Material and Properties Development Needs for Design and Development of Commercially Viable GEN IV Reactors

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Materials Development and Validation for LWR Applications

In-reactor, In-environment Mechanical Response, IASCC, Rad. Fatigue

Stress Corrosion Cracking of Pre-irradiated Material IASCC

Environmentally Assisted Fatigue (EAF) Stress Amplitude vs Life, Crack Growth Rates

Irradiation Effects on Creep – Creep Rates, Creep Life

Mechanical Properties, Toughness in Environment

Stress Corrosion Cracking Stress vs Life, Crack Growth Rates

Quantitative Irradiation Effects on Hardness, Toughness etc.

Time Dependent Creep Properties

Cyclic Properties Fatigue Life Cyclic σ/ε Curves

EAC Effects ?

Tensile Properties, Hardness, Microstructure

Corrosion Resistance

Qualitative Irradiation Effects – Hardening Embrittlement

Mechanical Properties

Environmental Effects

Irradiation Effects

Long Time Fleet Performance Life Prediction from Assessment of Aged Materials via “representative” lab testing

Moderate-time Multi-unit Performance data

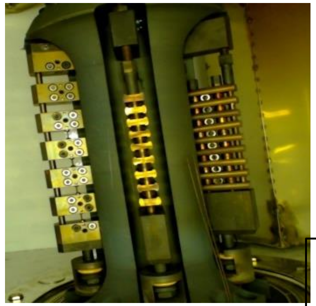
Laboratory test data for interacting variables generating durability data for lifing

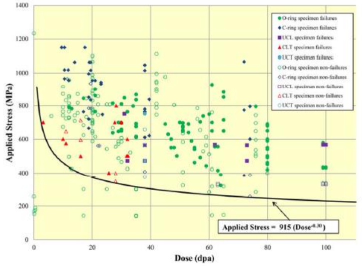
Prototype Performance Data

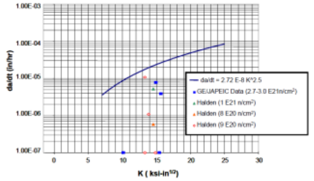
Intermediate-time durability test data for simple effects

Construction Code Data with margin of safety on short time durability data

Materials Development and Validation for LWR Applications







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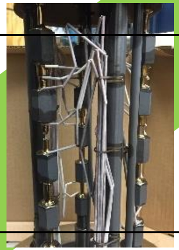

Environmentally Assisted Fatigue (EAF) Stress Amplitude vs Life, Crack Growth Rates

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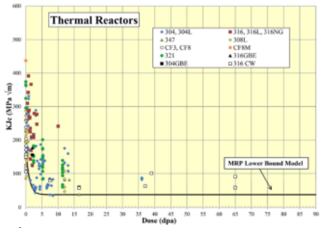
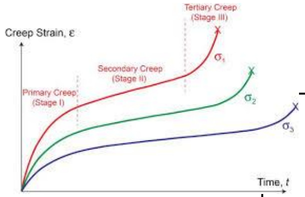
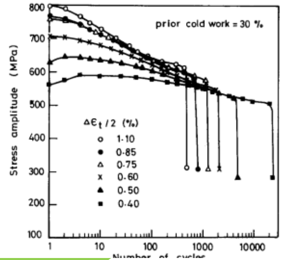
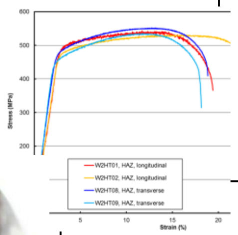




Mechanical Properties, Toughness in Environment



Stress Corrosion Cracking Stress vs Life, Crack Growth Rates



Quantitative Irradiation Effects on Hardness, Toughness etc.

Time Dependent Creep Properties

Cyclic Properties Fatigue Life Cyclic σ/ε Curves

Tensile Properties, Hardness, Microstructure

Corrosion Resistance

Qualitative Irradiation Effects – Hardening Embrittlement

Grade	Tensile Strength (MPa) min	Yield Strength 0.2% Proof (MPa) min	Elongation (% in 50 mm) min
304	515	205	40
304L	485	170	40
304H	515	205	40

Mechanical Properties **Environmental Effects** **Irradiation Effects**

Long Time Fleet Performance Life Prediction from Assessment of Aged Materials via "representative" lab testing

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What is the Data-driven Paradigm that Support Design of New LWRs and Life Extension of Operating Plants?

- Extensive data that describes the behavior of established LWR materials in water + irradiation environments but…
  - LWR's are still designed on simple properties
  - Service Aging Effects Identified
    - Measurements of the effects of irradiation – hardening and embrittlement
    - Measurements of the effects of environment – SCC rather than simple corrosion
  - "Discovery" of key life limiting factors during service
    - Subsequent simulation testing of materials in laboratories and hot cells
  - Post mortem investigations on reactor surveillance capsules and materials "Harvested" from operating reactors
- This extensive database has been built up over 60 years of plant operations and increasingly sophisticated materials testing.

Materials Development and Validation for Advanced Reactor Applications

Reactor Structures' Life Prediction and Safety Validation Data

In-reactor, In-environment Mechanical Response, IASCC, Rad. Fatigue

Stress-Corrosion Cracking Behavior of Previously Irradiated Material

Irradiation Effects on Lifing Parameters

Structure/Component Data for Realistic Lifing

Environmentally Affected Cyclic Deformation Response : Stress Amplitude vs Life, Crack Growth Rates etc.

Irradiation Effects on Creep : Creep Rates, Creep Life

Mechanical Properties, in Environment

Stress Corrosion Cracking Stress vs Life, Crack Growth Rates

Irradiation Effects on Mechanical Properties

Material Viability/ Selection for Components

Cyclic Properties Fatigue Life Cyclic σ/ε Curves

Time Dependent Mechanical Properties

Corrosion Behavior Weight Loss, IGA Attack

Irradiation Effects on Microstructure Swelling, He Production, Matrix Hardening, Phase Changes

Licensing and Qualification Construction Code Data

Mechanical Properties | **Environmental Effects** | **Irradiation Effects**

New Materials Development: Composition Control, Processing, Microstructural Optimization → Scale Up, Standardization and Commercial Availability

Data Generation and Material Testing for Structures in Advanced Reactors

Long Time Fleet Performance Life Prediction from Assessment of Aged Materials via “representative” lab testing

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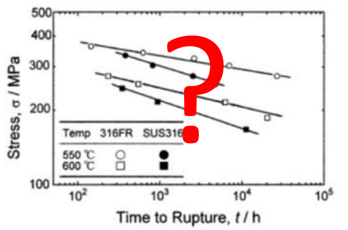
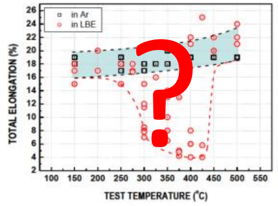
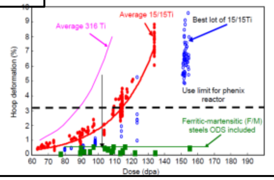
Irradiation Effects on Mechanical Properties

Prototype Performance Data





Mechanical Properties, in Environment



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Intermediate-time durability test data for simple effects

Time Dependent Mechanical Properties

Corrosion Behavior Weight Loss, IGA Attack

Irradiation Effects on Microstructure Phase Changes

Standard Code Data with margin of safety on short time durability data

Mechanical Properties

Environmental Effects

Irradiation Effects

New Materials Development: Composition Control, Processing, Microstructural Optimization → Properties

How Well Can We Follow The LWR Paradigm To Support The Development Of Advanced Reactors? (2)

- Lots of "white space" compared to the data that supports LWR reactors…
  - Immediate need for new materials/properties to be developed, validated and standardized
    - High temperatures, irradiation and corrosion data
  - Some "simple properties" are available to support concepts – but **there are many gaps** in supporting data - long time data, time dependent properties, severe environment service
  - Progression from properties under combined conditions– Stress + Environment, Cyclic at Temperature, Strain + Irradiation…
- Design and build of prototype systems can validate materials selections and identify key data needed to support longer term lifing predictions

Materials Gaps identified for Advanced Reactors (MSR, LFR, VHTR/GFR, SFR) in EPRI Material Gap Studied - 1 of 2

GEN IV REACTOR	COMPONENT	MATERIAL	NEEDED R&D
Molten Salt Reactors	Core Support/ Structural Materials	**316**	Proof of resistance to long time corrosion in properly controlled salt environment. Time dependent properties for ASME code Sec III Div 5 certification. Demonstration of performance (resistance to EAC) in salt under loading. Development and demonstration of cladding (Mo rich) for protection
		Hastelloy N and variants	Demonstration of radiation tolerance of Hast N variants (Proper understanding of chemistry→ microstructure → properties … Development of properties for ASME code Sec III Div 5 certification
	Coolant	**Salt**	Development of salt chemistry (and impurity) control. Demonstration of Te control
	Moderator	**Graphite**	Development of long time properties in salt etc. ***for the specific type of graphite to be employed***
High temperature Gas Reactor	Core Support/ Structural Materials	**316 and Austenitic Alloys**	Code approval of time dependent properties – creep, creep-fatigue
		316FR	Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties
	Vessel	**LAS**	Time dependent and fatigue properties for ASME code Sec III Div 5
	Moderator	**Graphite**	Development of long time properties etc. ***for the specific type of graphite to be employed***
Na SFR	Vessel and Core Support Structure	**316 Stainless**	Extend code properties to include time dependent behavior (Creep. Creep fatigue)
		D9	Development of for ASME code Sec III Div 5 properties (including time dependent properties) for D9 Development of swelling behavior at long times under realistic conditions – demonstrate adequacy
	Core Support Structure and Cladding	**Ferritic Martensitic**	Prove adequacy of swelling resistance at high fluence Development of fabrication technology and proof pf performance of welds

Legend:
- Stainless Steels
- Ferritic-Martensitic & LAS
- Nickel-based Alloys
- Other (Graphite, Ceramics)
- Corrosion
- Cladding

Materials Gaps identified for Advanced Reactors (MSR, LFR, VHTR/GFR, SFR) in EPRI Material Gap Studied - 2 of 2

GEN IV REACTOR	COMPONENT	MATERIAL	NEEDED R&D
GFR	Core support	**Ferritic Martensitics**	Demonstration of adequate resistance to swelling at high dpa. Time dependent properties for ASME code Sec III Div 5. (include development of fabrication technologies – and demonstrate properties of joints…)
	Cladding and reflector	**Ceramics**	For advanced GFR – SiC-SiC, Zr_3Si need materials endurance data for these materials
Lead Fast Reactor	Structural Materials/ Vessel	**316**	(code qualified already) but need creep and creep fatigue data to be added into code. Need corrosion data/demonstration of resistance to lead corrosion
		Type 15-15Ti stainless	Verification of swelling resistance Development of code properties for 15-15Ti material design
	Near core structures and cladding	**Ferritic Martensitics**	Demonstration of adequate resistance to swelling at high dpa. Time dependent properties for ASME code Sec III Div 5. (include development of fabrication technologies – and demonstrate properties of joints…) Demonstration of resistance to lead corrosion/development of corrosion data Development of fabrication and effective joining methods
High Temperature Lead Reactors	Structural Materials/ Vessel	**Alumina Forming Austenitic Stainless Steels**	Demonstration of resistance to lead corrosion Demonstration of adequate resistance to irradiation/swelling at expected high dpa Development of processing and joining of alumina forming austenitic stainless steels
	Cladding	**SiC-SiC**	Development of SiC-SiC structures Demonstration of resistance to lead corrosion Development of properties and support to code qualification

Stainless Steels
Ferritic-Martensitic & LAS
Nickel-based Alloys
Other (Graphite, Ceramics)
Corrosion
Cladding

Materials Properties Needed for Design and Development of Advanced Reactors

Mechanical Properties

Note: Some mechanical properties serve more than one reactor development

316H SS	Extend BPV-III Div 5. Code properties to include time dependent behavior (Creep. Creep fatigue) at increased temperatures (600C and greater) Development and demonstration of cladding (Mo rich) for protection
316FR SS	Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties
Type 15-15Ti SS	Verification of swelling resistance Development of code properties for 15-15Ti material design
Alumina Forming γ SS	Demonstration of adequate resistance to irradiation/swelling at expected high dpa Development of processing and joining of alumina forming austenitic stainless steels
D9 Stainless Steel	Development of for ASME Code Sec III Div 5 properties (including time dependent properties) for D9 Development of swelling behavior at long times under realistic conditions – demonstrate adequacy

Ferritic-Martensitic —9 Cr	Demonstration of adequate resistance to swelling at high fluence range. Time dependent properties for ASME Code Sec III Div 5. Development of fabrication and effective joining methods
Ferritic-Martensitic --12Cr	Demonstration of adequate resistance to swelling at high fluence range. Time dependent properties for ASME Code Sec III Div 5. Development of fabrication and effective joining methods with mechanical integrity
Ferritic Martensitic Generic	Validation of commercial reliability – Properties sensitivity to heat treatment/local microstructures Response to fabrication processes – welding practices
LAS	Time dependent and fatigue properties for ASME code Sec III Div 5 to higher temperatures

Hast N & Variants	Demonstration of radiation tolerance of Hast N variants (Proper understanding of chemistry→ microstructure → properties Development of properties for ASME Code Sec III Div 5 certification
800H and 617	Summary Document of Properties (High temperature, time dependent)

Corrosion Properties

316	Demonstration of long time resistance to molten salt Demonstration of sustained mechanical behavior in molten salt (Salt equivalent of SCC) Demonstration of sustained mechanical behavior of CW/Irrad. material mechanical behavior in molten salt Data/demonstration of resistance to lead corrosion Sustained mechanical behavior in molten lead
316H	Proof of resistance to long time corrosion in properly controlled salt environment. Demonstration of performance (resistance to EAC) in salt under loading.
Alumina Forming Υ SS	Demonstration of resistance to Lead corrosion Demonstration of resistance to molten salt corrosion Determination of the effects of potential EAC

Ferritic-Martensitic 9Cr	Demonstration of resistance to lead corrosion/development of corrosion data Demonstration of sustained mechanical properties in lead
Ferritic-Martensitic 12Cr	Demonstration of resistance to lead corrosion/development of corrosion data Demonstration of sustained mechanical properties in lead

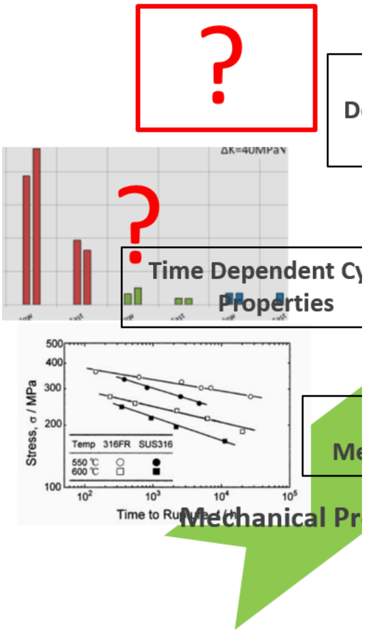
Hast N & Variants	Extended corrosion data/demonstration of resistance to molten salt Demonstration of sustained mechanical behavior in molten salt (Salt equivalent of SCC) Demonstration of sustained mechanical behavior of CW/Irradiated material mechanical behavior in molten salt
Alloys 800H and 617	Proof of resistance to long time corrosion in properly controlled salt environment. Demonstration of performance (resistance to EAC) in salt under loading. Comparison of behavior vs 316 and Hastelloy N

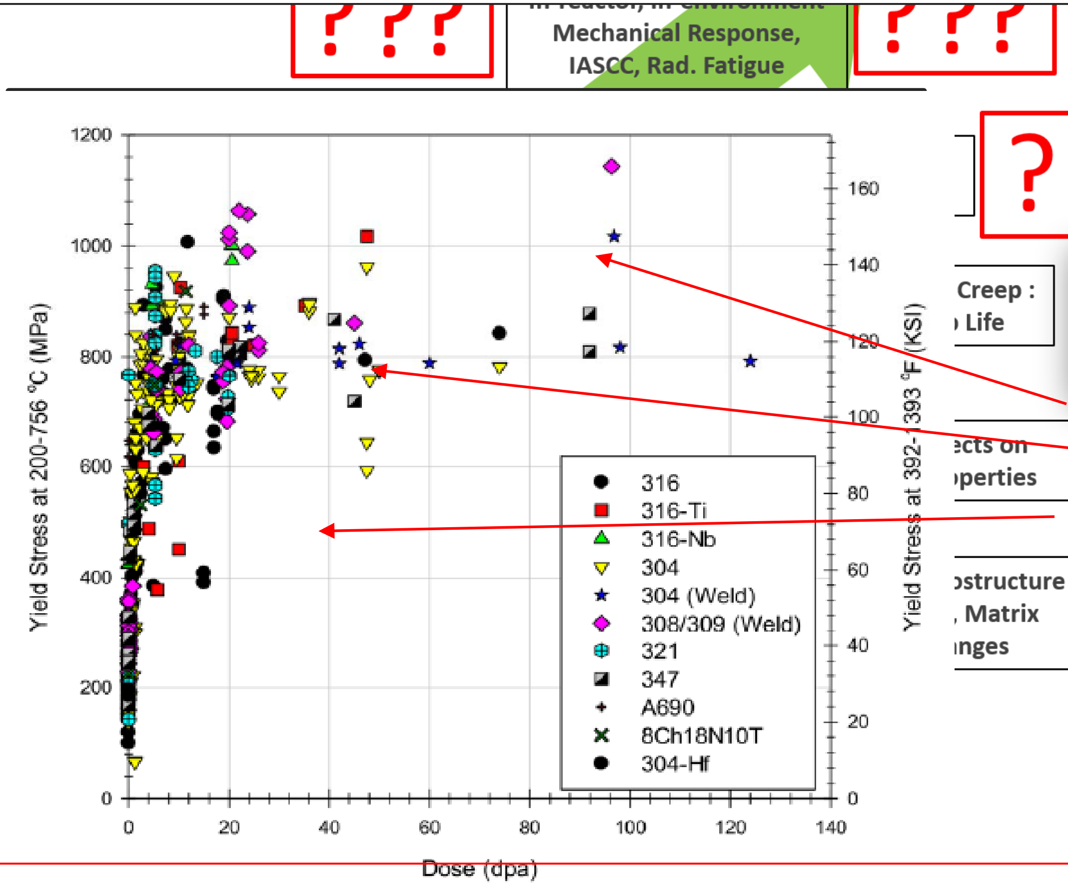
Development of Materials Technology for Advanced Reactors' Design and Development

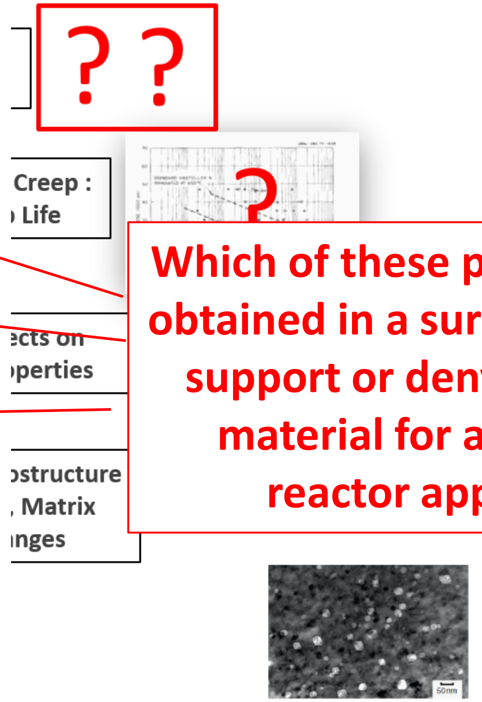
- Three categories of development needed:
  - **Materials properties to support initial design** and to attain ASME code acceptance for constructions - including high temperature and time dependent properties
  - **Response of candidate materials to neutron irradiation** – effects of realistic levels of irradiation on microstructural and property stability
  - **Materials' response in environment** - effects measured in realistic environments: stand alone & effects on mechanical behavior (equivalent to IASCC)
- Initial Focus on development of code required material properties
  - Support for design and build of prototype(s) ← Simple properties
  - Initial design for short life (predict prototype performance) ← Analysis incorporates some time dependent property data
  - Development of extended time dependent properties & properties of appropriately aged and exposed materials ($T,t + \sum \phi_n,t$)

Caveat :Materials Robustness for Advanced Reactors' Development

There is ALWAYS a need to understand the potential for variability in materials properties: development materials sampling vs production scale up







Which of these points would be obtained in a survey program to support or deny the use of a material for an advanced reactor application?

New Materials Development: Composition Control, Processing, Microstructural Optimization → Scale Up, Standardization and Commercial Availability

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