Advanced Manufacturing with Advanced Materials for Nuclear Applications

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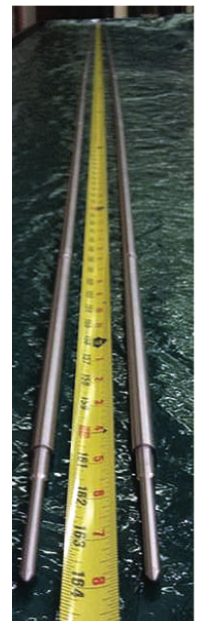
Advanced Materials with Advanced Manufacturing

- Additive Manufacturing: Components are now being introduced into commercial LWRs
  - PWR thimble plug assembly installed at Exelon's Byron Unit 1 in Spring 2020
  - BWR channel fasteners to be installed at Brown's Ferry in Spring 2021
- Advanced Manufacturing: Accident Tolerant Fuel (ATF) coated cladding also being introduced in PWRs and BWRs
  - GNF Armor-coated Zirconium at Plant Hatch
  - Framatome EATF Chromium-coated M5® into Vogtle 2
  - Westinghouse EnCore® Chromium-coated rods in Byron 2



GE Armor-Coated Cladding
Source: Power Magazine April 1, 2018

Westinghouse – PBF Thimble Plug
Source: World Nuclear News May 5, 2020

Framatome/TVA/ORNL TCR – AM Channel Fasteners
Source: ORNL Press Release October 19, 2020

Advanced Materials with Advanced Manufacturing

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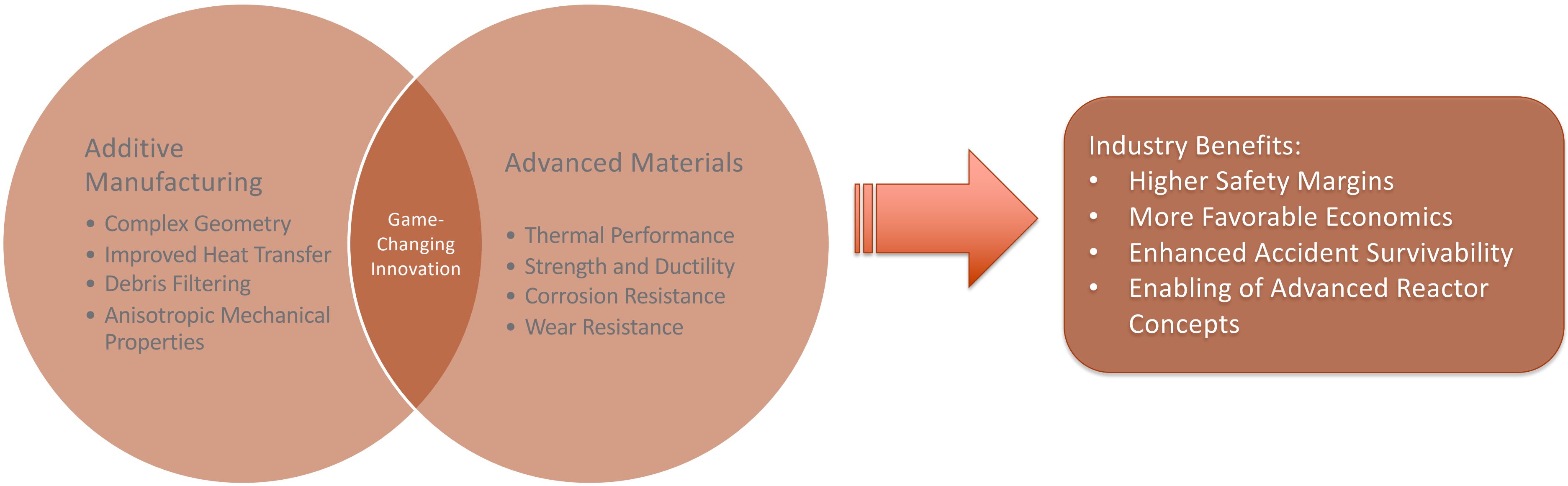
The combination of Additive Manufacturing flexibility with advanced materials can result in innovation that was previously unachievable.

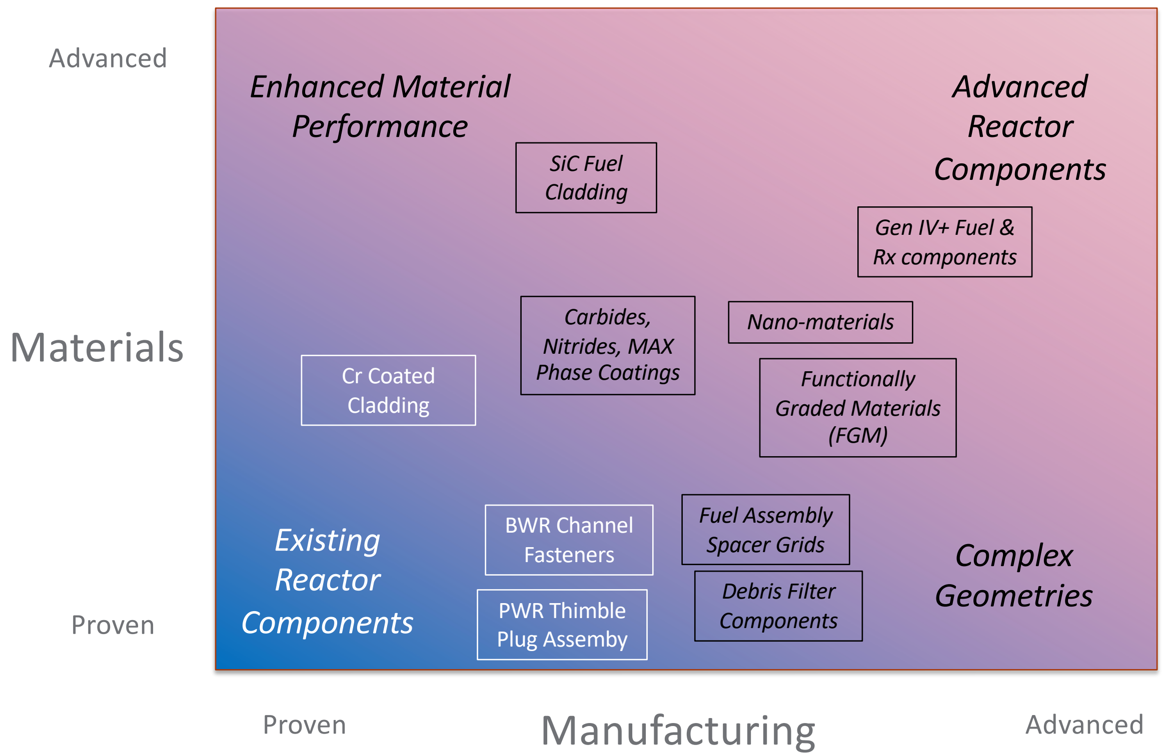


Advanced Materials with Advanced Manufacturing

- **Advanced Manufacturing**
  - Complex geometries not possible with traditional manufacturing
  - Material and weight savings
  - Materials: SS 316L, Inconel 718, Zirconium, Titanium & Aluminum alloys
- **Advanced Materials**
  - Improved thermal and mechanical properties
  - Enhanced radiation, wear and corrosion resistance
  - Materials: new alloys, carbides, nitrides, MAX phase, ceramics, ODS steels
- **Advanced Manufacturing with Advanced Materials**
  - Functionally Graded Materials (FGM)
  - Applications of some new non-traditional reactor materials
  - New components for advanced reactors (unrestricted by existing environments and configurations)

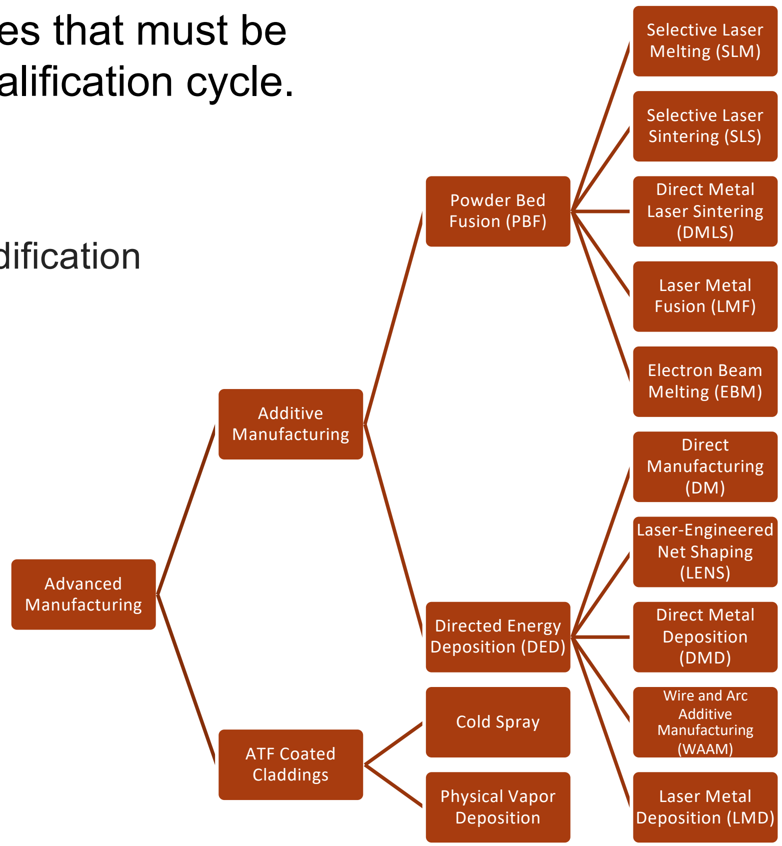
Advanced Materials with Advanced Manufacturing

- Advanced Manufacturing (AM) can be useful for direct component replacement, and/or to implement evolutionary improvements in performance or weight
  - However, costs may not justify AM for high volume parts or for long qualification processes
- Strongest opportunities may be for totally new concepts for future advanced reactor components which may not be constrained by pre-existing requirements: enveloping geometry, thermal and other environmental conditions, licensing bases, etc…



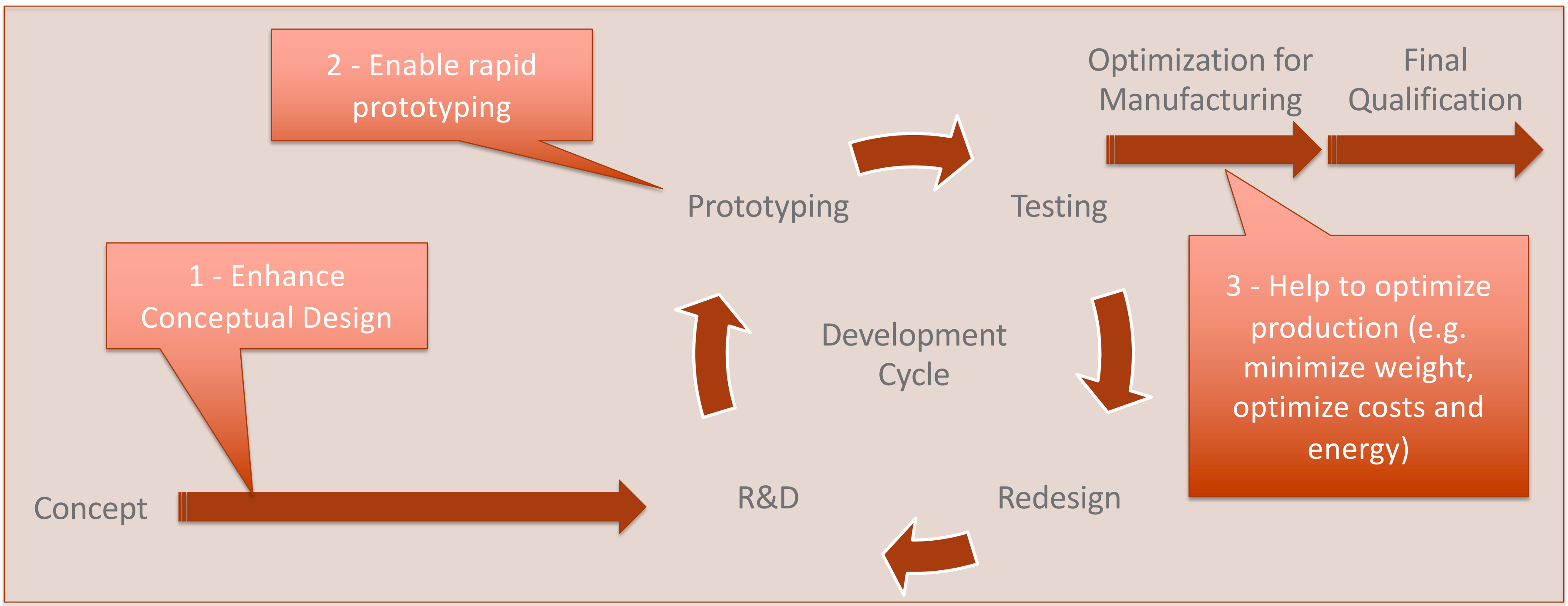
Advanced Materials with Advanced Manufacturing

- Additive Manufacturing introduces new variables that must be controlled throughout the development and qualification cycle.
- Parameters
  - Energy, speed of deposition
  - Thermal conditions, temperature gradients, solidification velocities, localized annealing rates
  - Powder characteristics
  - Alloys, impurities
- Material Properties
  - Isotropic/Anisotropic performance
  - Strength, Ductility
  - Production Rates
  - Surface Finish
  - Microstructure
  - Composition Homogenity



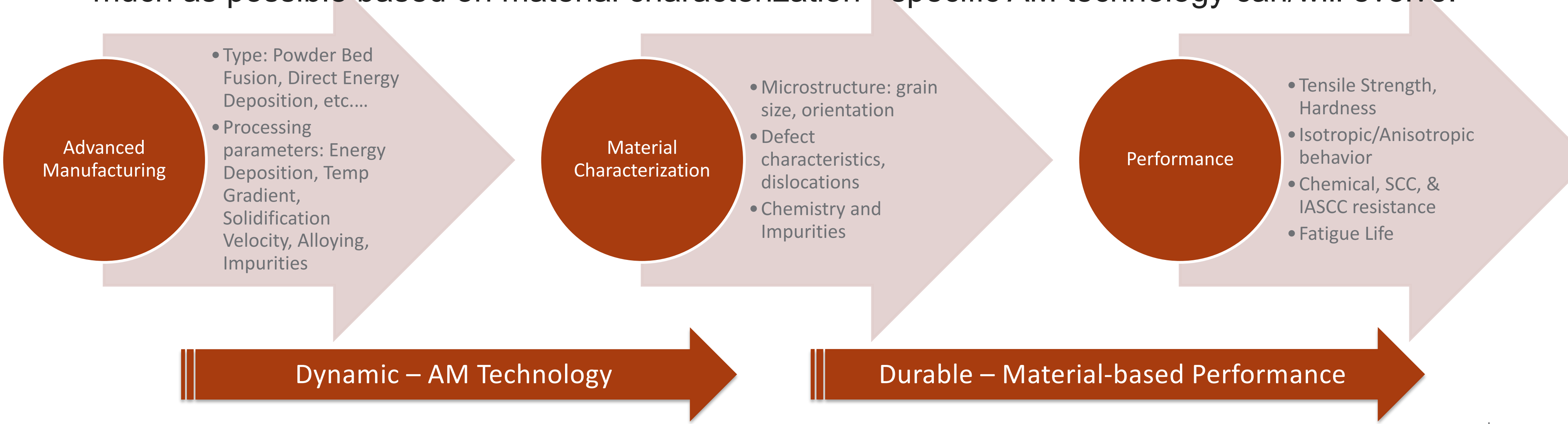
Advanced Manufacturing in the Development Process

- There are at least three separate opportunities to introduce Advanced Manufacturing into the development and qualification process…



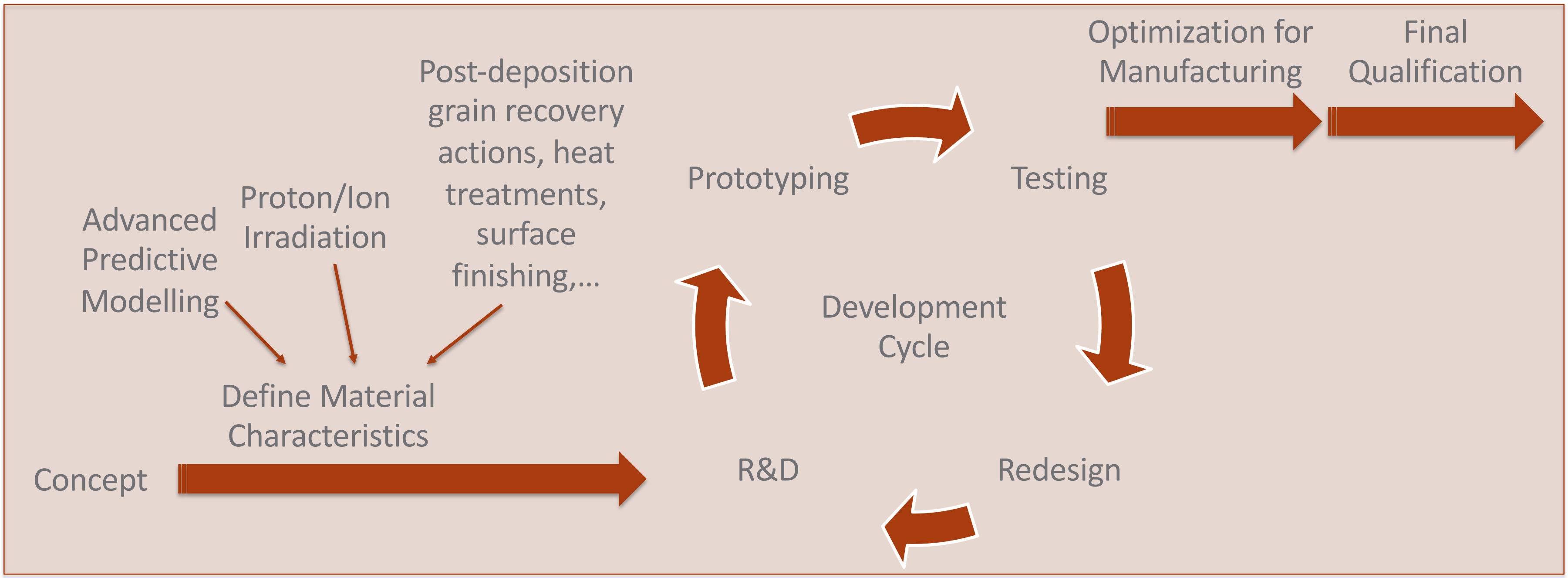
Advanced Manufacturing in the Development Process

- The many forms of Advanced Manufacturing introduces new flexibility into the development and qualification process. Also, AM technology continues to evolve at a fast pace.
  - Technology can outpace the qualification and licensing process.
  - Traditional certification and qualification processes need to be improved.
- To retain the most flexibility from AM, consider qualifying material and irradiation performance as much as possible based on material characterization - specific AM technology can/will evolve.



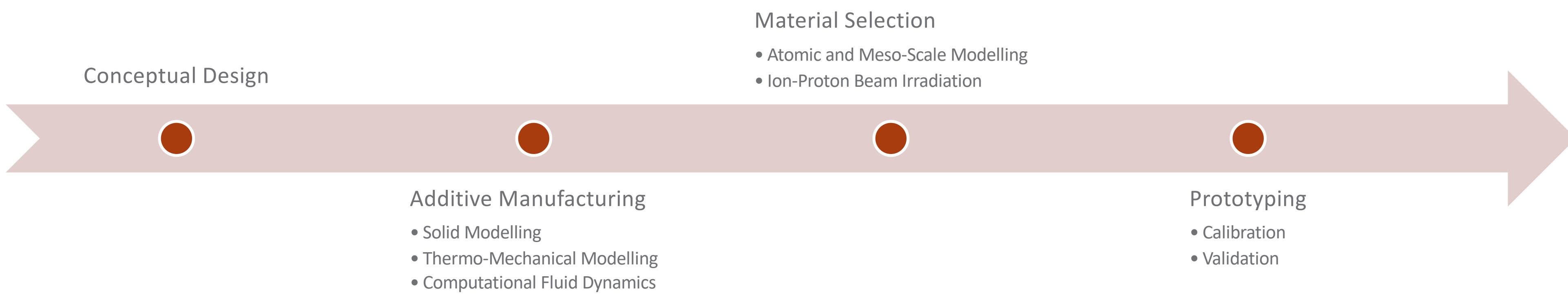
Advanced Manufacturing in the Development Process

- Evolving AM technology can disrupt material performance, jeopardizing the qualification process.
- Define and control basic material characteristics early in the process.
- Also inform regulators in advance of new technology as early as possible.



Advanced Manufacturing in the Development Process

- The third “AM”, Advanced Modelling, supports Additive Manufacturing and Advanced Materials
  - Additive Manufacturing can enable rapid prototyping in the testing phase
  - However, it also introduces additional variables into the prototyping/testing process
  - So, empirical modelling and qualification can be much more challenging
- Advanced modelling can be utilized to better predict and control the governing AM parameters influencing the product performance
- Finally, with so much more computer-based modelling earlier in the development cycle, Cyber Security becomes even that much more critical to protect Intellectual Property.



Case Study – Accident Tolerant Fuels

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- ATF coated cladding development represent a similar qualification and licensing challenge as other AM development programs
  - Material properties are heavily dependent upon new but controllable process parameters, such as temperature, speed, carrier gas, energy of deposition, impurities
- Critical to understand and control desired microstructure characteristics, not just process parameters
  - Qualification and licensing based on fundamental material properties, not simply deposition process parameters
  - Key modelling and material characterization must be brought forward in the process

Case Study – Accident Tolerant Fuels

- IL TROVATORE:
  - An international collaboration with strong academic input & industrial support
  - Beneficiaries: 28 from Europe, 1 from the US, and 1 from Japan
  - External Expert Advisory Committees:
    - Scientific Advisory Committee
    - End Users Group (Oelrich member)
    - Standardization Advisory Committee (ASTM/C28, CEN/TC 430, ISO/TC 85)

Case Study – Accident Tolerant Fuels

- Goal: Help to address the global societal & industrial need for improved nuclear energy safety by optimizing and validating select ATF cladding material concepts in an industrially relevant environment (i.e., under neutron irradiation in PWR-like water in the BR2 research reactor)
- Candidate ATF Cladding Material Concepts:
  - SiC/SiC composite clads, different concepts
  - Coated clads (e.g., Cr-coated zircaloys); innovative coating materials: MAX phases, doped oxides
  - GESA surface-modified clads
  - ODS-FeCrAl alloy clads

Case Study – Accident Tolerant Fuels

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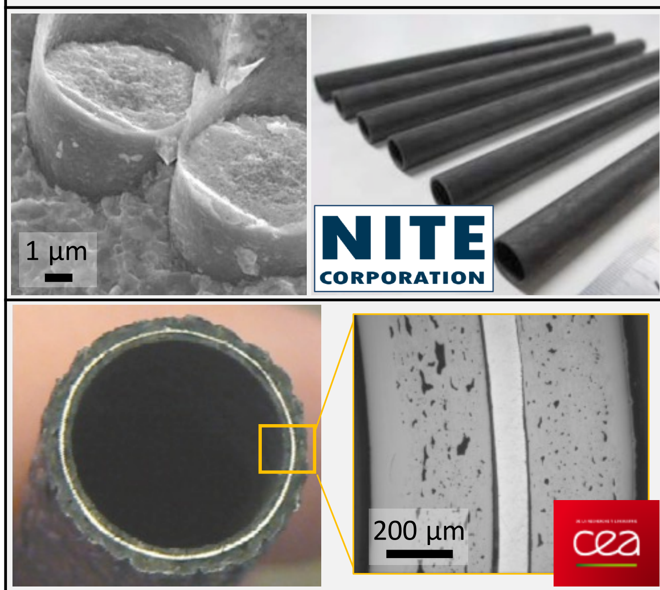
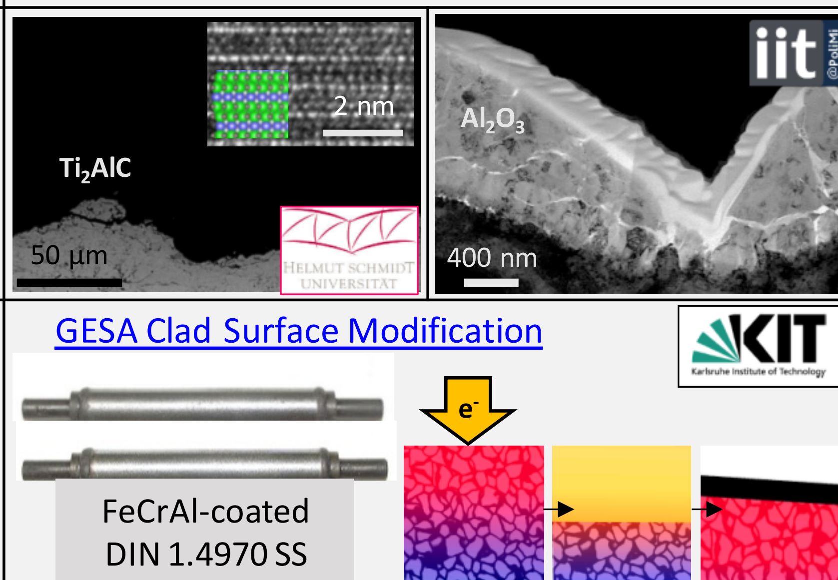
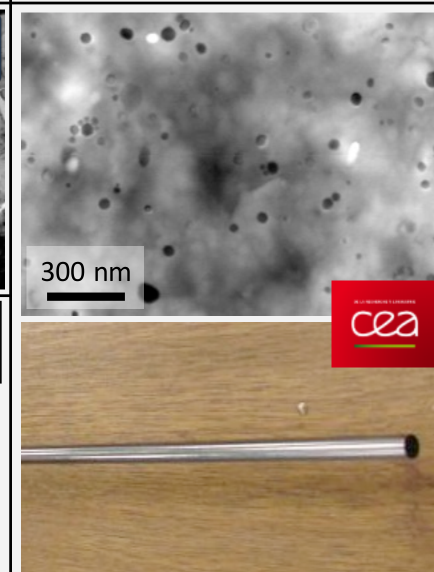
SiC/SiC Composite Clads



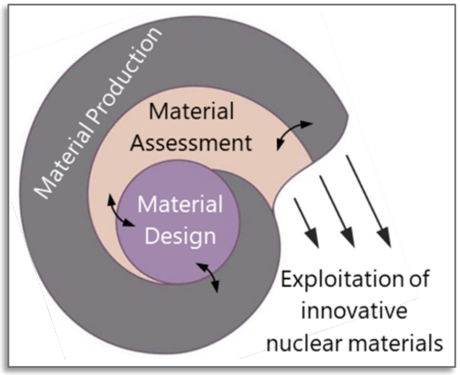
Coated & Surface-Modified Clads



ODS-FeCrAl Clads



Case Study – Accident Tolerant Fuels



- The accelerated development of nuclear materials entails:
  - Interconnectivity of *application-driven material design*, *material production and material performance assessment* in application-relevant conditions
  - Development of *reliable high-throughput material screening tools*, e.g., use of *ion/proton irradiation* to assess radiation tolerance; *select modelling approaches* (atomic scale, FE, etc.) to predict in-service material behavior

Case Study – Accident Tolerant Fuels

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Accelerated Development of MAX Phase-Based Materials for the ATF Cladding Application

Predictive modelling

input

Material Design

feedback

Material Production (tailored composition, microstructure, layout/configuration)

materials

Material Performance Assessment (mechanical properties, compatibility with coolant, radiation tolerance)

feedback

Property requirements

Interactions with coolant

Screening irradiations (ions/protons)

materials

Material Demonstration in Industrially Relevant Conditions (neutron irradiation in primary coolant)

optimized materials

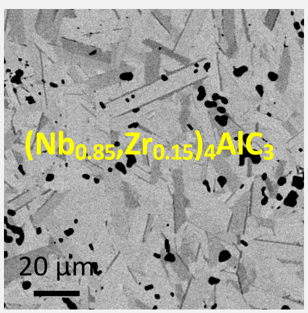
Innovative Nuclear Material Licensing (market uptake)

Optimum Composition

(Zr,Cr)-Based MAX Phase Solid Solutions

Material Design: Basic Considerations

Phase Purity



Minimize cracking by differential swelling

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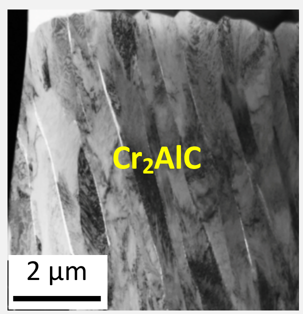
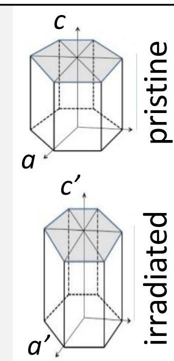
Texture





Minimize cracking by anisotropic swelling

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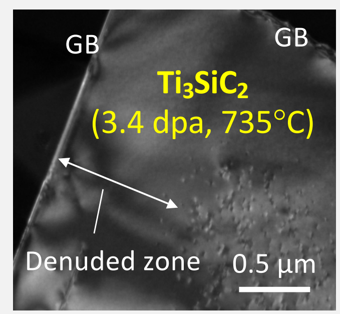
Grain Size



Maximize radiation defect annihilation

In conclusion…

- Ensure the value proposition (business case) up front: safety and economics
  - Balance potential benefits against realistic risks of new materials and processes
  - Introducing AM to existing parts without advanced materials may not justify costs of development and qualification
- Seek successful collaboration approaches between industry, DOE, national labs, and NRC
- Leverage prior qualification of first-of-a-kind AM processes, materials, and modelling
  - Apply lessons learned from ATF coated cladding development and qualification
  - Coated cladding workshop at PNNL
- Plan well in advance for a successful qualification process
  - NRC AMT Application Guidance
  - Apply advanced predictive technology, including atomic and meso-scale modeling and in-situ testing
  - Meet with regulators early in cycle to share new technologies and qualification bases as early as possible

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Thank you for your attention…