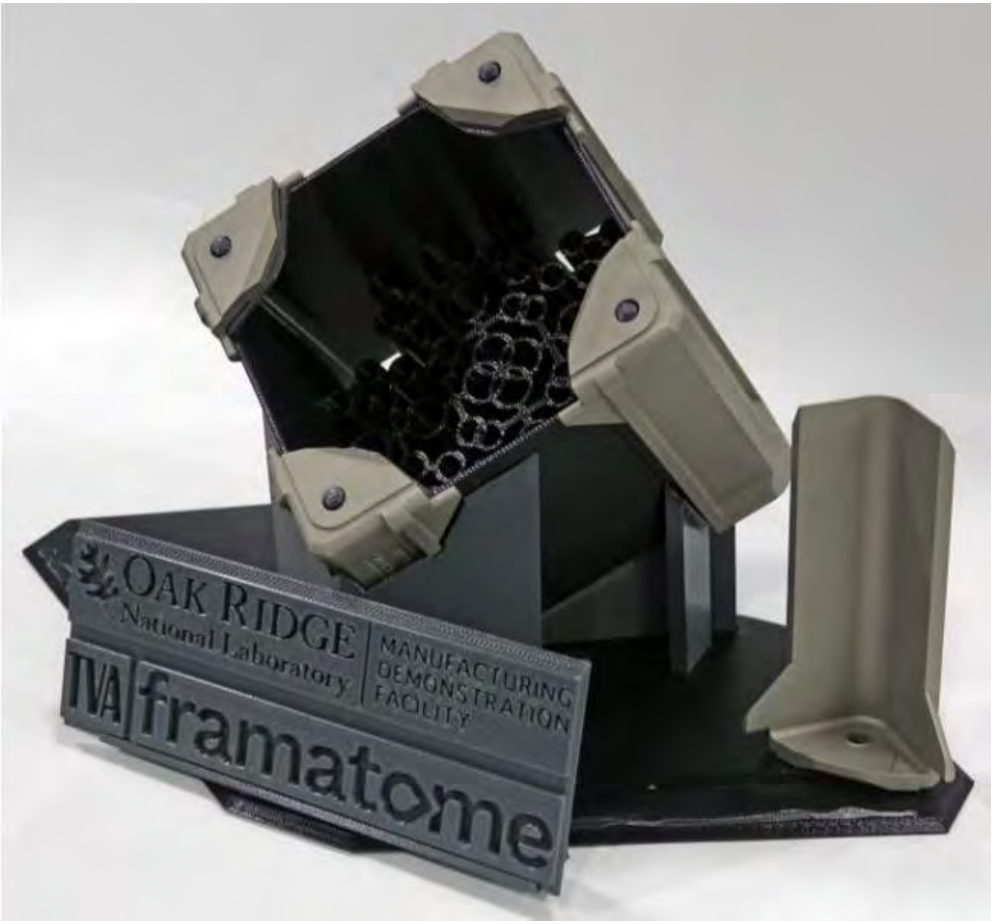
Courtesy: Westinghouse

Courtesy: Framatome

Hilary Lane (Nuclear Energy Institute), 2023, "Securing the Future of th
Nuclear Industry," **NRC AMT Workshop**, Rockville, MD, USA.
https://www.nrc.gov/docs/ML2332/ML23324A239.pdf

Nuclear Components

- Fuel assembly channel fasteners printed at Oak Ridge National Laboratory using AM and installed on ATRIUM 10XM fuel assemblies at Framatome's nuclear fuel manufacturing facility in Richland, Washington.

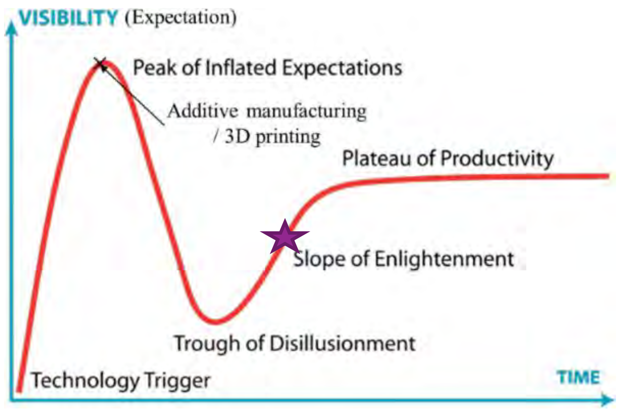


Advanced Materials and Manufacturing Technologies 2022 Roadmap, Department of Energy.

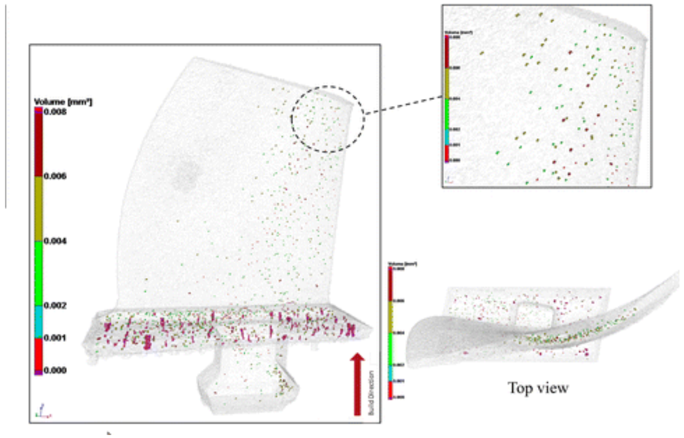
Challenges

“ u d u f i ddi iv
uf c u d i ?”

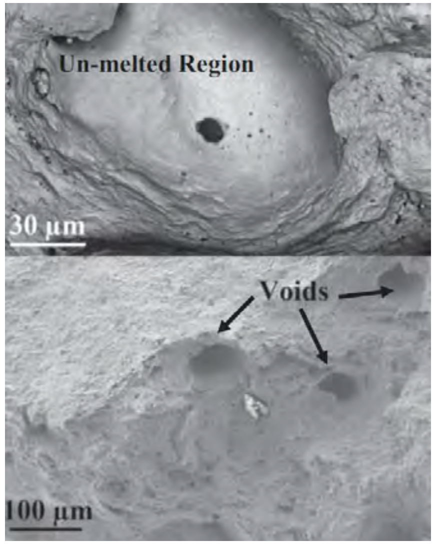
- **Defects in as-printed parts are common and the severity of the defects for a given application are not well quantified**
- Process repeatability is low
- Hundreds of process/design variables
- Structural integrity of AM parts not known
- Minimal standards and regulation for production and end-parts
- Machine-to-machine variability
- Certification needed
- Demand for an AM-trained workforce
- Slow process
- Quality control technology lagging



Huang Y, Leu MC, Mazumder J, Donmez A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. ASME. *J. Manuf. Sci. Eng.* 2015;137(1):014001-014001-10. doi:10.1115/1.4028725.



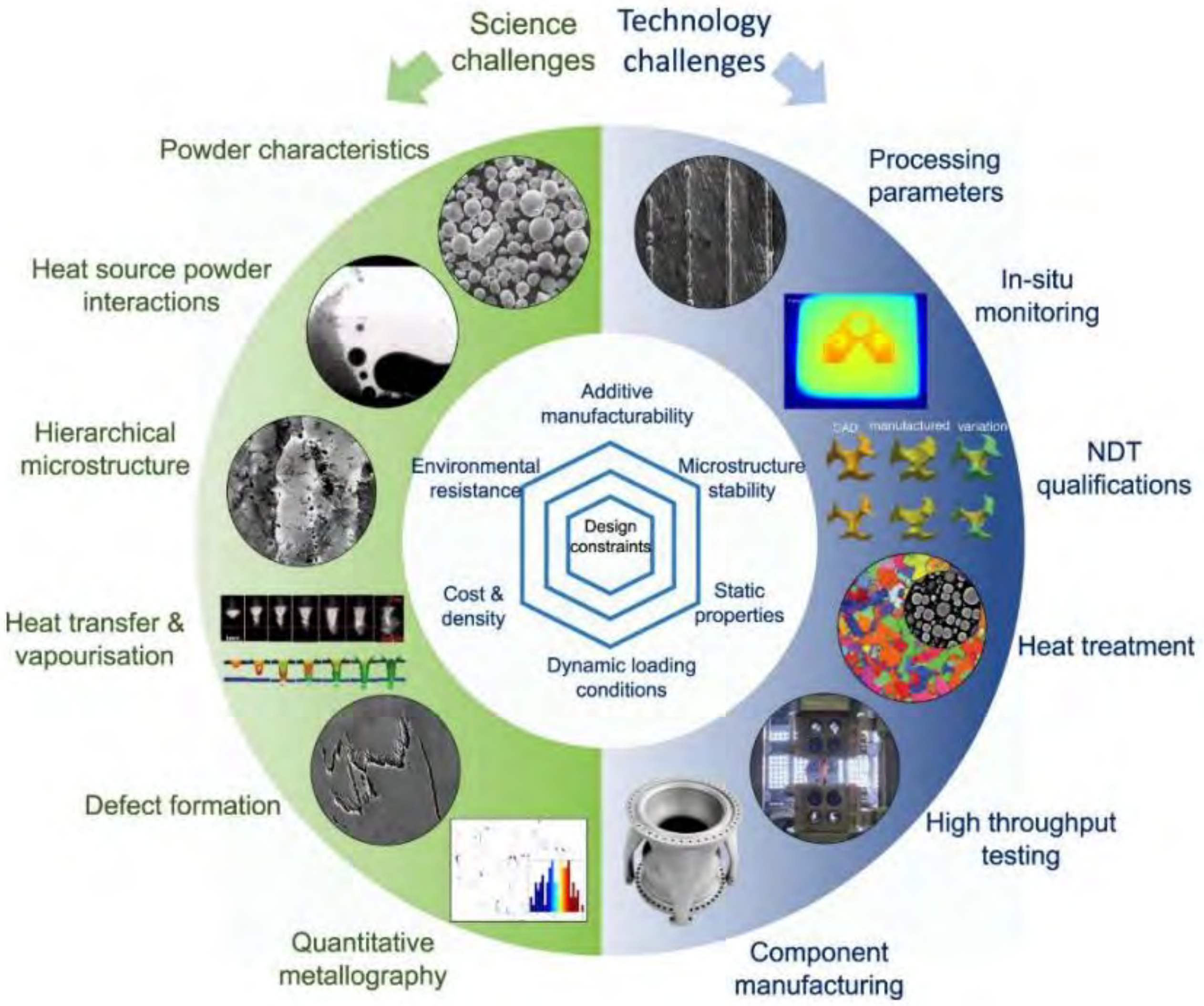
Seifi, M., Gorelik, M., Waller, J., Shamsaei, N., et al. JOM (2017) 69: 439. doi:10.1007/s11837-017-2265-2



Challenges

- Challenge: Part certification and the claims of material equivalency
  - Code acceptance is taking too long; uncertainty in qualifying new alloys of interest

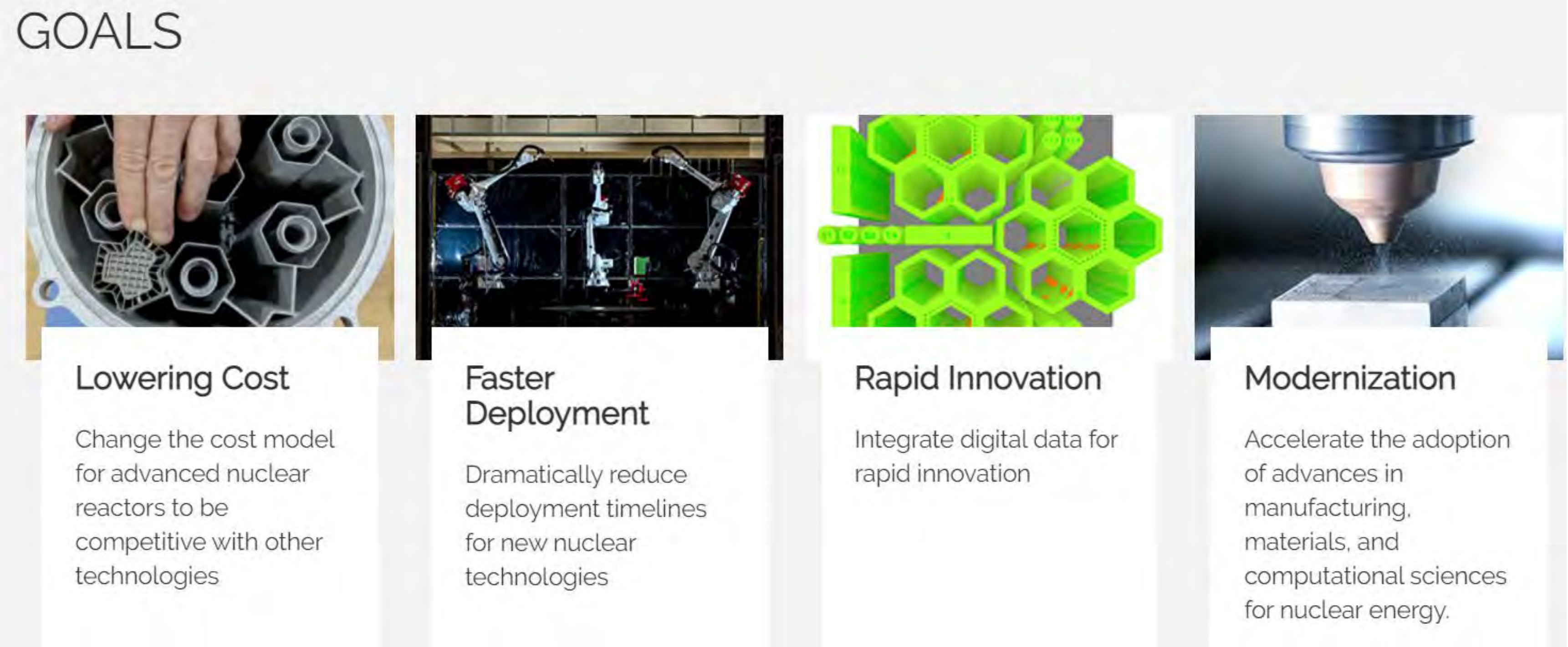
U.S.NRC



C. Panwisawas, Y. T. Tang, R. C. Reed, Nature Communications 11 (2020) 232

Transformational Challenge Reactor Program

- The Transformational Challenge Reactor Program combines AM with artificial intelligence (AI) to deliver enabling technologies for advanced reactors.
- The program targets delivering solutions to the high costs and lengthy deployment timelines that threaten the future of nuclear energy—the country's largest source of carbon-free energy.



Oak Ridge National Laboratory

C. Panwisawas, Y. T. Tang, R. C. Reed, Nature Communications 11 (2020) 232

DOE's AMMT Program

AMMT
ADVANCED MATERIALS AND MANUFACTURING TECHNOLOGIES

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Mission

Accelerate the development, qualification, and deployment of advanced materials and manufacturing in support of U.S. leadership in a broad range of nuclear energy applications.

Vision

Expansion of reliable and economical nuclear energy enabled by advanced materials and manufacturing technologies.

Goals

Four major goals were set to realize the mission and vision of the AMMT program:

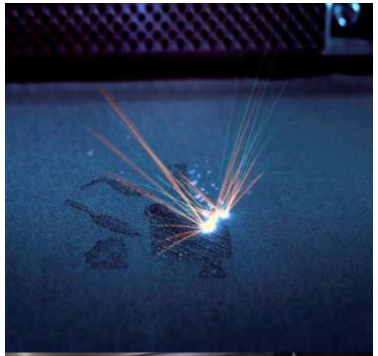
- Develop advanced materials & manufacturing technologies.
- Evaluate materials performance in nuclear environments.
- Establish and demonstrate a rapid qualification framework.
- Accelerate commercialization through technology demonstration.

Argonne NATIONAL LABORATORY | INL Idaho National Laboratory | Los Alamos NATIONAL LABORATORY | OAK RIDGE National Laboratory | Pacific Northwest NATIONAL LABORATORY

Metals AM at Mizzou!

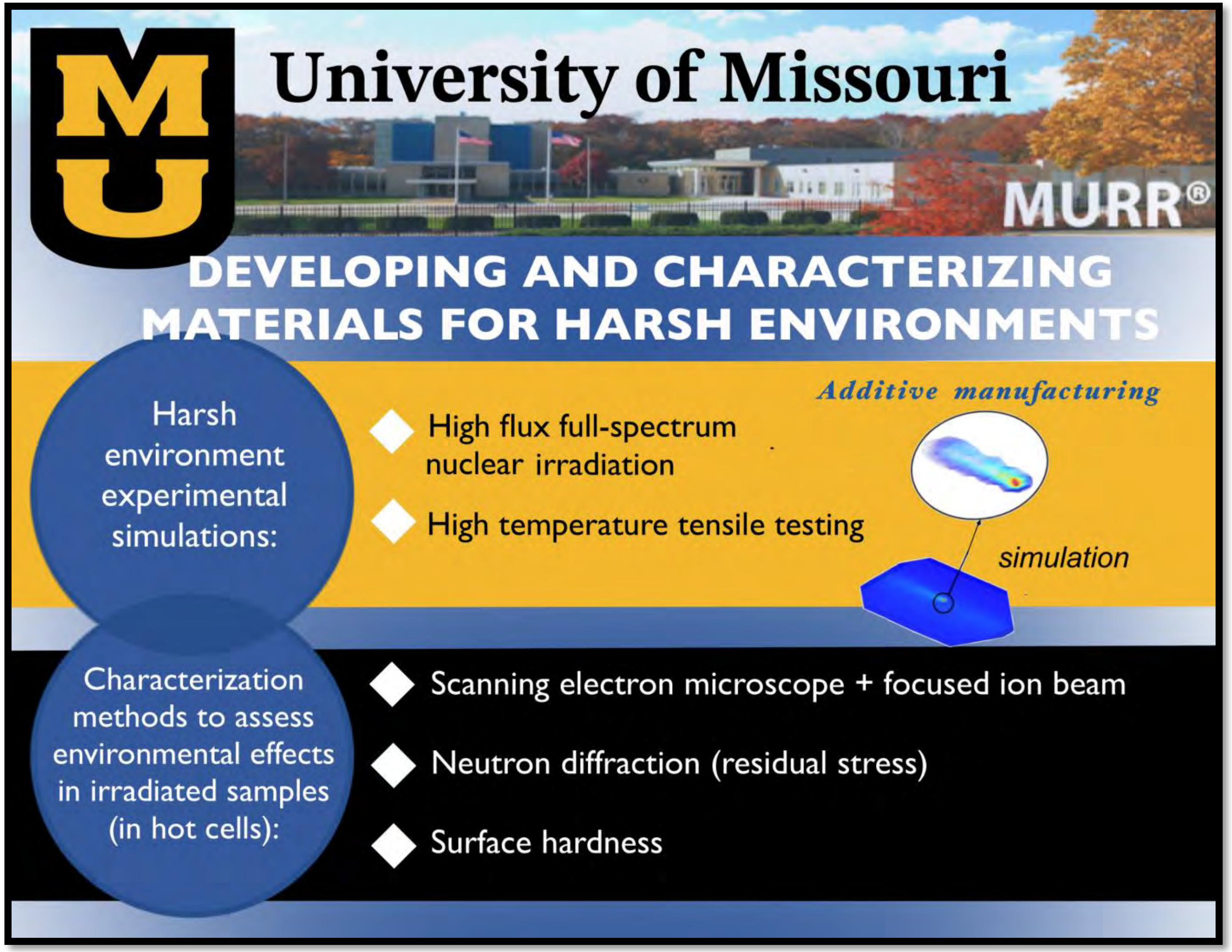
- Metals Additive Manufacturing Laboratory (Lafferre C3252)
  - Laser powder bed fusion of specimens for characterization and process optimization
  - Engineering AM’ed materials for their safe operation in harsh environments (radiation and high temperature)
  - Determining radiation damage mechanisms in AM materials
  - Quality control: Real-time detection of flaws during AM, methods for preventing and rectifying flaws
  - AM design rules for various materials and applications
- Metals AM Working Group forthcoming!

Trumpf Dual-Laser TruPrint 2000 PBF System
- Installed September, 2024



MURR®-Enabled Research

- We are using the unique capabilities of the University of Missouri Research Reactor (MURR) for characterizing nuclear irradiation effects on materials to fill knowledge gaps and support the nuclear industry.
- Largest university-based research reactor in the US (10 MW)
  - Can irradiate specimens for accelerated damage testing, through various methods, including positioning them near the reactor core.
  - Scanning electron microscope (SEM), tensile testing, and hardness testing capabilities all in-house.



Thanks!

For more information, please reach out:

Scott M. Thompson
smthompson@missouri.edu