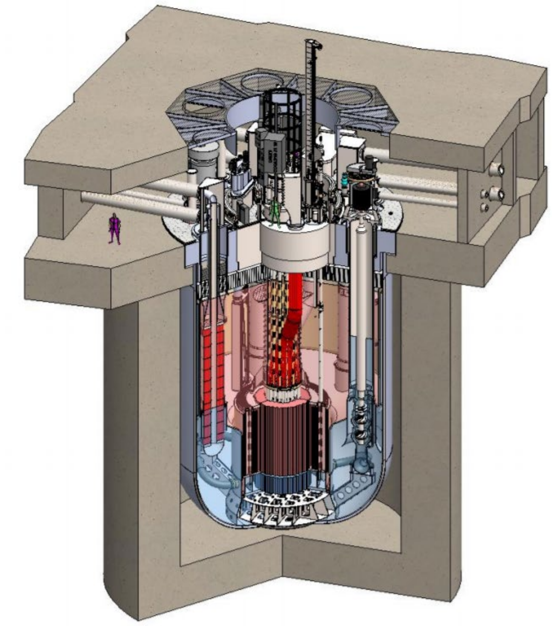
Materials Selection and Development for Advanced Reactors at TerraPower

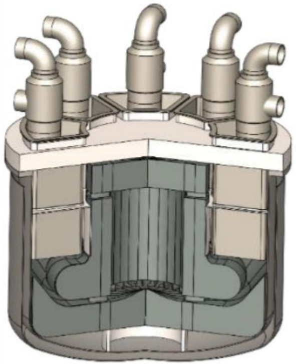
Greg Vetterick

TerraPower's Reactors



TWR

Based on high-readiness sodium cooled fast reactor technology



MCFR

Based on novel molten chloride salt technology

Shared Benefits

- Deep-burn open fuel cycle with no reprocessing
- Strong inherent safety features and passive safety systems
- Flexible siting
- Production of high temperature heat
- Reduced waste

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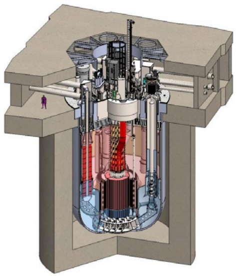
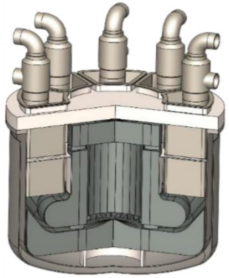
Key Materials Challenges

TWR©



- High endurance materials to enable breed-and-burn
- Swelling and creep

MCFR



- Structural (e.g. ASME B&PV Code) materials see fuel salt
- Fuel/coolant-component interactions

Clever design choices and good project planning are needed to drive down cost and reduce time to market

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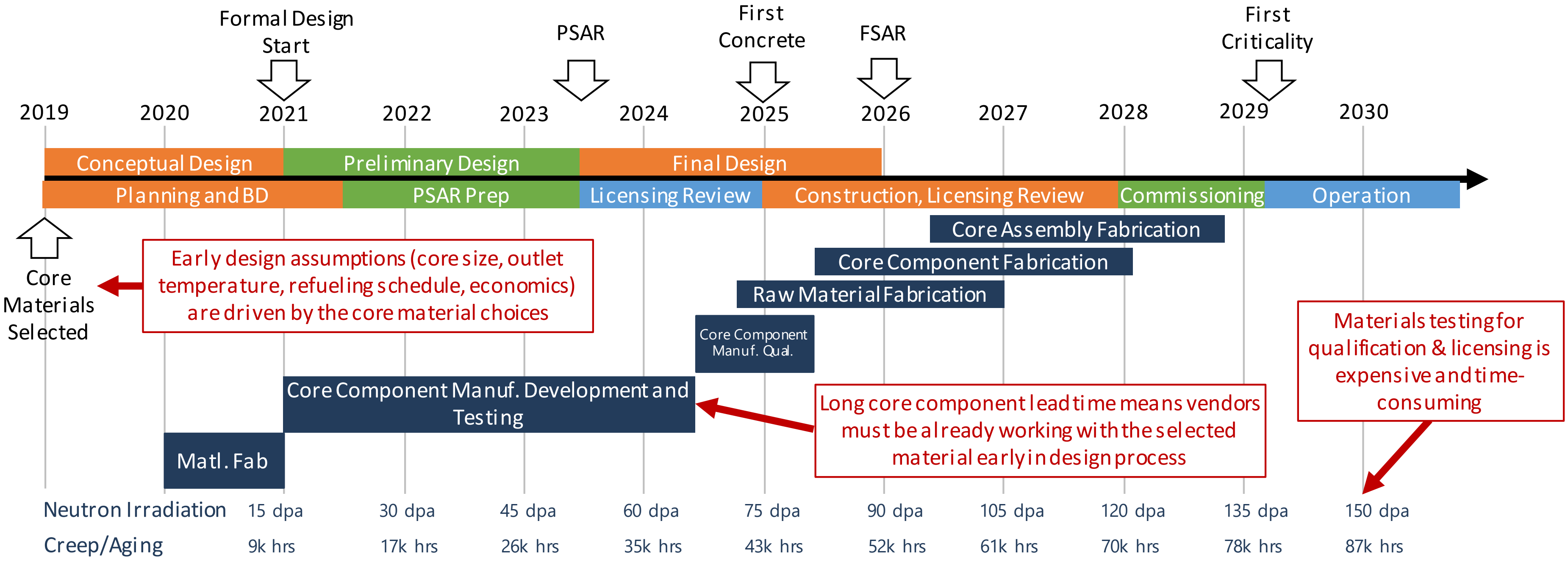
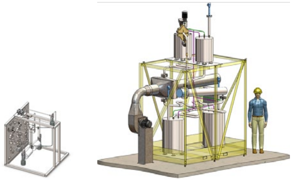
Material Selection Driven by Timeline

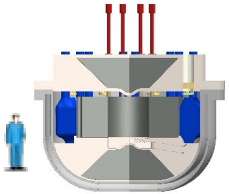
- The market is looking for reactors around 2030. Here's a *hypothetical* timeline for an SFR:

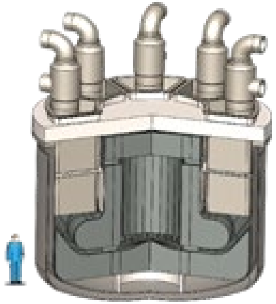


Timeline for Commercialization

- Materials selection has a strong impact on early, major design decisions
- Testing has to start early
- Momentum is important to maintain
- **Common, well-understood materials take priority**







e.g., MCFR…

Separate Effects Tests & Materials Scoping	Integrated Effects Test (IET) & Materials/ Component testing	Demo Reactor 30 - 150 MW_{th} Class 104 License & Component Scale up/ Materials Validation	Commercial Prototype Reactor 600 - 2500 MW_{th} Class 103 License
Today	2019 -2022	2020-2027	2025 – 2030s

Uprate?

Phase 1 – TRL 1 to 5

Phase 2 – TRL 5 to 7

Phase 3 – TRL 8 to 9

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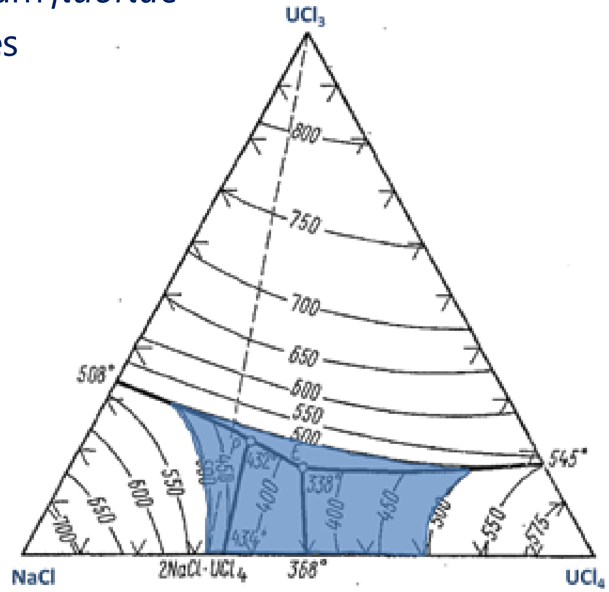
Fuel Salt Development

- Materials selection for the MCFR is fundamentally dependent on the fuel salt composition
- The MCFR is fast spectrum *chloride* rather than a thermal spectrum *fluoride*
- We are focused upon high-U salts with low melting temperatures
- Multiple fuel salt synthesis pathways demonstrated.



Along with fundamental fuel research, understanding how each salt composition interacts with available structural materials is key

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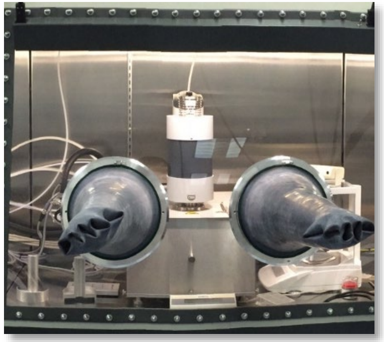
Thermophysical Property Measurement

- Melting temperature, heat capacity, viscosity, and density are critical measurements for reactor physics
- TerraPower has procured and custom-built equipment to measure these properties
- Also collaborating with ORNL for thermal conductivity

Heat capacity



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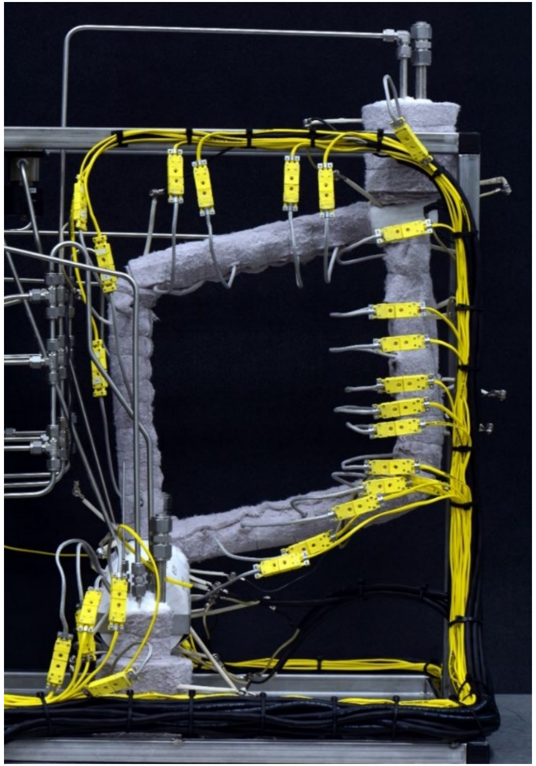
Density

Viscosity

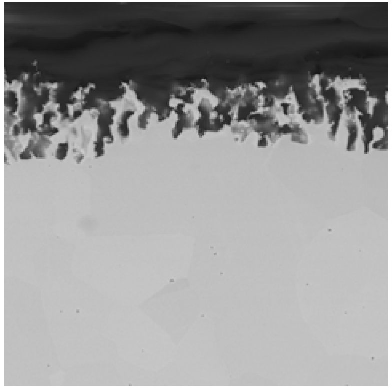
Materials Selection and Testing for MCFR

- Multiple rounds of static corrosion completed for up to 1500 hours at 650 and 750°C.
- Nearly three dozen natural circulation flow loops operated at up to 750°C and 10,000 hrs
- Austenitic and FM steels, Inconels, Hastelloys, and refractory alloys

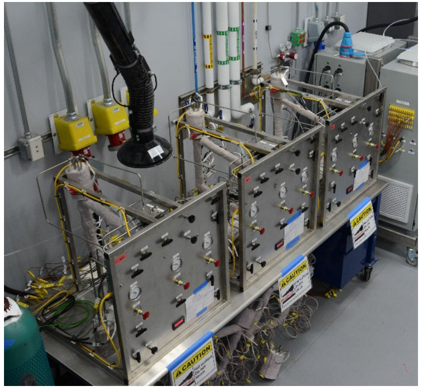


Static Corrosion Testing

Corrosion Test Results



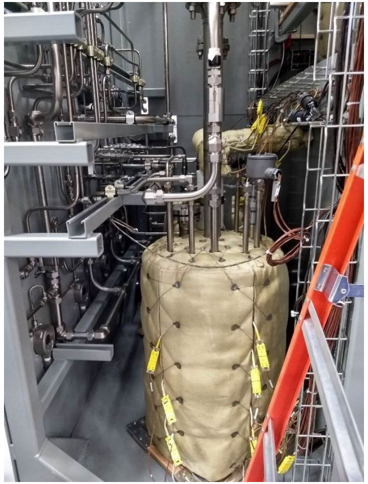
Natural Circulation Loops



Scaling Up for Separate Effects Testing

- Salt loops are being scaled up for separate effects testing (e.g. thermohydraulics)
- Testing being extended to forced flow
- Incidental materials testing through operational experience

Isothermal Coolant Salt Loop (run complete)



Polythermal Coolant Salt Loop

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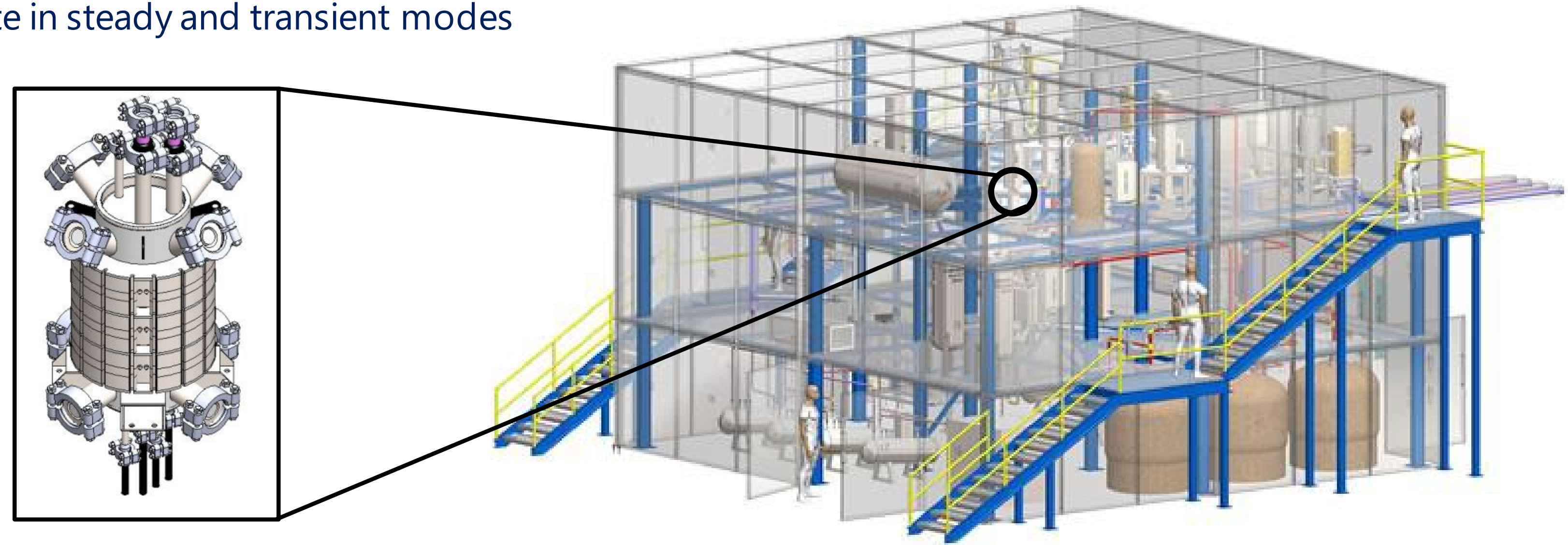
Construction of IET Underway

Goals:

- Provide technical support for design and licensing of MCFR test reactor
- Increase technical readiness of all MCFR technologies
- Provide thermal-hydraulic performance data
- Operate in steady and transient modes



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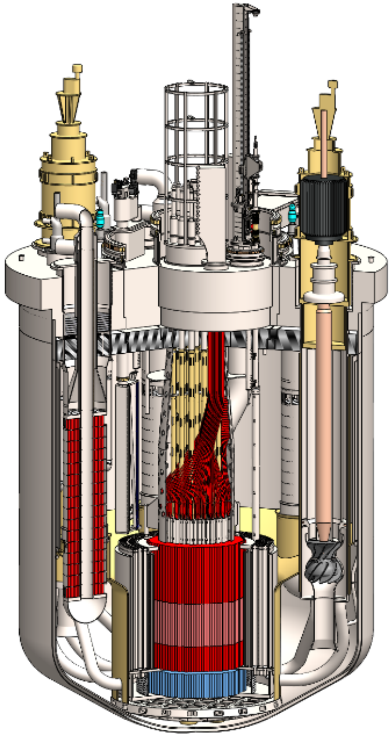
TWR Materials

- The TWR reactor leverages DOE program (e.g. FFTF, EBR) design experience
  - Extensive R&D and downselection of reactor materials
  - Documented operating experience
- ASME Code Case materials for
  - Pressure boundary components
  - Supports for pressure boundary components
  - Components welded <2t from the pressure boundary
  - Attachments that form a structural function (e.g., CSS)
- Non-ASME Code materials for
  - Internal baffles
  - Non-structural or non-welded attachments
  - Valve and pump internals
  - Reactor core (fuel assemblies and blankets)



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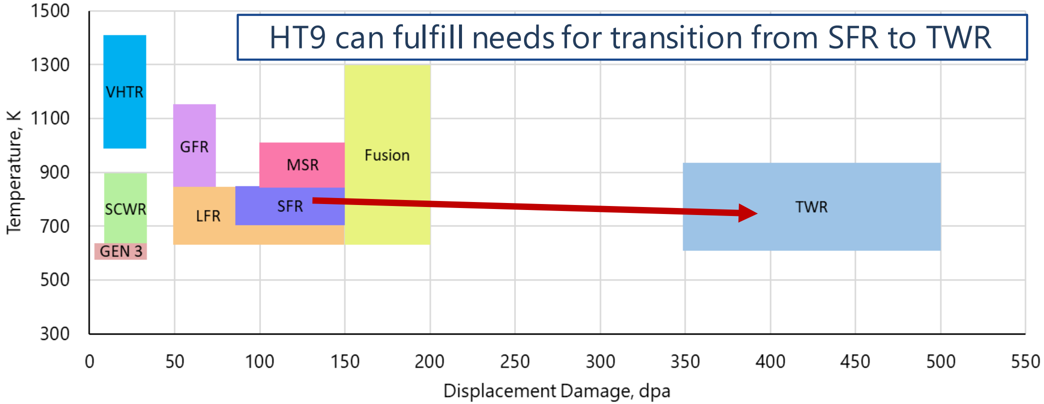
Selection of HT9

Pros

- Extensive operational experience in both the EBR-II and FFTF sodium fast reactors
  - FFTF ACO3 assembly reached ~155 dpa over 6 years
- Large body of irradiation data for FM steels
- Demonstrated excellent swelling performance
- No reduction in creep rupture strength from irradiation
- Simple, predictable failure mechanism (ballooning of cladding tube)

Cons

- Higher than desirable DBTT
- Lower thermal expansion coef.
- Not ASME approved (OK for clad/duct)
- Difficult material sourcing



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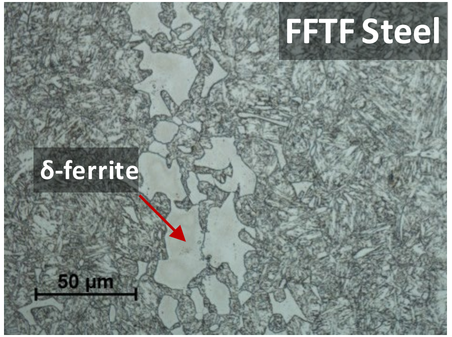
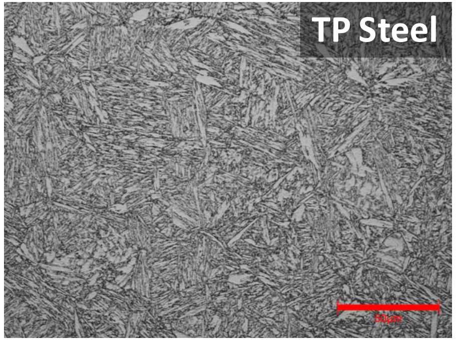
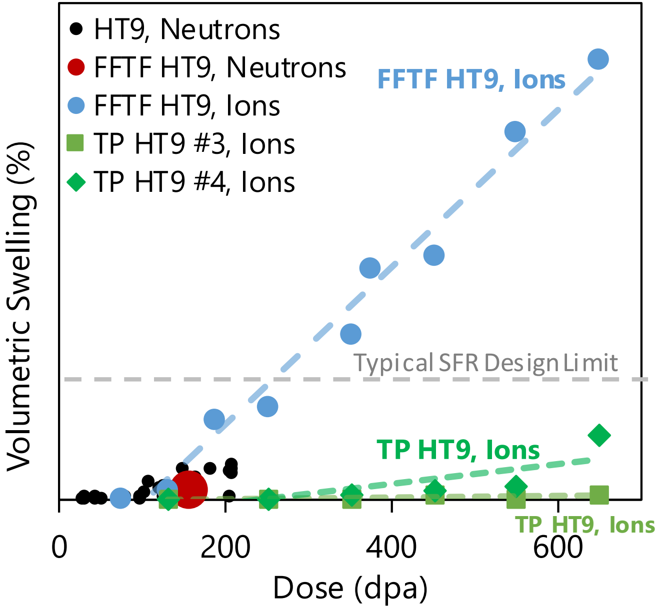
HT9 Development Program

- Optimize chemistry and processing parameters
  - Improve the swelling resistance
  - Improve the mechanical properties (e.g. creep, fracture toughness)
  - Material must stay within original specification
- Testing of HT9 to benchmark performance against legacy data
  - Accelerated (ion) irradiation to high doses for scoping
  - Neutron irradiation for licensing case







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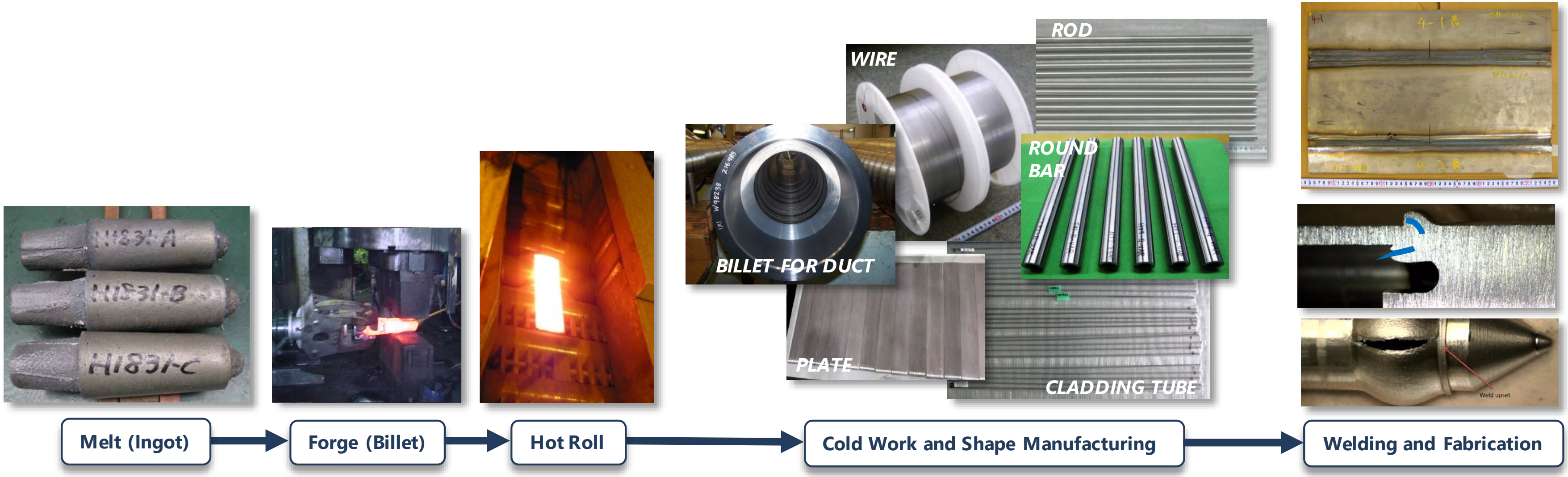
The Supply Chain is Key

Must Have:

- A manufacturing process capable of consistently achieving the desired microstructure
- A thorough understanding of how process variability affects performance
- Domestic and international suppliers with the capability to manufacture bar, tube, wire, and ducts



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Need for Qualification Testing of HT9

- The HT9 licensing basis will rely heavily on historical (FFTF) HT9 data; however, additional testing is required for several key reasons:
  - To fill in missing gaps of knowledge (e.g. friction, fracture toughness)
  - To provide additional confirmatory data points to enable qualification of the existing data for licensing purposes
  - To prove to the regulator that the manufacturers can produce HT9 with consistent properties that meet or exceed historical performance
  - To take advantage of additional design margin provided by the optimized TerraPower HT9 material

Most long-lead testing has started and is producing favorable results

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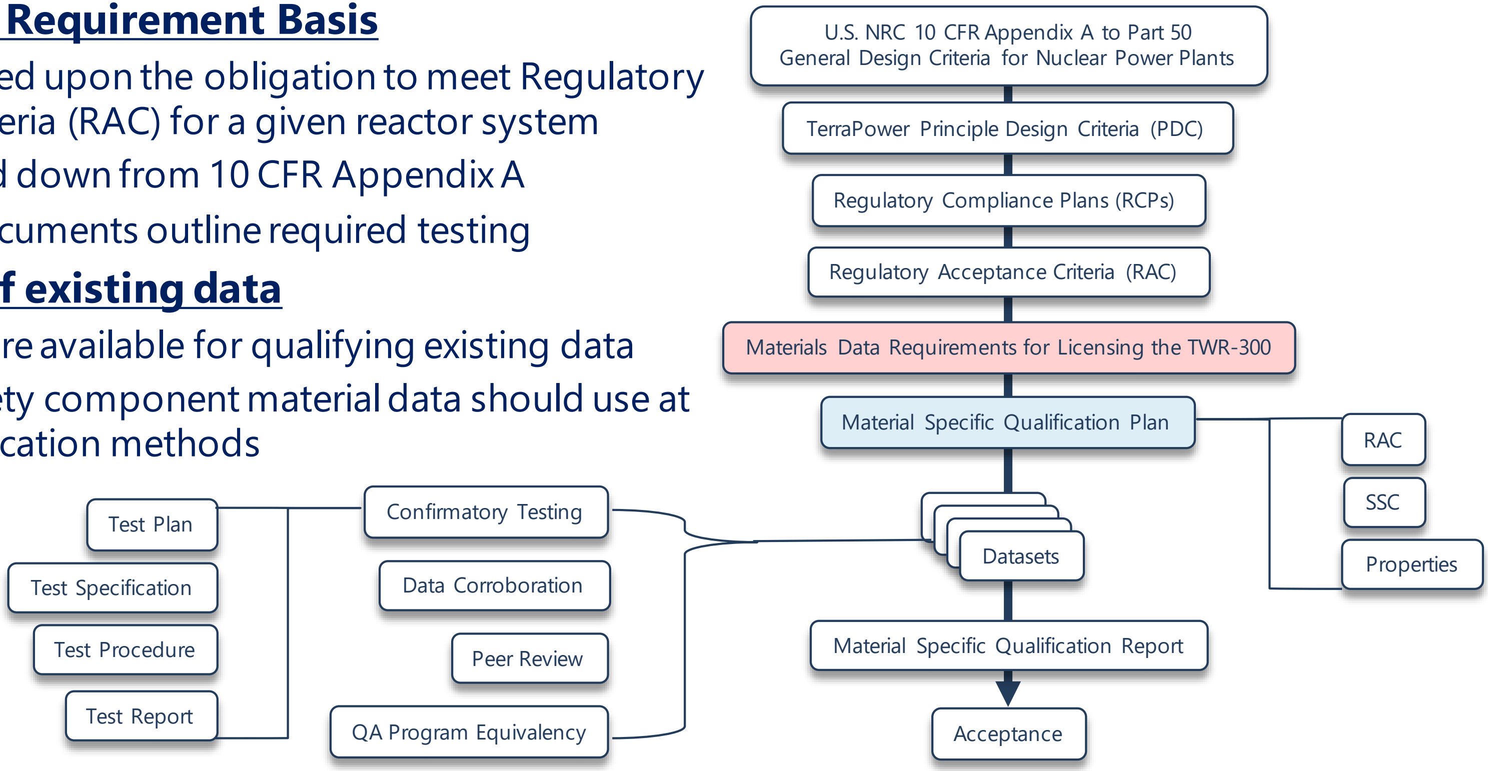
Qualification Summary

Materials Data Requirement Basis

- Data needs based upon the obligation to meet Regulatory Acceptance Criteria (RAC) for a given reactor system
- RACs are flowed down from 10 CFR Appendix A
- Two internal documents outline required testing

Qualification of existing data

- Four methods are available for qualifying existing data
- SSC Class 1 safety component material data should use at least two qualification methods



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Material Property Needs for Licensing

Properties	Unirradiated	Irradiated
Physical Properties (CTE, Poissons, specific heat, etc)	**Complete**	Planned
Thermal Conductivity	**Complete**	Planned
Strength (Yield, Ultimate, Fracture, Elongation)	**Complete**	***In Progress***
Fracture Toughness	**Complete**	***In Progress***
Thermal Creep	***In Progress***	***In Progress***
Fatigue, Creep Fatigue	Planned	Planned
Thermal Aging	***In Progress***	**NP**
Young's Modulus	Planned	**NP**
Corrosion	Planned	**NP**
SCC	Planned	**NP**
Erosion	Planned	**NP**
Wear Rates	***In Progress***	**NP**
Coefficient of Friction	***In Progress***	**NP**
Irradiation Creep	**N/A**	***In Progress***
Stress-Free Swelling	**N/A**	***In Progress***
Stress-Enhanced Swelling	**N/A**	***In Progress***
FCCI	**N/A**	***In Progress***
ACCI	**N/A**	***In Progress***

Complete = testing complete, may require Dedication

In Progress = equipment fabrication and/or testing underway

Planned = testing scheduled based on technical or licensing need. In some cases, equipment has been designed and/or preliminary testing has been performed.

NP = technical or licensing need not expected

N/A = does not apply (e.g. swelling is only a phenomena in irradiated materials)

Qualification Data Organization

Materials Database

- SQL based data management system with a Django front-end
- Stores raw data from samples irradiated in BOR60

Mat_Props

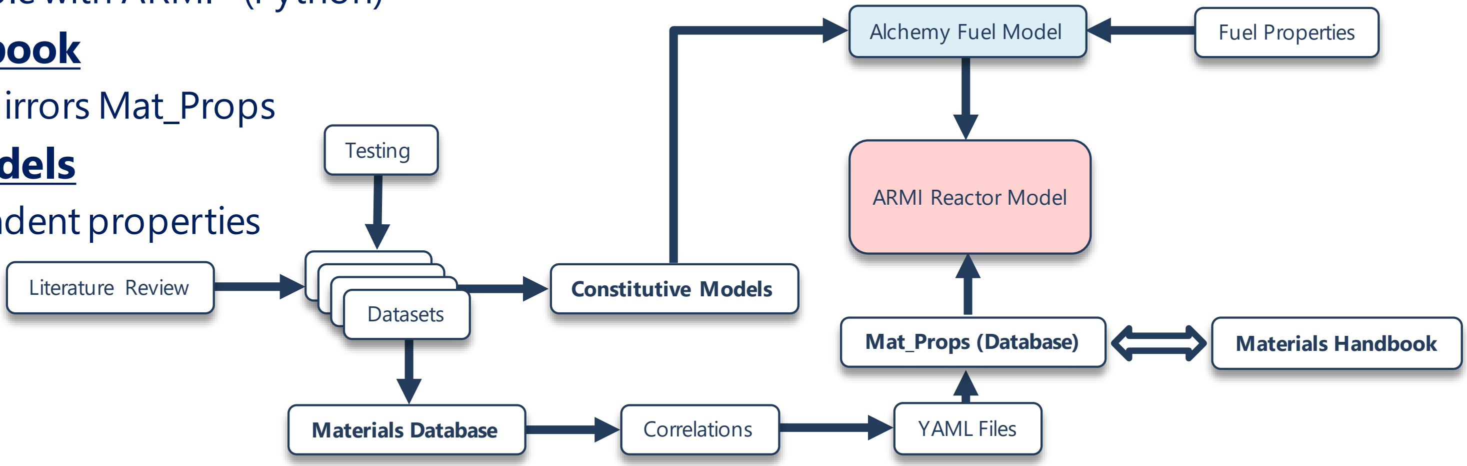
- V&Ved temperature-dependent material properties
- Directly compatible with ARMI© (Python)

Materials Handbook

- Document that mirrors Mat_Props

Constitutive Models

- Time/dose dependent properties



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Summary

Two Reactor Designs, Similar Challenges

- No. 1 challenge is meeting timeline for reactor construction
- Early design decisions require material selection -> need "off-the-shelf" solutions

MCFR Reactor

- Needs Code or "near-Code" materials that can withstand chloride salts
- TerraPower makes and tests salts in-house
- Multi-scale corrosion testing is being used to screen candidate materials

TWR Reactor

- Needs well-understood materials that can survive long core lifetimes
- Focus has been on establishing supply chain for HT9
- TerraPower is ~4.5 years into a ~10 year qualification plan for its HT9 material
- Most long lead testing has started and is producing favorable results

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Q&A

Qualification Summary

Materials Data Requirements for the TWR Design

- 77 RACs identified related to materials development for the TWR, for example:

RAC	SSC Class	System Number	Materials	Data Types	Qualification Method
4.2-1.1 Stress, strain, or loading limits for all fuel system components shall be established. [9]	1	31.1 31.2	HT9 316H IN718 Welds	• Creep (thermal & irradiation) • Yield strength (thermal & irradiation) • Young's modulus • Poisson's ratio • Fracture toughness (thermal & irradiation) • Thermal aging • Thermal expansion coefficient • Thermal conductivity • Density • Irradiation swelling • Stress enhanced swelling	Data corroboration • Confirmatory testing • Peer review

Qualification Plan for HT9 Materials Data for Licensing the TWR-300

- Identifies the material properties required (tied to associated RACs)
- Recommends test methods and standards
- Recommends qualification method

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