Material issues for design and licensing of MYRRHA ADS system

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Outline

- Role of material research for MYRRHA development
- Challenges
  - Material properties for design
  - Incorporation of environment(coolant) effects
  - Problems with existing experimental data
  - Testing procedures
  - Access to irradiation facilities
- MYRRHA materials program
  - General approach
  - Example: Liquid Metal Corrosion

Role of material research for development of MYRRHA

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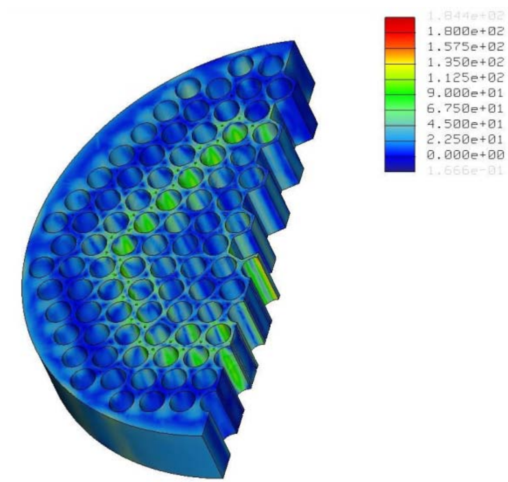
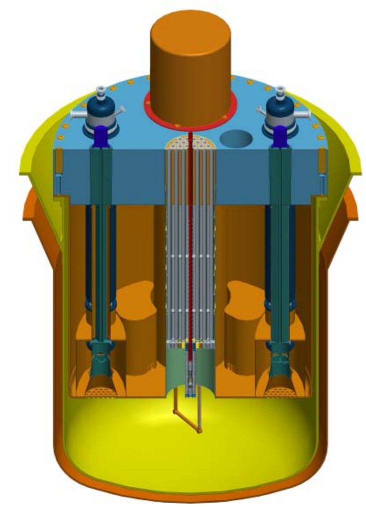
Design tools:

- Nuclear manufacturing codes: RCC-MRx, …
- Fuel codes
- FE calculations

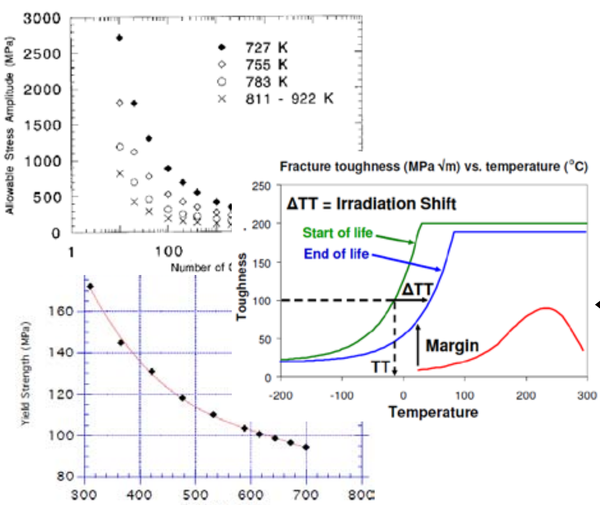
Design



Construction



Materials properties



Approaches

Data

Missing data for MYRRHA:

- Some basic characteristics of candidate materials (T91, SS 316L & 15-15Ti)
- Effects of LBE & irradiation on material properties
- Physical effects: Liquid metal embrittlement (LME), SCC, etc.

Material scientists should

- Provide material property data for design and licensing of MYRRHA

- Assist in
  - Materials selection
  - Components design
  - Fuel development
  - Safety analysis
  - Coolant technology development
  - Surveillance program development
  - Development of testing infrastructure
  - …

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Material properties for design

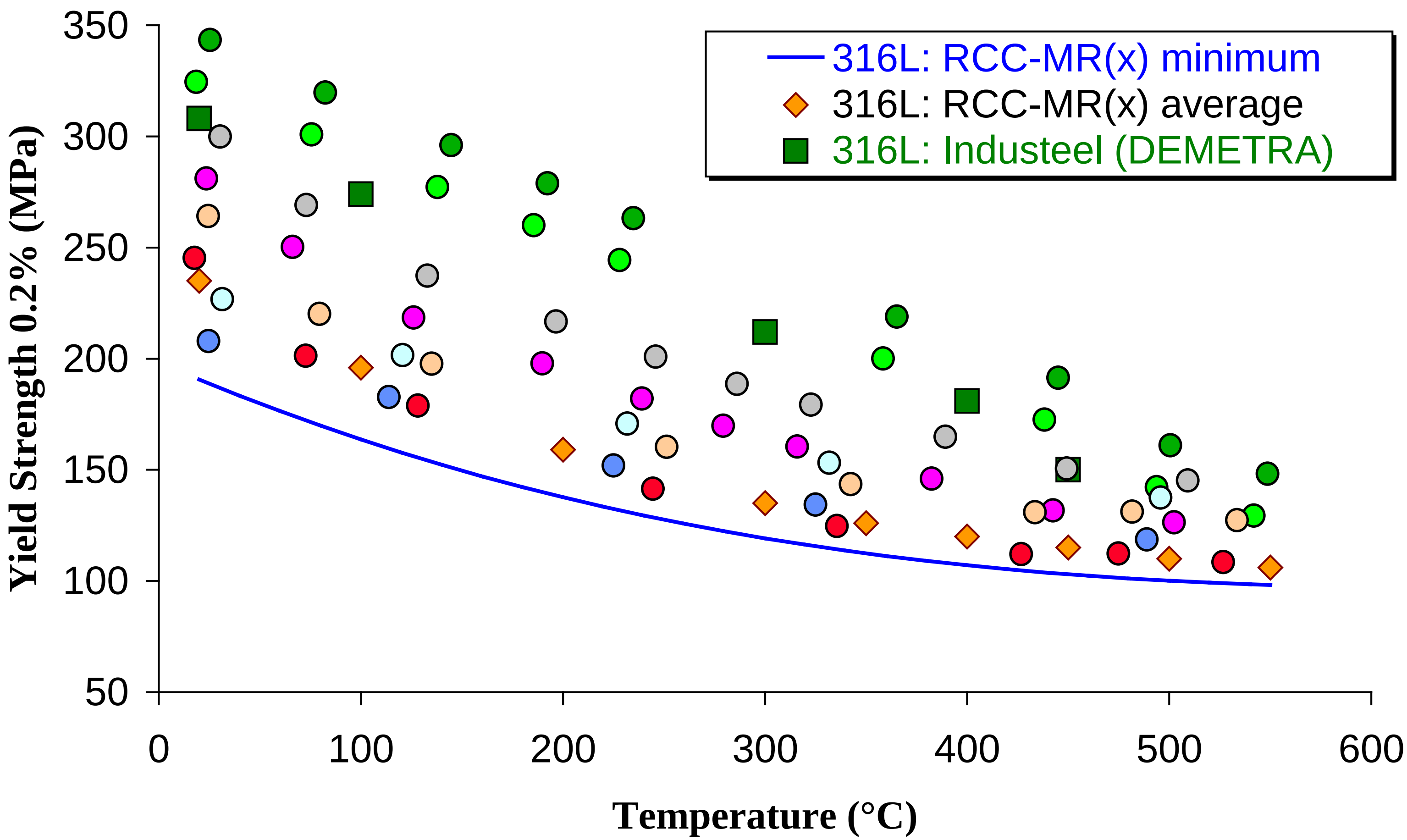
MYRRHA candidate materials:

T91
316L
15-15Ti
Welded joints

- Fabrication
  - Composition, Product Forms, and Specifications
  - Joining and welding technologies
- Physical properties
  - Crystal Structure and Phases
  - Melting Point
  - Density
  - Thermal Conductivity
  - Thermal Expansion
  - Specific Heat
- Corrosion
- Mechanical properties
  - Elastic Properties
  - Tensile Properties
  - Fatigue Properties
  - Fracture Toughness
  - Creep Behavior
  - Other

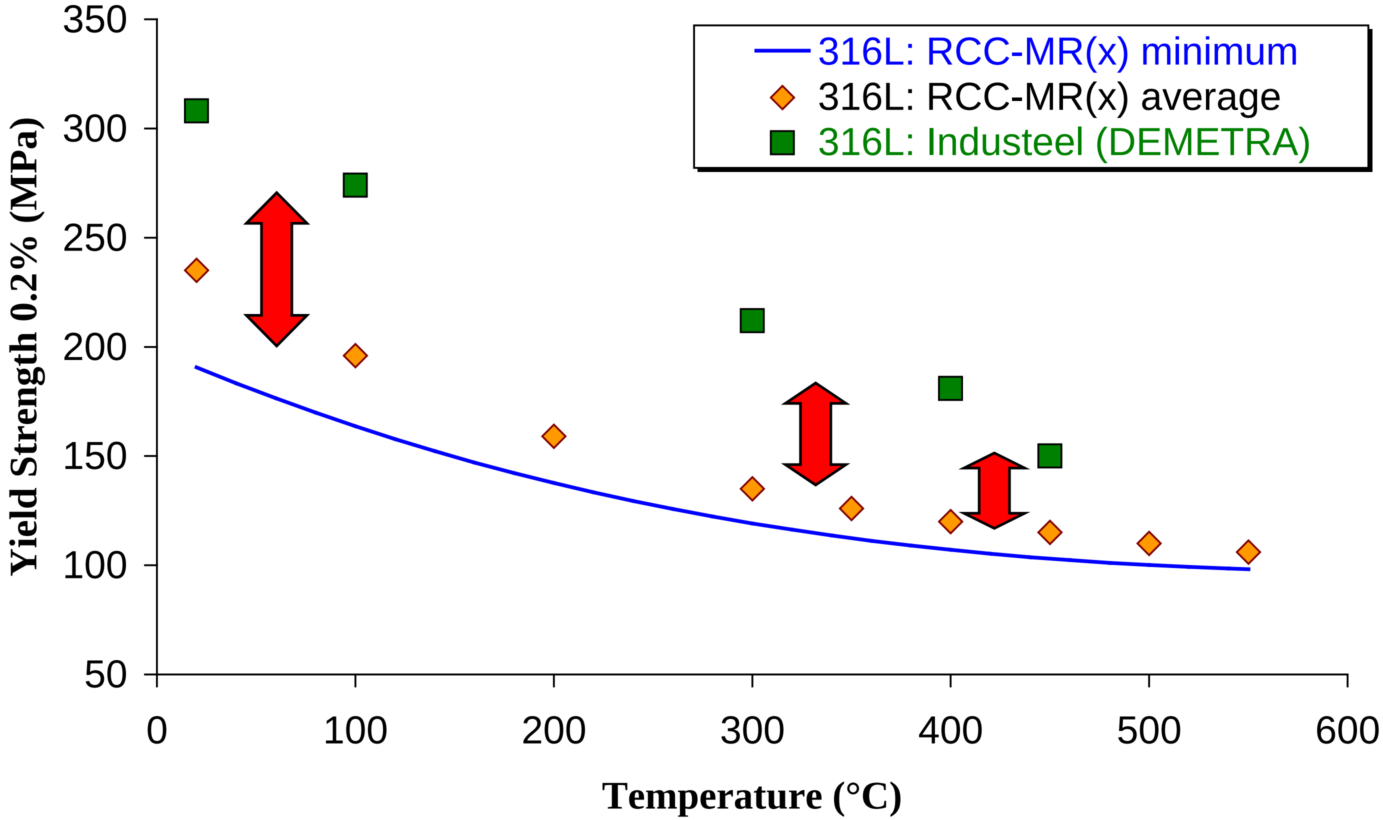
Influence of Irradiation, Environment, and Combination of both

Example: Yield strength of SS 316L



Implementation of material properties in design tools

- The existing material properties in codes are derived from the results of multiple tests performed on multiple material heats



- The “distance” between single experimental data point and “material property for design” is quite big!

Imaginary situation

Assume that tomorrow somebody will propose us a new material with excellent strength, good ductility, good corrosion and radiation resistance, excellent fabricability, good welding properties, etc.

Will we be able to use this material to build MYRRHA structures in the foreseen timeframe?

Most probably no! Why?

A material becomes "structural material for nuclear power plant" after a very long way of testing and characterization!

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How to take into account environmental effects?

- Liquid Metal **Corrosion** (LMC) → Corrosion allowance
  - Uniform
  - Localized
- **Environment** assisted cracking → Reduction of values? Increase margins?
  - Liquid metal embrittlement (LME)
    - Tensile properties
    - Fracture toughness
  - Corrosion fatigue
  - Corrosion Creep (Time to rupture)
- Effect of **irradiation** → New reduced values (RCC-MRx) Max dose, standards?

To introduce effect of LBE(environment) in the code, the term “environment” should be introduced first. It includes parameters of the environment and means to control them. Additionally the results of mechanical test should be obtained according to the standard procedures which do not exist for tests in environment.

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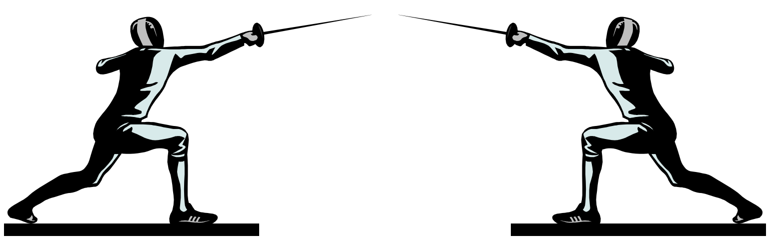
Problems with existing experimental data

- Generation of consistent and reliable database for single material properties is long term efforts of few properly equipped teams
- Existing experimental data for characterization of material degradation effects in LBE can be divided in the following groups
  - Some experimental results, but important data are still missing (e.g.LMC)
  - Limited experimental data, mostly results of screening tests (e.g. LME, fatigue, creep)
  - No experimental data (e.g. SCC, crevice corrosion)
- Many existing experimental data are inconsistent, moreover – there are some data which “pollute” databases
  - Some important parameters are not reported or in the worst cases are reported incorrectly

Existing contradictions in materials research for GEN IV

- GEN IV: very harsh conditions
- High temperatures
- High radiation damage doses
- Very corrosive environments
- Very high demands on material properties with questionable feasibility

- Limited experimental capacity
- Absence of common guidelines for testing procedures
- Big scatter of test results
- Limited understanding of underlying phenomena
- As result: Wide safety margins



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Liquid metal fast reactors

	Name	Country	Thermal power	Criticality	Status
EXPERIMENTAL	CLEMENTINE(Hg)	USA	0.02 MW	1945	Shutdown: 1952
	EBR 1(NaK)	USA	1.4 MW	1951	Shutdown: 1963
	BR1	Russia	0.03 MW	1955	Shutdown: ?
	BR2 (Hg)	Russia	0.2 MW	1956	Shutdown: 1957
	BR5 – BR10	Russia	5/10 MW	1958/1973	Shutdown: 2002
	DFR (NaK)	GB	75 MW	1959	Shutdown: 1977
	LAMPRE	USA	1 MW	1951	Shutdown: 1955
	EBR 2	USA	60 MW	1965	Shutdown: 1993
	RAPSODIE	FRANCE	24/40 MW	1967/1970	Shutdown: 1983
	BOR 60	Russia	60 MW	1968	Operating->2015
	SEFOR	USA	20 MW	1969	Shutdown: 1972
	KNK1 - KNK2	FRG	60 MW	1972/1977	Shutdown: 1991
	JOYO	Japan	50 MW	1977	Shutdown: 2009
	FFTF	USA	400 MW	1980	Shutdown: 1992
	FBTR	India	40 MW	1985	Operating
	PEC	Italy	120 MW		Closed: 1987
	CEFR	China	60 MW	2010	Operating

Challenge to obtain missing data for radiation effects

	Name	Country	Electric power	Criticality	Status
DEMONSTRATORS	FERMI (EFFBR)	USA	100 MW	1963	Shutdown: 1972
	BN 350	USSR	150 MW	1972	Shutdown: 1999
	PHENIX	France	250 MW	1973	Shutdown: 2009
	PFR	GB	250 MW	1974	Shutdown: 1994
	SNR 300	FRG	300 MW		Closed: 1992
	MONJU(JPFR)	Japan	280 MW	1992/2010/?	Under review
	Clinch River (CRBR)	USA	350 MW		Closed: 1977

	Name	Country	Electric power	Criticality	Status
POWER	BN-600	Russia	600 MW	1980	Operating
	SUPERFENIX	France	1200 MW	1985	Shutdown: 1998
	BN-800	Russia	800 MW	2013?	Constr.
	PFBR	India	500 MW	2010	Constr.

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MYRRHA materials R&D program

- Identification of key material issues
  - Collaboration with designers, fuel, safety and coolant chemistry groups
  - Assistance in design
    - Material choice justification
    - Various scenarios related to material failure
    - Preliminary assessment of material damage mechanisms
- Assessment of material properties
  - Development of testing procedures (FP7 MATTER)
  - Identified material issues and our related R&D program
    - Liquid Metal Corrosion (LMC)
    - Liquid Metal Embrittlement (LME)
    - Irradiation effects
- Development of testing infrastructure

Identification of key material issues

- Identification of the operational and potential accidental conditions during lifetime of the component (e.g. for the fuel assembly, it should cover the whole range from fabrication of fresh fuel up to the waste disposal)
- Identification of the failure criteria for every identified condition (e.g. dimensional stability of wrapper) and compilation of the potential failure cases based on the design criteria.
- Identification of the underlying physical phenomena including possible synergy between various mechanisms which can prematurely cause the failure of the component (e.g. creep–fatigue, etc.) It obviously difficult to address all the material degradation mechanisms, however priority according to the impact on safety should be kept in mind.
- Examination of the design rules for their ability to handle all identified failures.
- Revision of the existing material properties databases and identification of the missing material properties.
- Definition of the form in which material properties should be incorporated in the code.
- Identification of the material tests required to obtain the missing properties.

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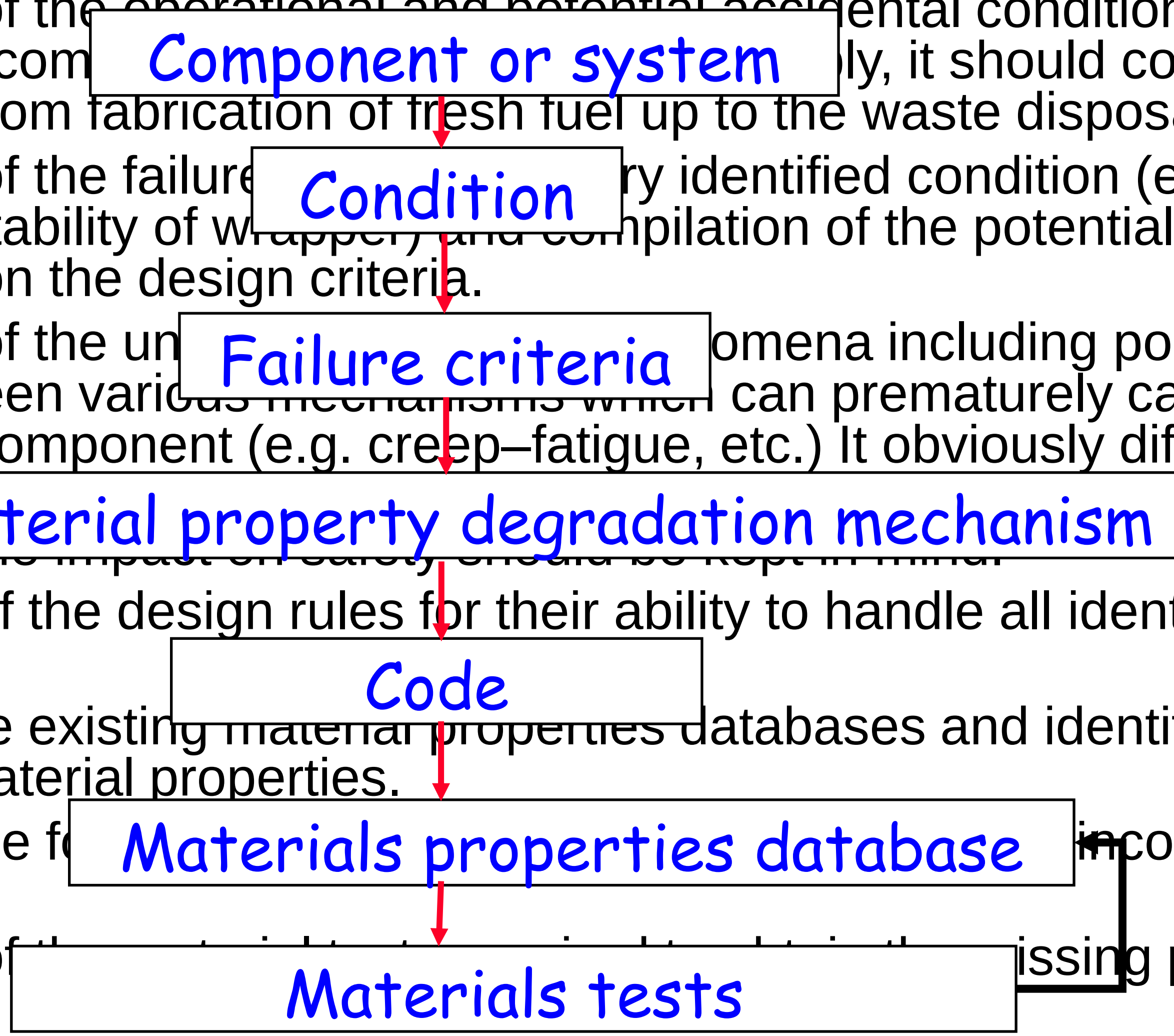

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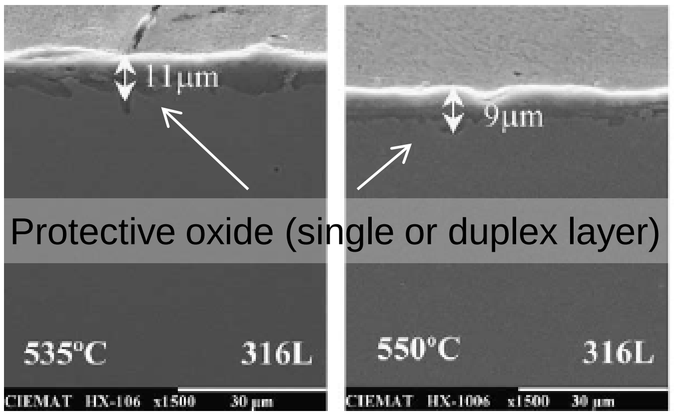
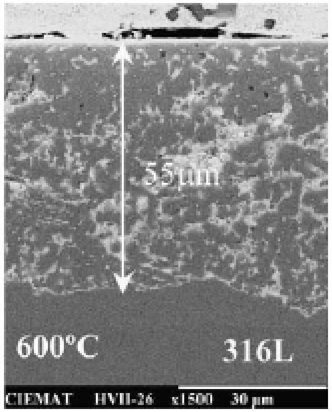
Liquid Metal Corrosion in LBE (uniform)

1. Oxidation



316L: 500 h, stagnant LBE, [O] = 3-8×10^{-6} wt%
(Martín et al., J Nuclear Mater, **335** (2004) 194-198)

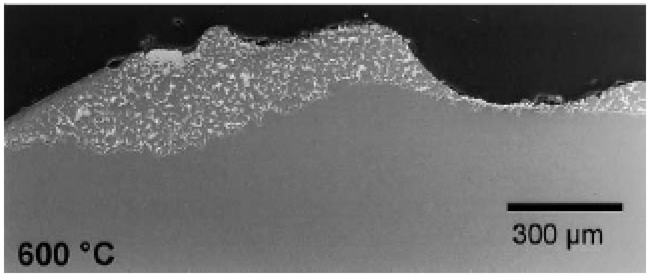
2. Dissolution



- LBE penetration
- Loss of elements, esp. Ni and Cr

316L: 500 h, stagnant LBE, [O] = 3-8×10^{-6} wt%
(Martín et al., J Nuclear Mater, **335** (2004) 194-198)

3. Erosion



- Severe material loss & compromise of structural integrity
- Observed at high LBE flow velocities, two-phase flow, and sites of flow diversion

316L: 2000 h, flowing LBE - flow velocity: 2 m/s, [O] = 1×10^{-6} wt%
(Müller et al., J Nuclear Mater, **301** (2002) 40-46)

Effects of Corrosion on Reactor Operation

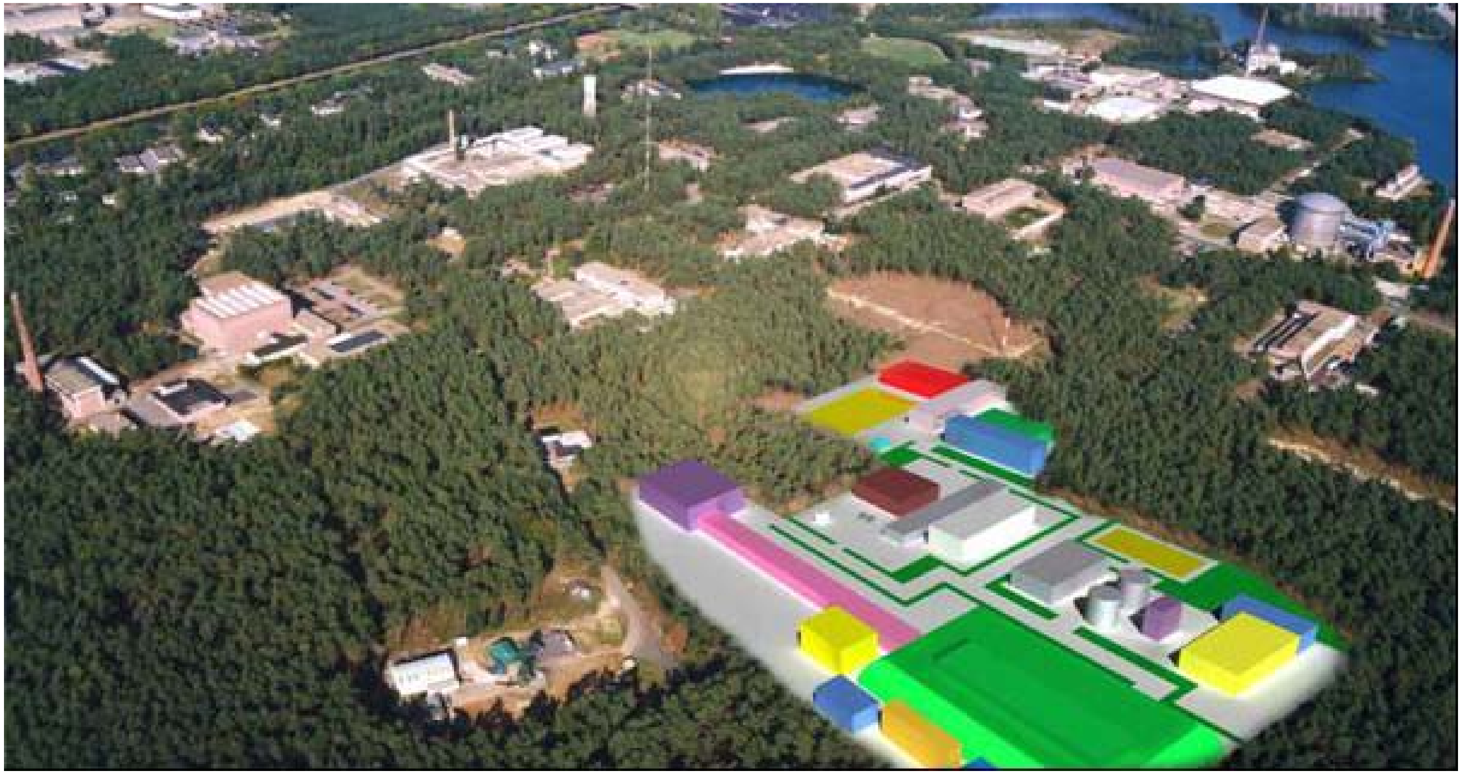
Effects of Corrosion on Reactor Operation

- Material loss (dissolution, erosion) → compromise of component integrity
- Change in thermal conductivity (oxidation) → change of heat transfer characteristics
- Plugging due to deposition of corrosion products → flow obstruction

Principal directions of corrosion program

- Prediction of max corrosion depth (deterministic↔empiric approach)
  - Boundary operating conditions and a little bit beyond
    - For oxidation ([O]↑, T↑, v↑)
    - For dissolution ([O]↓, T↑, v↑)
- Investigation of oxide layer properties
  - Maximum and average thicknesses
  - Thermal conductivity
- Assessment of corrosion products release to the coolant and oxygen consumption

Critical core: The distance between neutronic physicists, thermo-hydraulic specialists, material scientists, chemists, designers and safety engineers does not exceed few hundred meters



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