Nuclear Reactor – Current state, challenges and future needs from materials perspective

Nov 21, 2019

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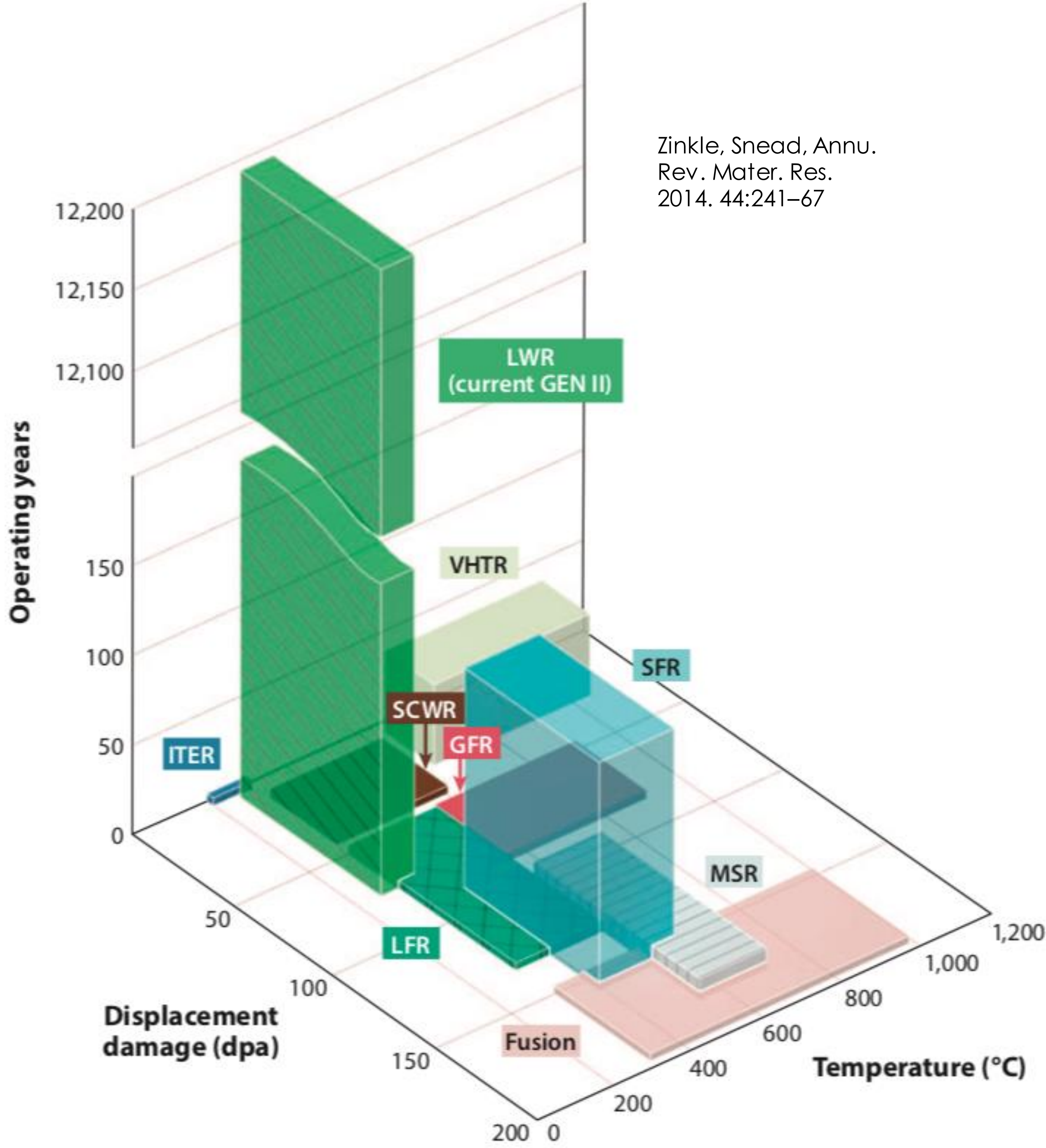
TCR Technical Director

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Outline

- Current status
- Towards high dose
- Towards high temperature
- What is TCR?
- Opportunities in advanced manufacturing
  - Advanced processing and designs
  - new approach to qualification



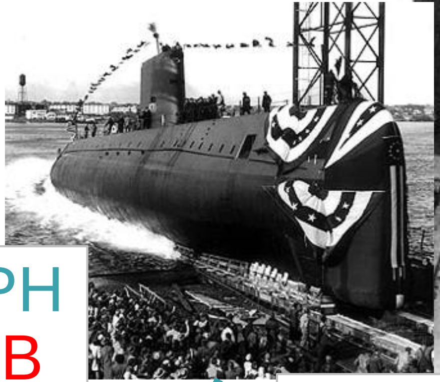
Zinkle, Snead, Annu. Rev. Mater. Res. 2014. 44:241–67

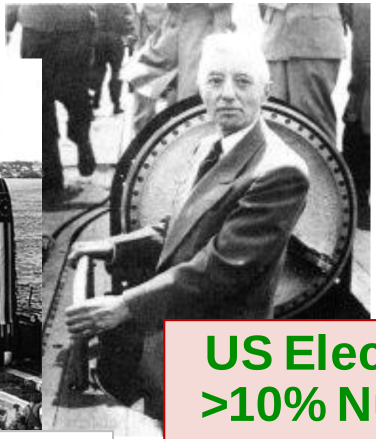
A Timeline

Chicago Pile-1

17-4 PH
A302B

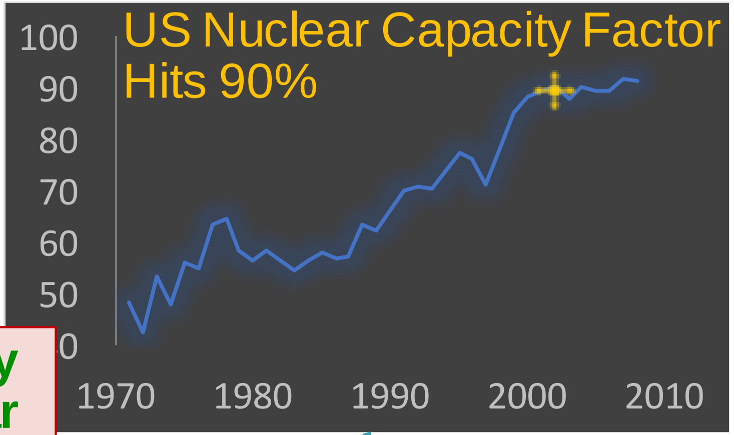
USS Natilus





IN 690

US Electricity >10% Nuclear



Chernobyl

Fukushima

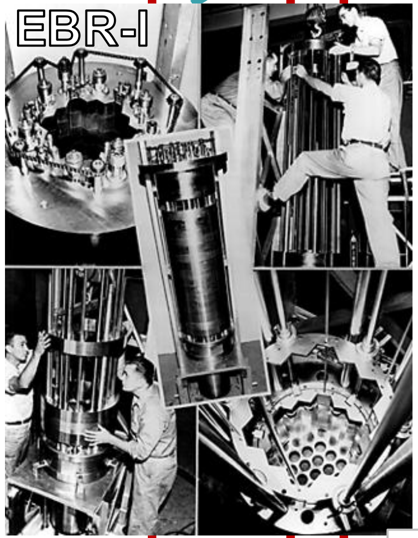
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

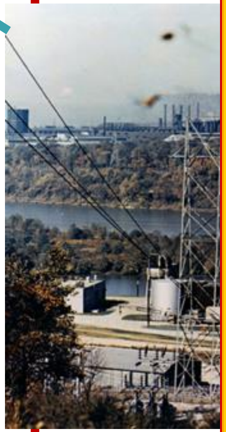
304SS

316SS
A286

IN 600

EBR-I





Shippin
Powe

X750

Zr-2
IN 800

Zr-4

A533B

No new materials after 1970s

Failure Rate = 0

Zirlo & M5

Core Structure
High Strength
Steam Generator
RPV
Cladding

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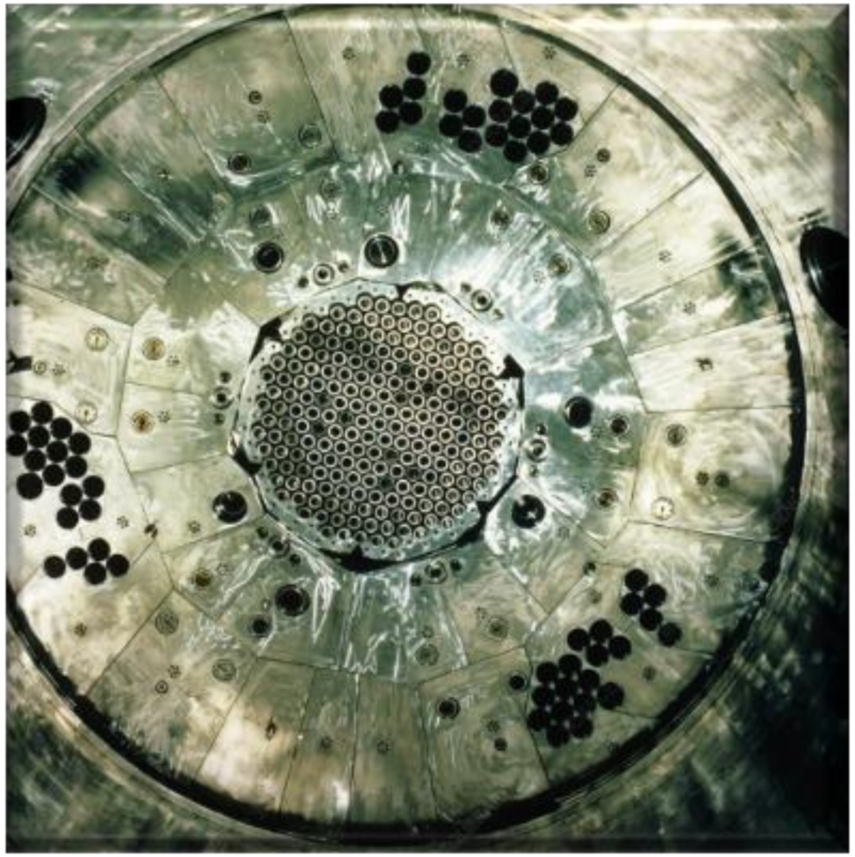
It has been 40 years since a non-LWR reactor was started up in the United States

- New nuclear energy is associated with high costs and long timelines with large uncertainty

- Few if any technological advances in **design**, **materials**, **sensing**, and **qualification approach** have been brought to bear since the 1970s



FFTF core, HEDL

Towards high dose

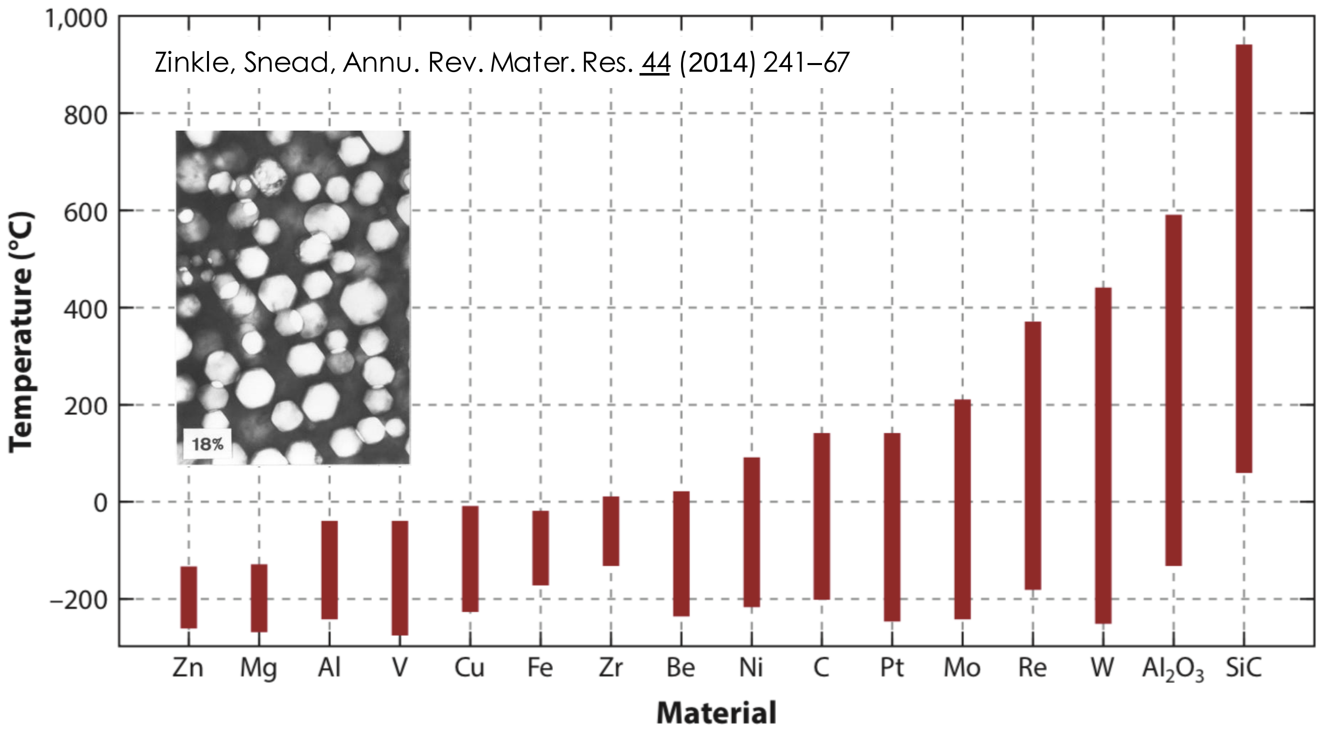
Basic Definitions

- Structural materials are those that are primarily responsible to bear a load and maintain geometry with specific strength or strain requirements
- Radiation stability for nuclear structural applications is defined as the ability of the material to limit its dimensional change to an acceptable design envelope and to withstand degradation in mechanical properties as a function of irradiation dose

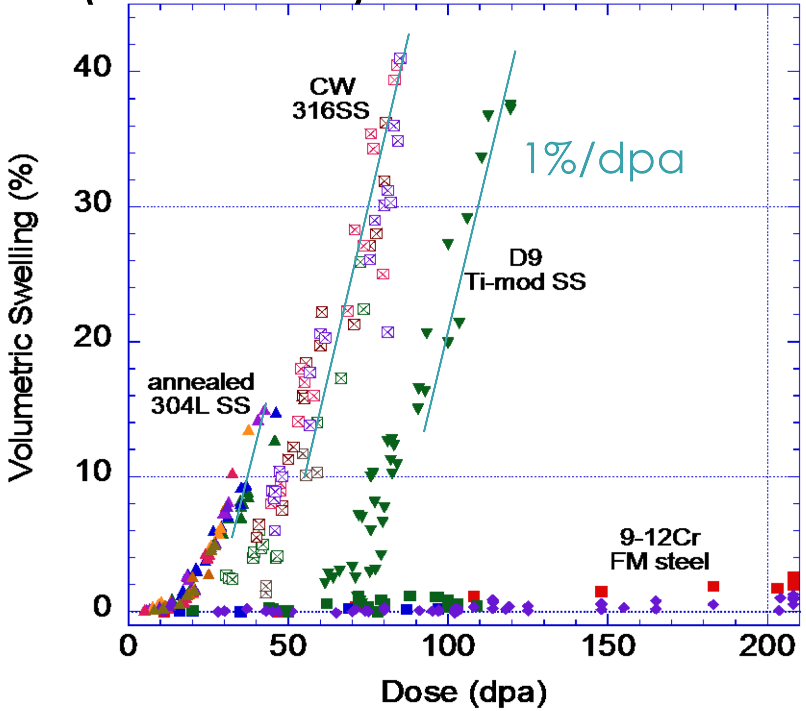
time + stress + temperature + radiation

Realization of radiation tolerant materials relies on three distinct strategies

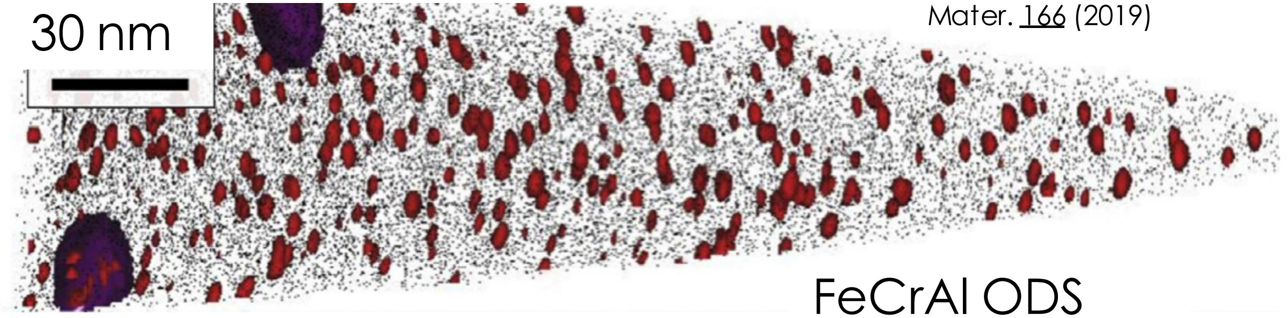
- Immobile point defects
- Crystal structure with intrinsic resistance (BCC)
- High density of recombination centers (surfaces)



S.J. Zinkle & G.S. Was, Acta Mater. 61 (2013) 735



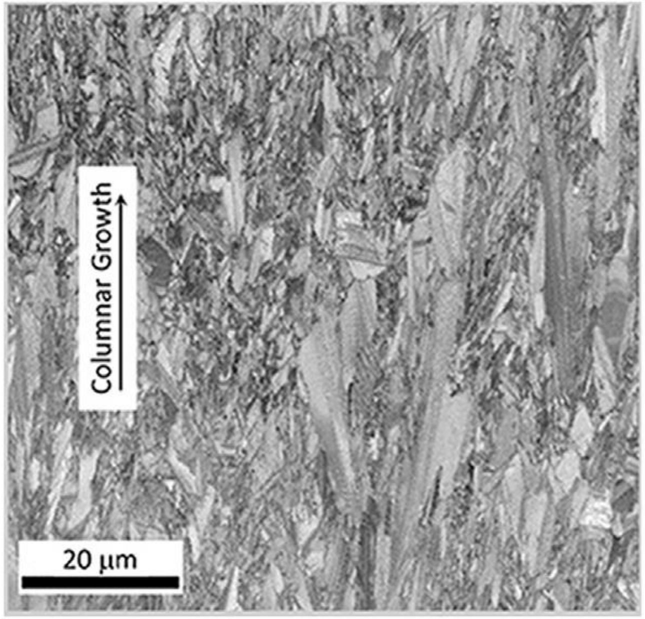
C. Massey et al., Acta Mater. 166 (2019)



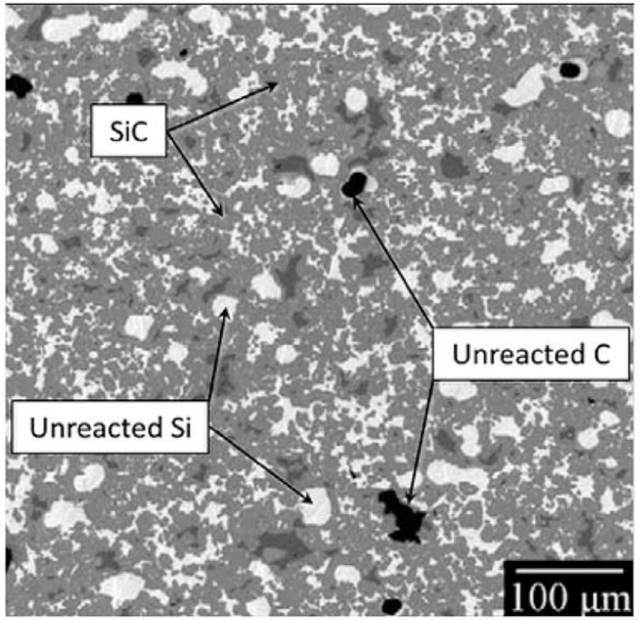
Towards high temperature

High temperature operation requires microstructural stability and creep resistance

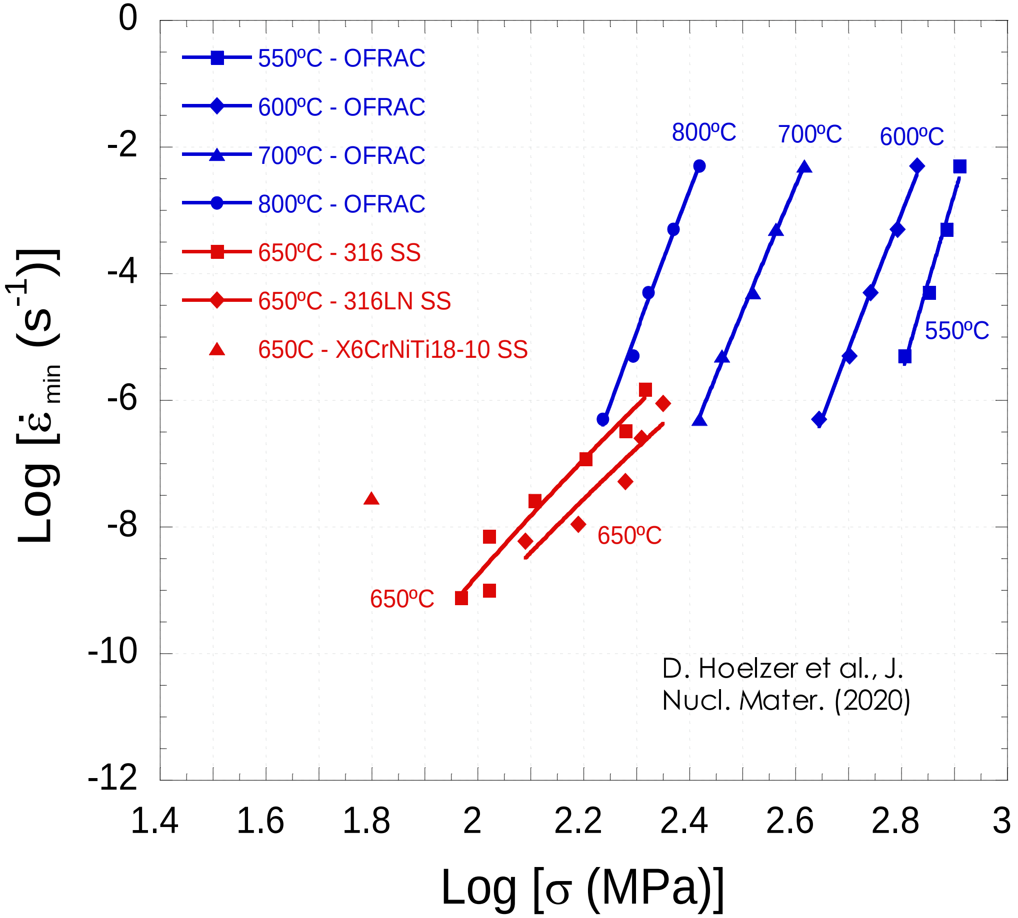
- Fine precipitates in metal alloys
- Refractory metals
- Ceramics (CMCs)



CVD-SiC



RB-SiC



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What is TCR?

Transformational Challenge Reactor is committed to an audacious timeline to build and operate a 3D-printed reactor core

Mission

Rapidly demonstrate application of advanced manufacturing to build and deploy an efficient nuclear energy system

Enable adoption of technologies by U.S. nuclear industry and regulator

Vision

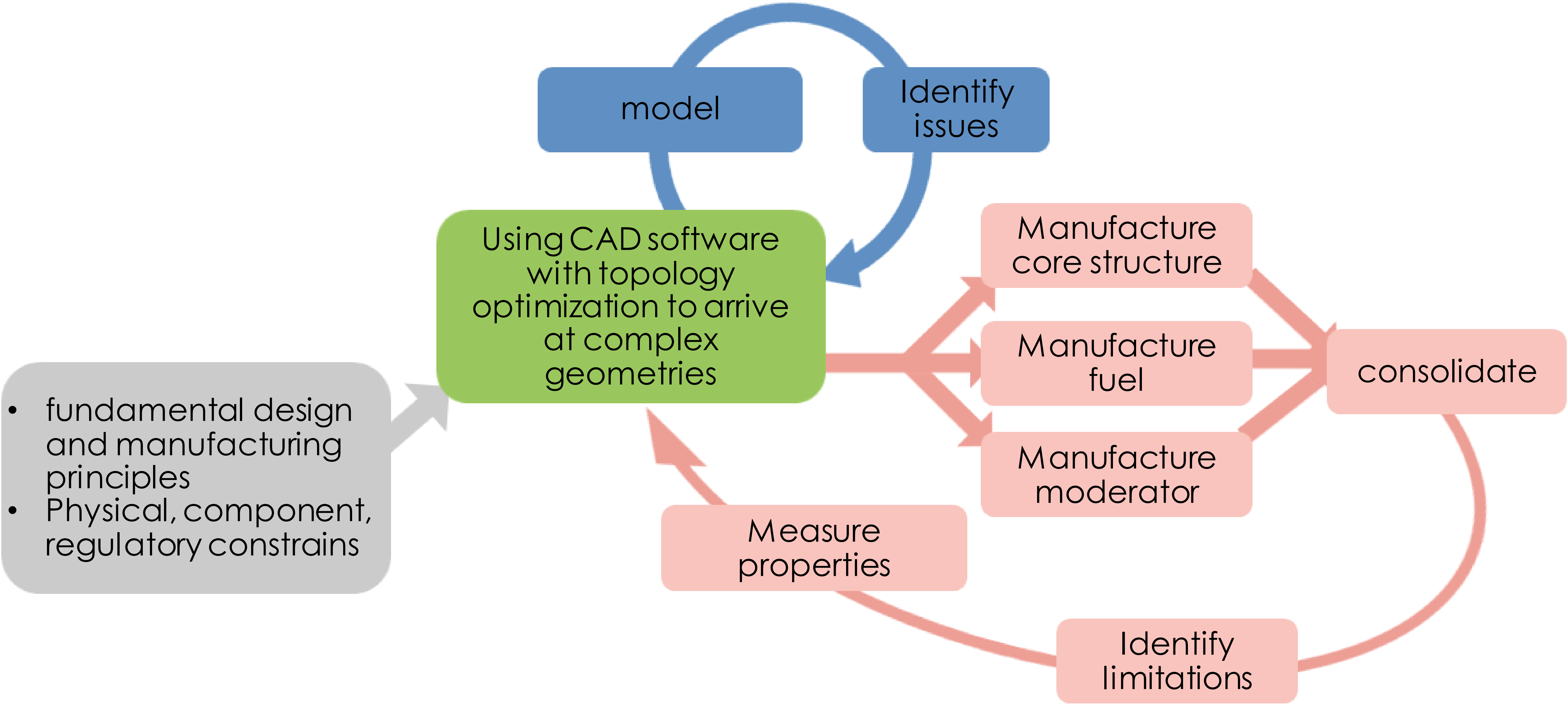
Reliable, available, and low-cost clean energy facilitated using modern technology

Feb 2019 — Phase I — **Feb 2021** — Phase II — **Feb 2023** — Phase III — **Jan 2025**

Nuclear Demo

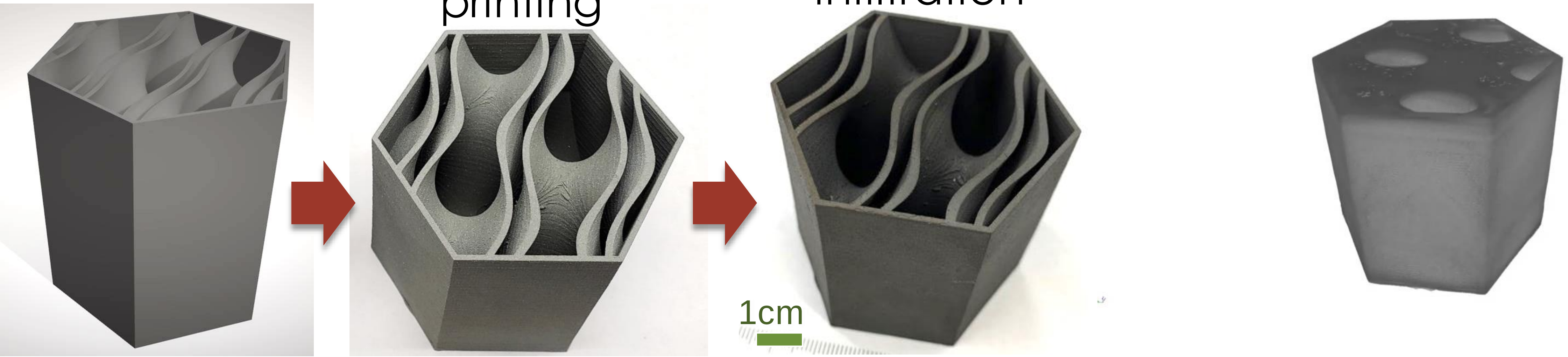
Opportunities in advanced manufacturing - Advanced processing and designs

How is the design approach different with TCR?

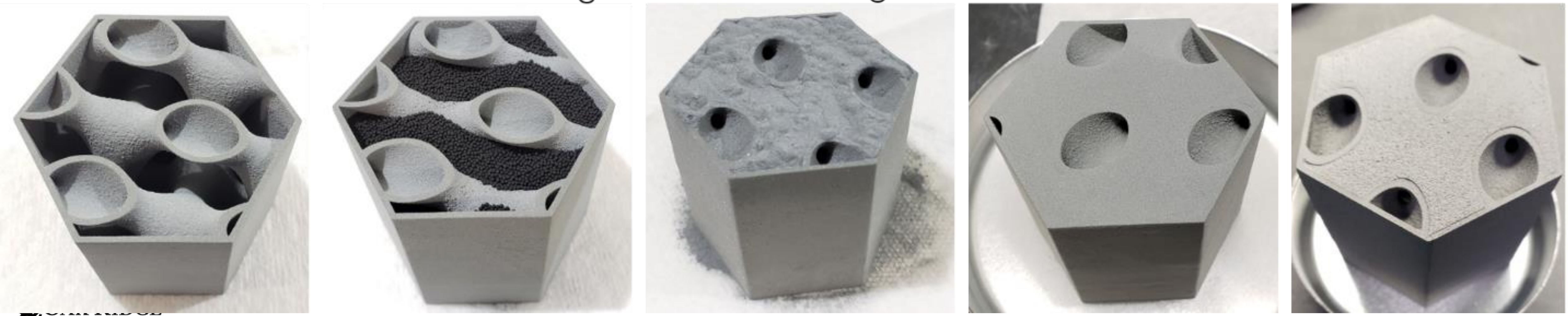


3D printing of nuclear-grade SiC in complex geometries

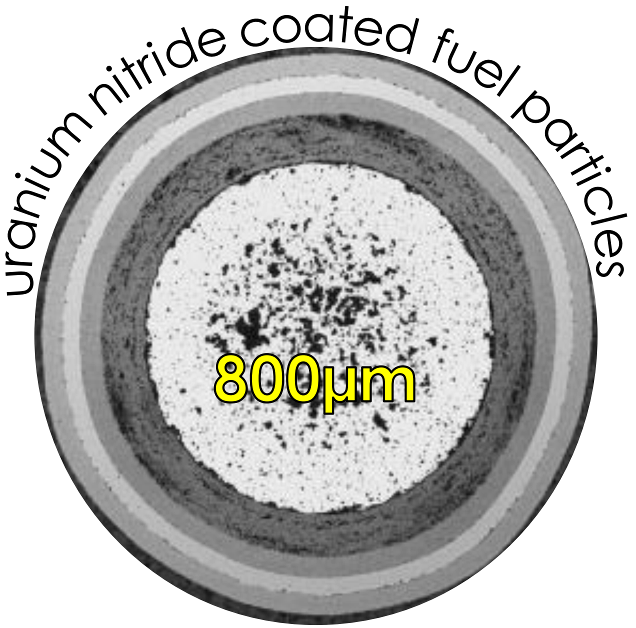
CAD model | Binder jet printing | chemical vapor infiltration

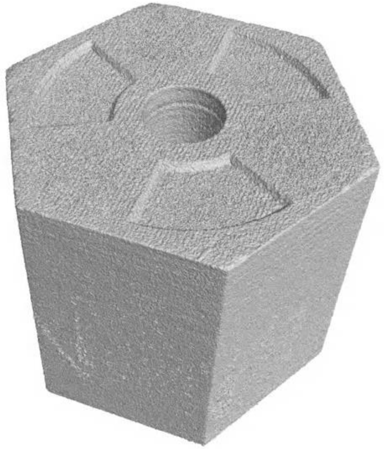


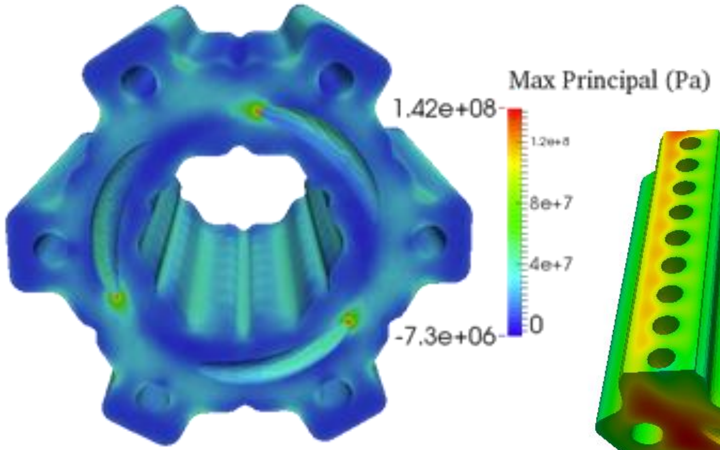
As Printed | Particle Loading | SiC Loading | Before CVI | Post CVI

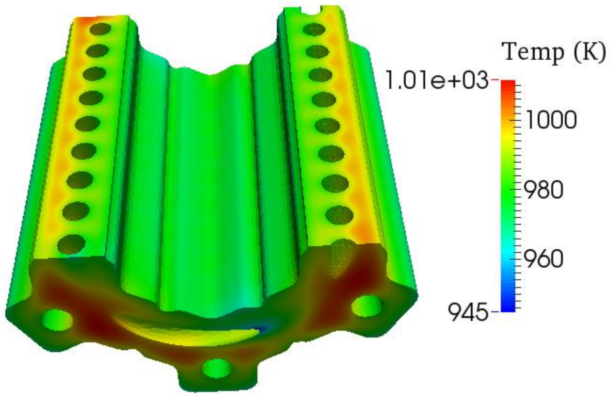


Design optimization via parallel modeling, manufacturing, and testing

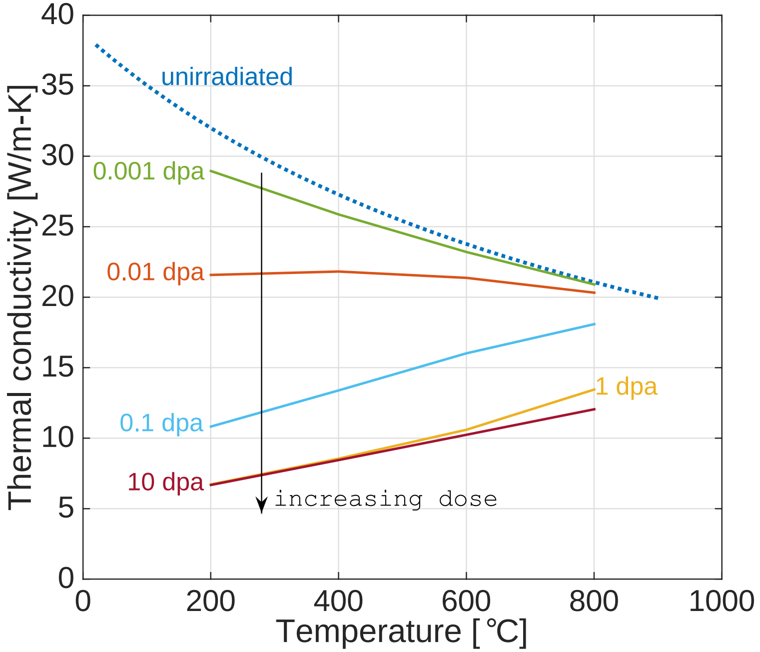


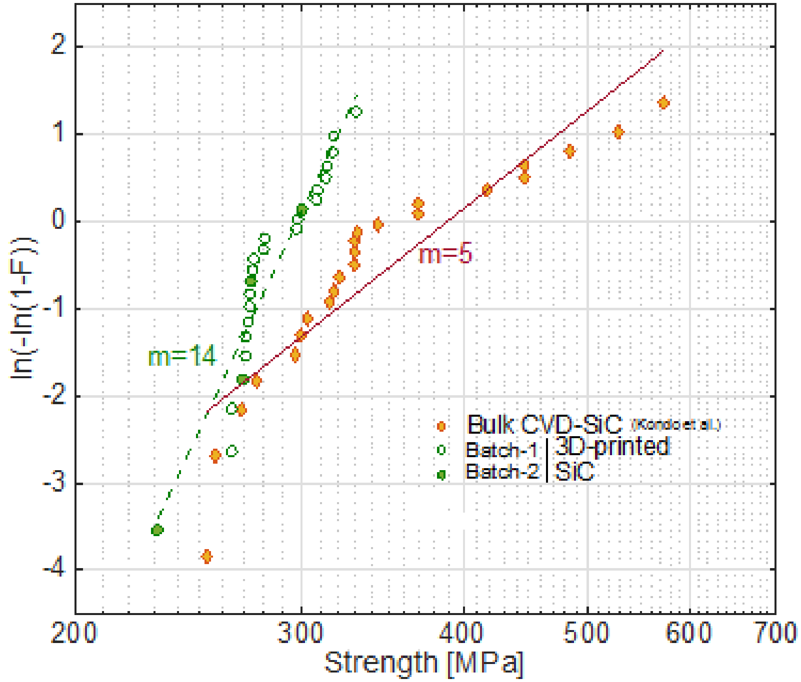






K. Terrani, B. Jolly, M. Trammell, "3D printing of high-purity silicon carbide" *J. Am. Cer. Soc.*, (2019) DOI: 10.1111/jace.16888





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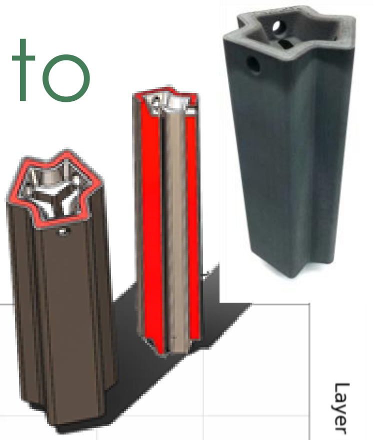
Opportunities in advanced manufacturing - New approach to qualification

Is it possible to exploit Advanced Manufacturing to deliver a new approach to qualification?



Conventional Qualification Scheme

Conform to feedstock quality requirements → pass → Conform to manufacturing quality requirements → pass → Conform to examination quality requirements → pass → Qualified component

failure → Rejected

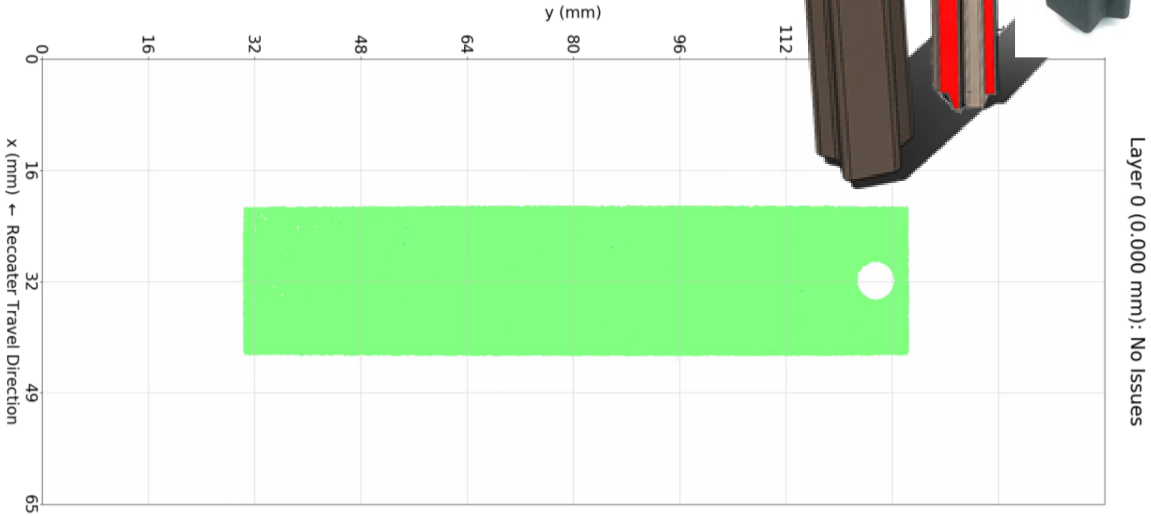


Fig. 26. Hot bonding HFIR fuel plates, exit side.

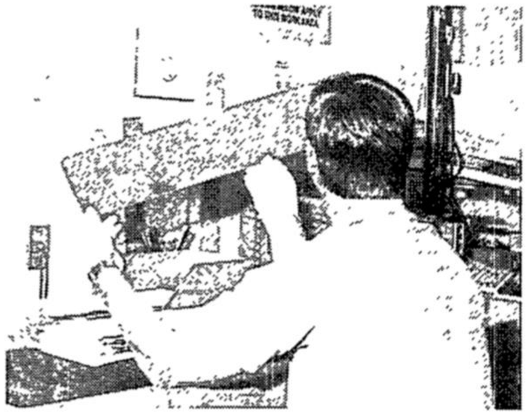


Fig. 30. Visual inspection of HFIR fuel plates for blisters, scratches, dents, and inclusions.

New Qualification Scheme

- Collect feedstock data → Data repository
- Collect environmental data during manufacturing → Data repository
- Collect spatially selective data throughout manufacturing → Data repository

Data repository → Trained data analytics

Trained data analytics → Instantaneously ascertain quality → Qualified component / Rejected component

provide live feedback to manufacturing

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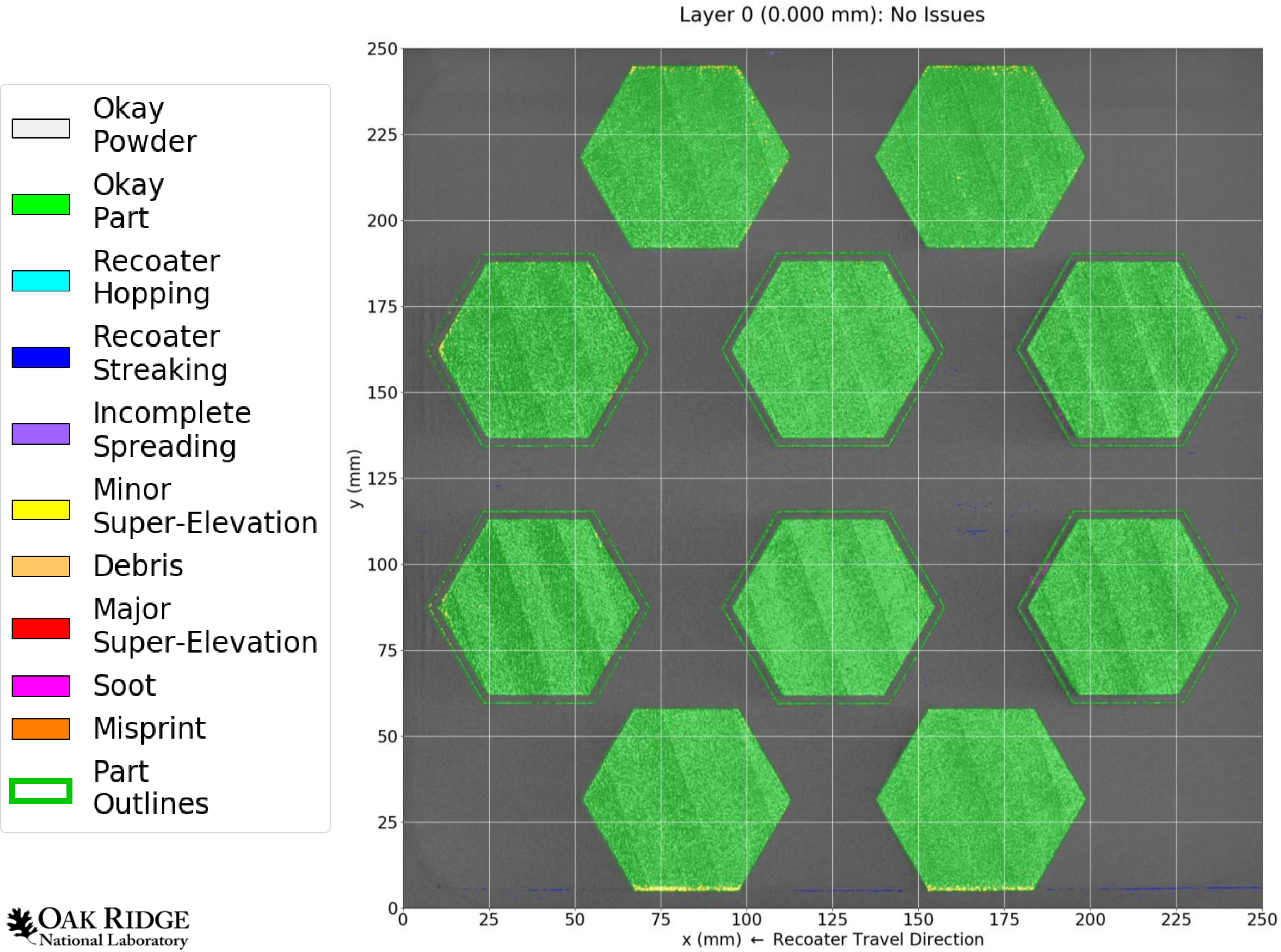
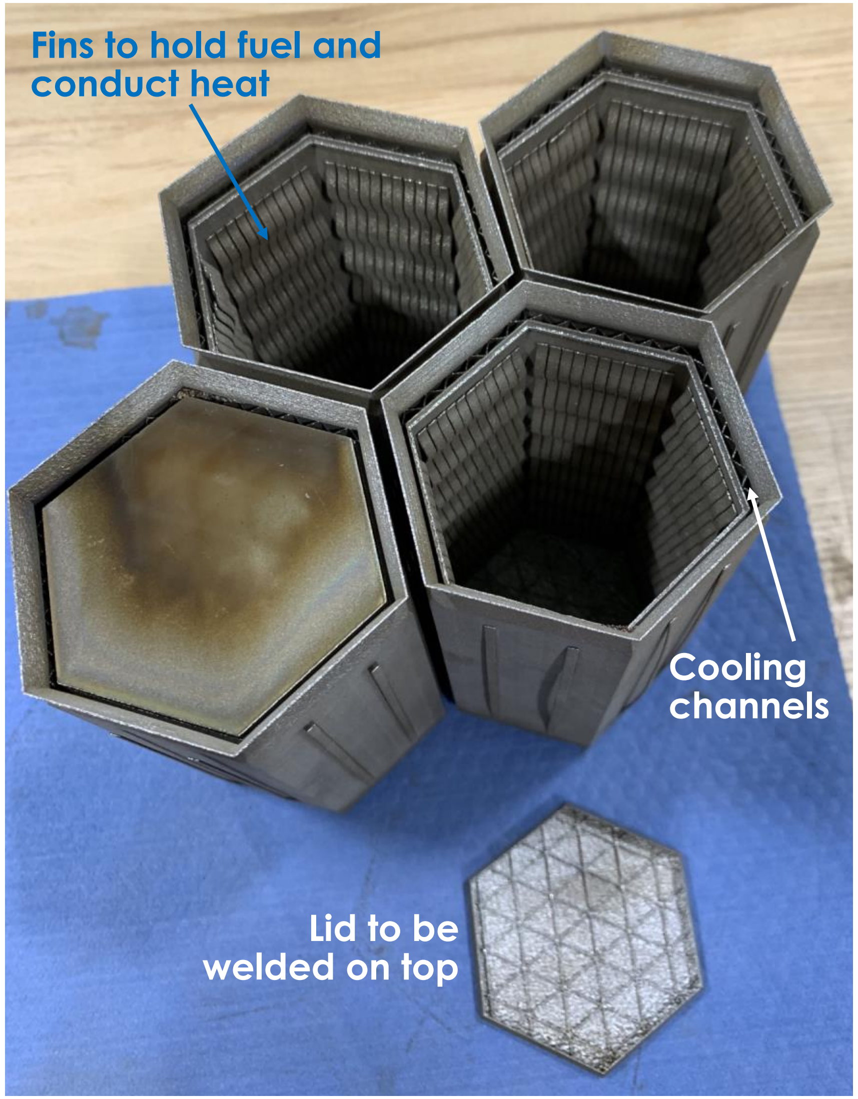
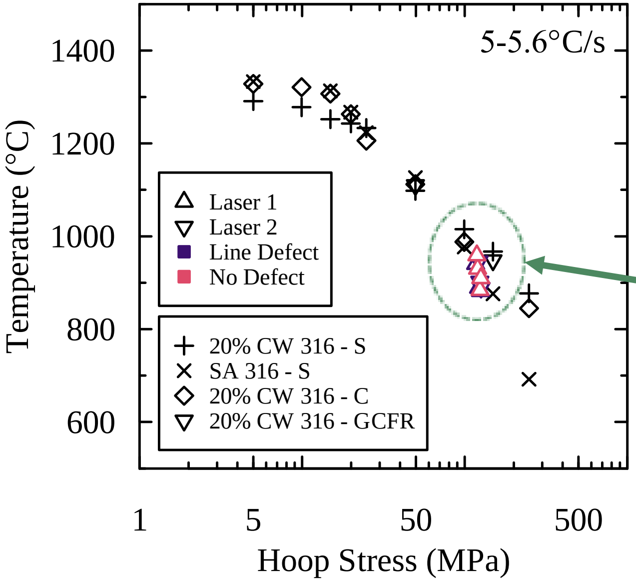
Monitoring to assess quality during advanced manufacturing (in situ)

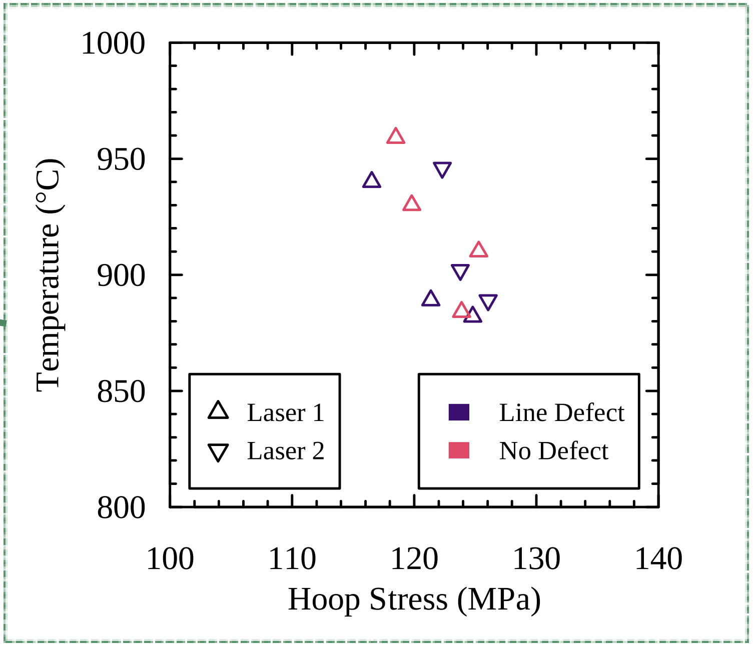


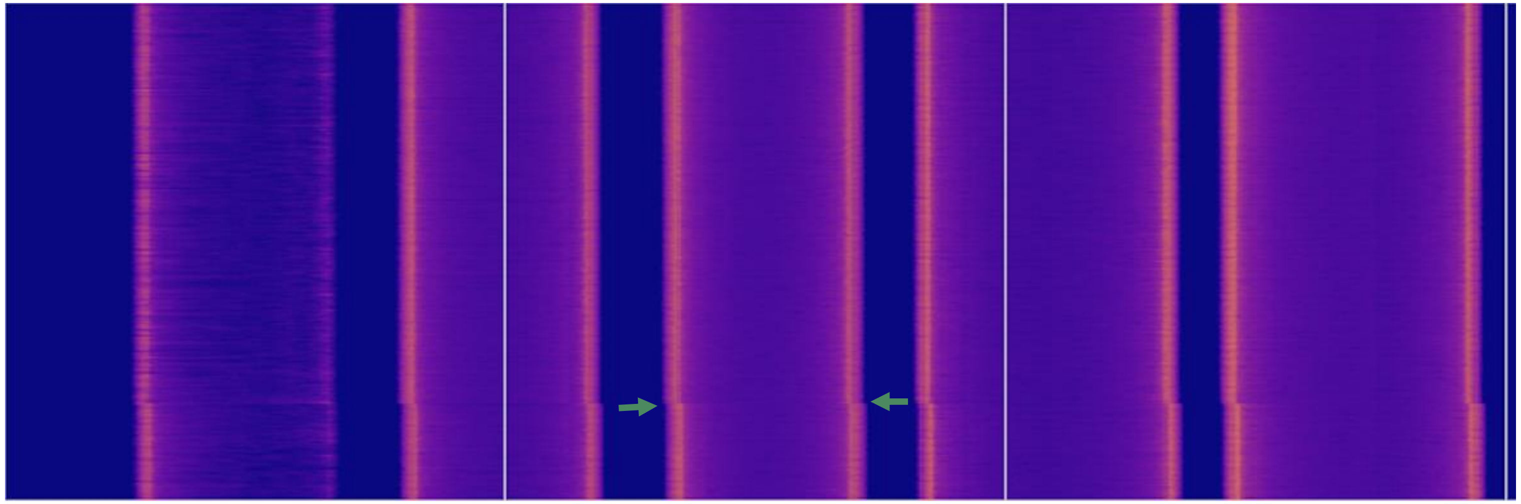


TCR fuel cladding concept

Establishing links between in situ and ex situ data







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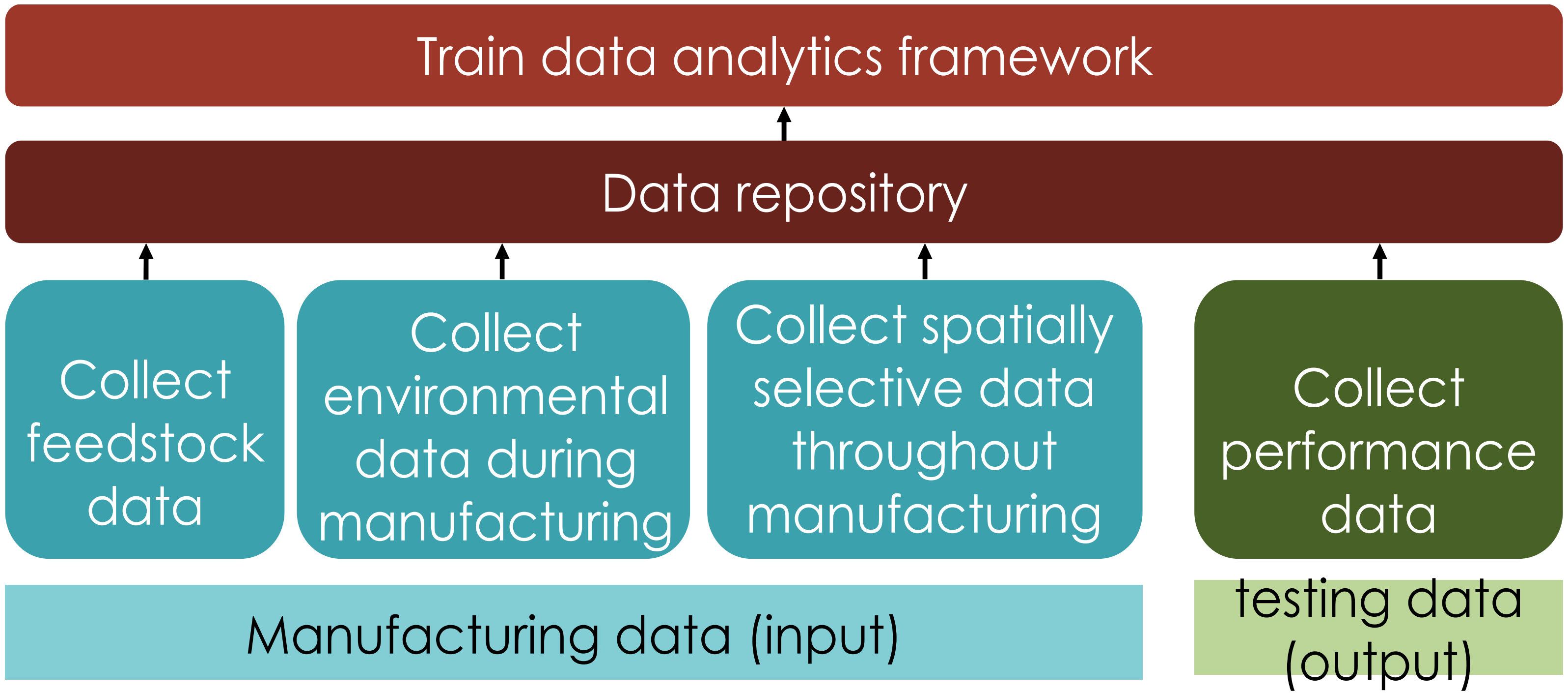
A new approach to qualification is warranted and possible



Summary

- Nuclear energy advancement requires new materials, manufacturing methods, and approaches to qualification
- Advanced nuclear energy systems require materials that can withstand higher dose and temperature regimes. Strategies for radiation tolerance and classes of materials that offer high temperature operation capability are known.
- Advanced manufacturing when performed in parallel with design and testing allows for an agile and informed development process
- In situ data during additive manufacturing have the potential to provide a new paradigm for critical component qualification