Generation IV Systems and Materials

presented at

Advanced Computational Materials Science: Application to Fusion and Generation-IV Fission Reactors

by

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Overview

- Generation IV Initiative
- Generation IV Concepts and Operating Environment
- Significant Material R&D Challenges

Generation IV International Forum

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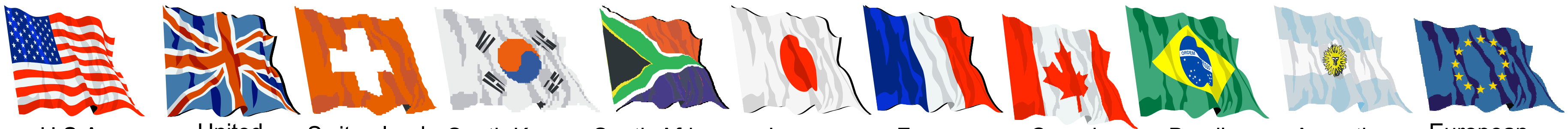

U.S.A. | United Kingdom | Switzerland | South Korea | South Africa | Japan | France | Canada | Brazil | Argentina | European Union

Established in January 2000 to develop: systems that are deployable by 2030 or earlier and offer significant advances towards:

- Sustainability
- Economics
- Safety and reliability
- Proliferation resistance and physical protection

A Long-Term U.S. Strategy for Nuclear Energy

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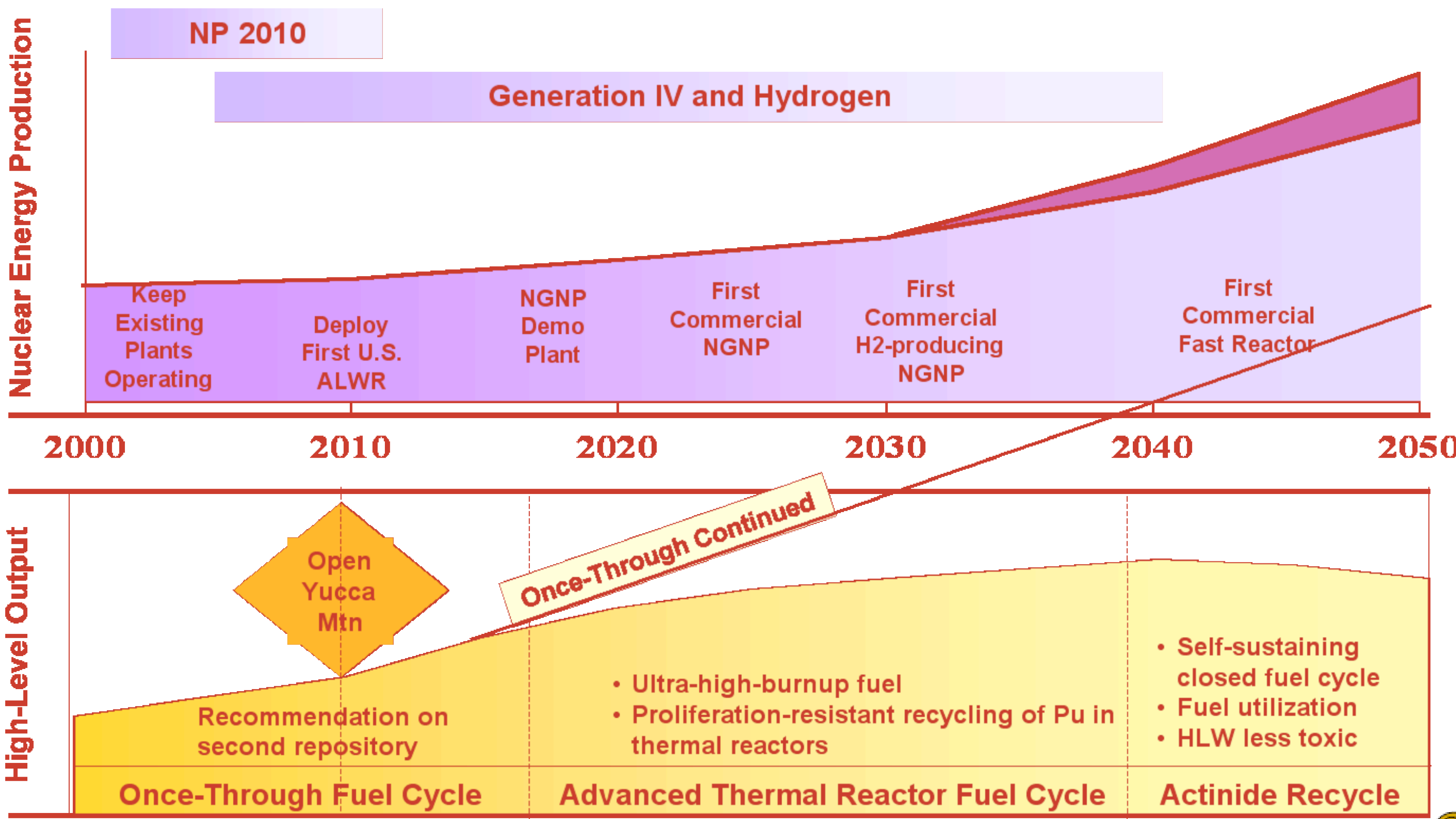


U.S. Generation IV Implementation

Gen IV Top Priority

VHTR + H_2 → NGNP

SCWR

Next-Generation Nuclear Plant

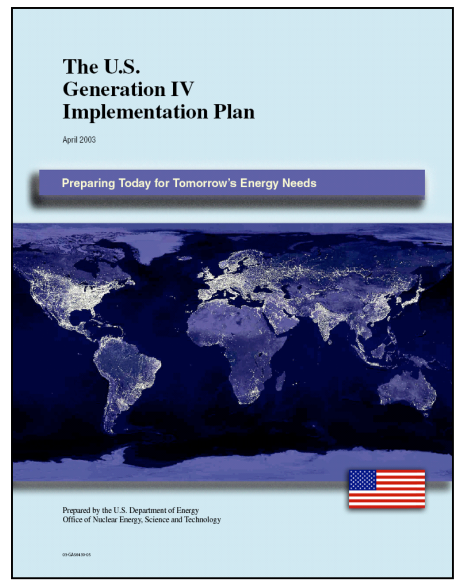
- Collaborative with international community
- Collaborative with industry, especially utilities
- Demonstrate H_2 and direct-cycle electricity production
- Result in a commercially viable plant design

Gen IV Second Priority

- GFR
- LFR
- SFR

→

U.S. Fast Reactor
Closely coordinated with Advanced Fuel Cycle Initiative



Generation IV Next Generation Nuclear Plant (NGNP)

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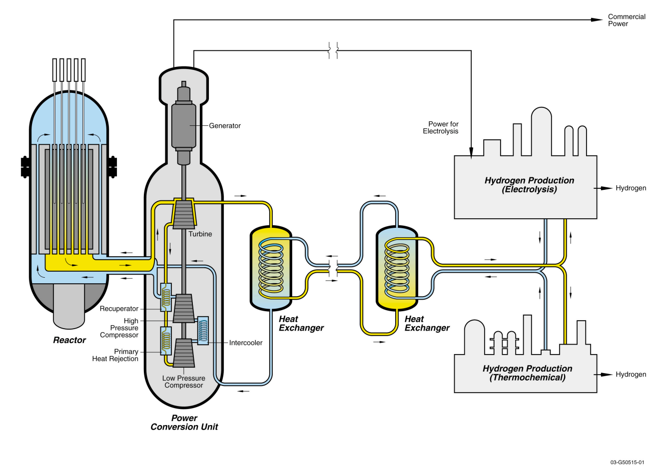
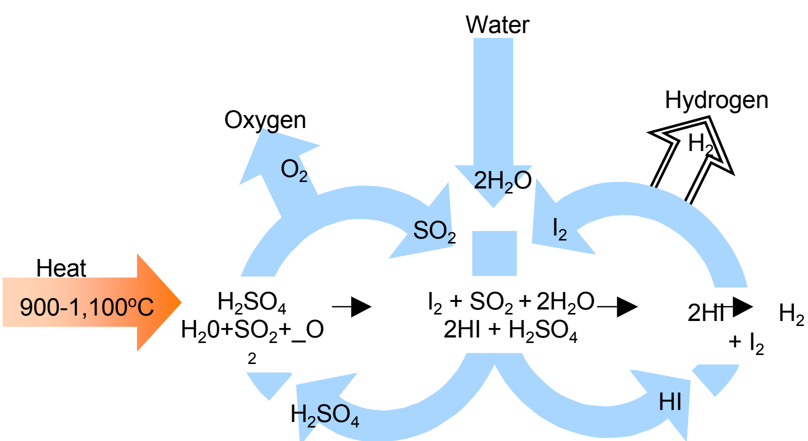
- **Generation IV NGNP: Advanced VHTR designed for production of hydrogen and electricity**
  - High outlet temperature (1000°C) allows use of thermochemical and temperature-assisted electrolysis methods for producing hydrogen
  - High electrical conversion efficiency
  - Attractive safety aspects





- **Modular construction**
  - 600 MW_{Th}
  - At 50% efficiency, could produce up to 200 MT of H_2 a day, the equivalent of 200,000 gallons gasoline per day.
- **Objective: build NGNP demo plant by 2017**

Very-High-Temperature Reactor (VHTR)

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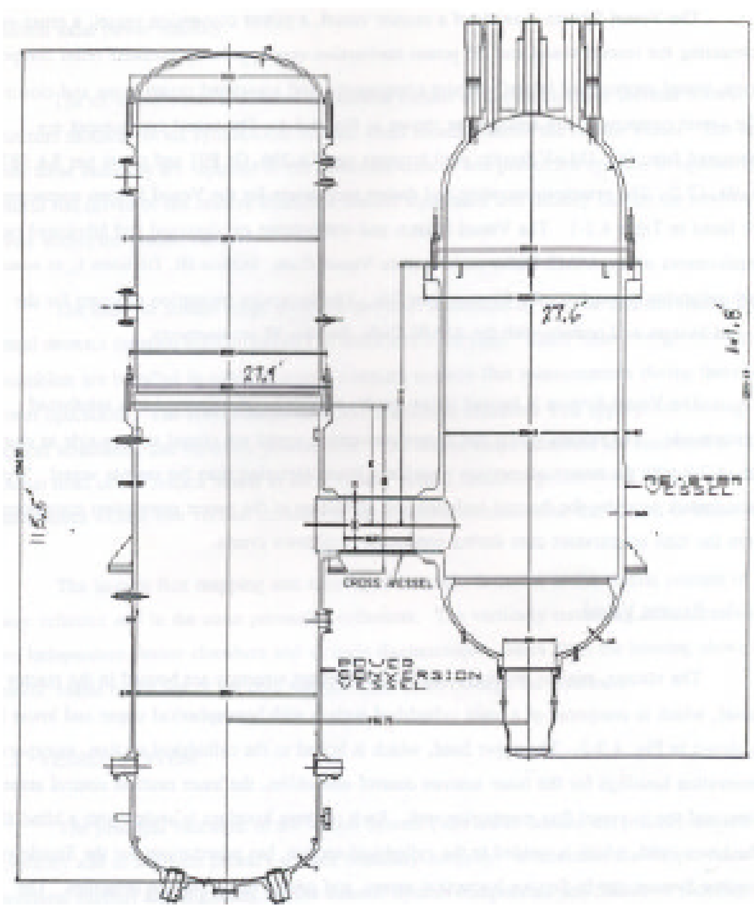
GTMHR and Pebble Bed options being considered



- The temperature of many reactor internals is expected to range from 600-1000°C
- Current Code Case materials will be inadequate for usage for selected key components in the NGNP
- The most promising mature metallic alloys for these applications are Alloy 617, 800H, Hastelloy X or variants
- Another option is to perform the required R&D, fabricate and perform licensing reviews on C-C or SiC-SiC (or similar materials) for key core components

Summary of ASME Code Section III, Subsection NH

Material	Maximum Allowable Metal Temperature °C (300,000 hours max)
304 SS	**816**
316 SS	**816**
Alloy 800H	**760**
2.25Cr-1Mo	**593**
Alloy 718	**566**

Reactor Pressure Vessel

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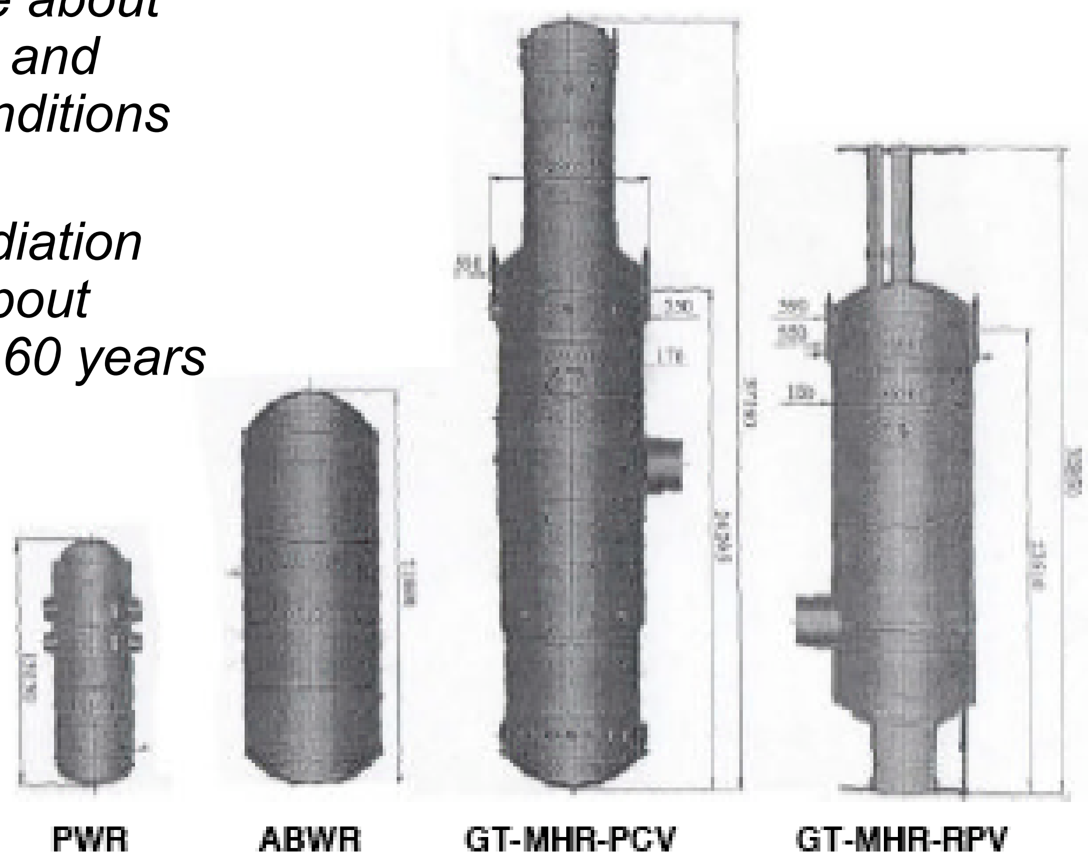
- *Reference design temperatures for the Reactor Pressure Vessel (RPV) and Cross Vessel (CV) are about 650°C (normal conditions) and 770°C under abnormal conditions (up to 50 hours)*
- *Current estimates for irradiation exposure for the RPV is about 0.0075dpa (>0.1 MeV) for 60 years*



Gas-cooled Fast Reactor

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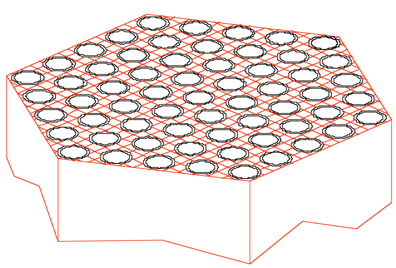
Core structural materials

- -Particles concept: Basket & supporting structures
- -Composite concepts: Hex.canning (block) & casing (plate)
- -Solid solution fuel concept: clad & wrapper
- -Other structures: reflectors & control rods

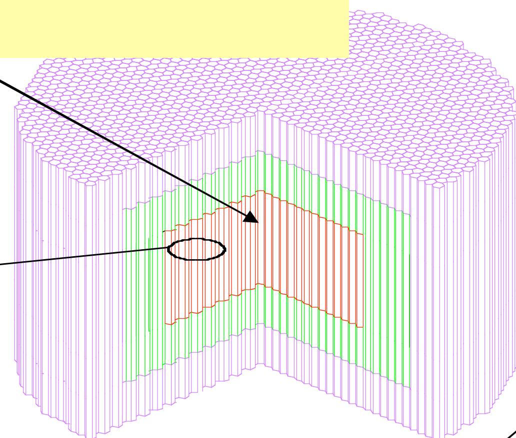
Gas circuits & turbine (not visualized)

- -Other hot gas circuits of the power conversion system
- -Discs & blades of the turbine

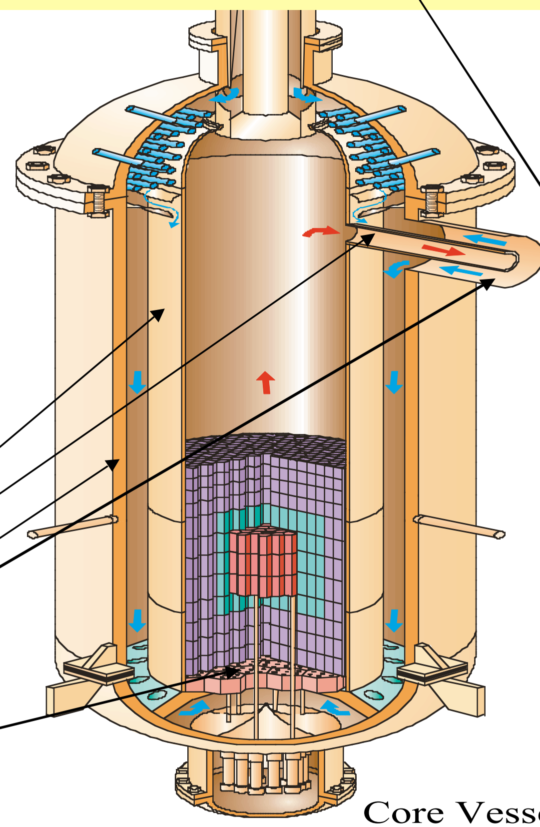
Block concept



Composite Ceramics Fuel Element



Core Lay-out



Core Vessel

Internal & vessel structures

- -Gas duct barrel & hot gas duct
- -Reactor vessel & cross vessel
- -Core support components

Gas-Cooled Fast Reactor (GFR)

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Reactor Parameters	Reference Value
Reactor power	600 MWth
Net plant efficiency (direct cycle helium)	42%
Coolant inlet/outlet temperature and pressure/Helium flow rate	490°C/850°C at 7 MPa, 312.4 kg/s
Core structures temperatures (normal operations)	500-1200°C
Transient temperature in accidental conditions	1600-1800°C
Out-of-core structures	440-850°C, low irradiation exposure, mechanical loading < 50-60 MPa and high useful life (400000 h)
Average power density	50-100 MWth/m^3
Reference fuel compound	UPuC/SiC (70/30%) with about 20% Pu content
Volume fraction, Fuel/Gas/SiC	50/40/10%
Conversion ratio	Self-sufficient (BR~0)
Burnup, Damage (initial values)	5% FIMA; 80 dpa

- Very High Temperatures
- Need to minimize moderators (carbon)
- Maximum dose ~40 dpa

GFR-Metallic options

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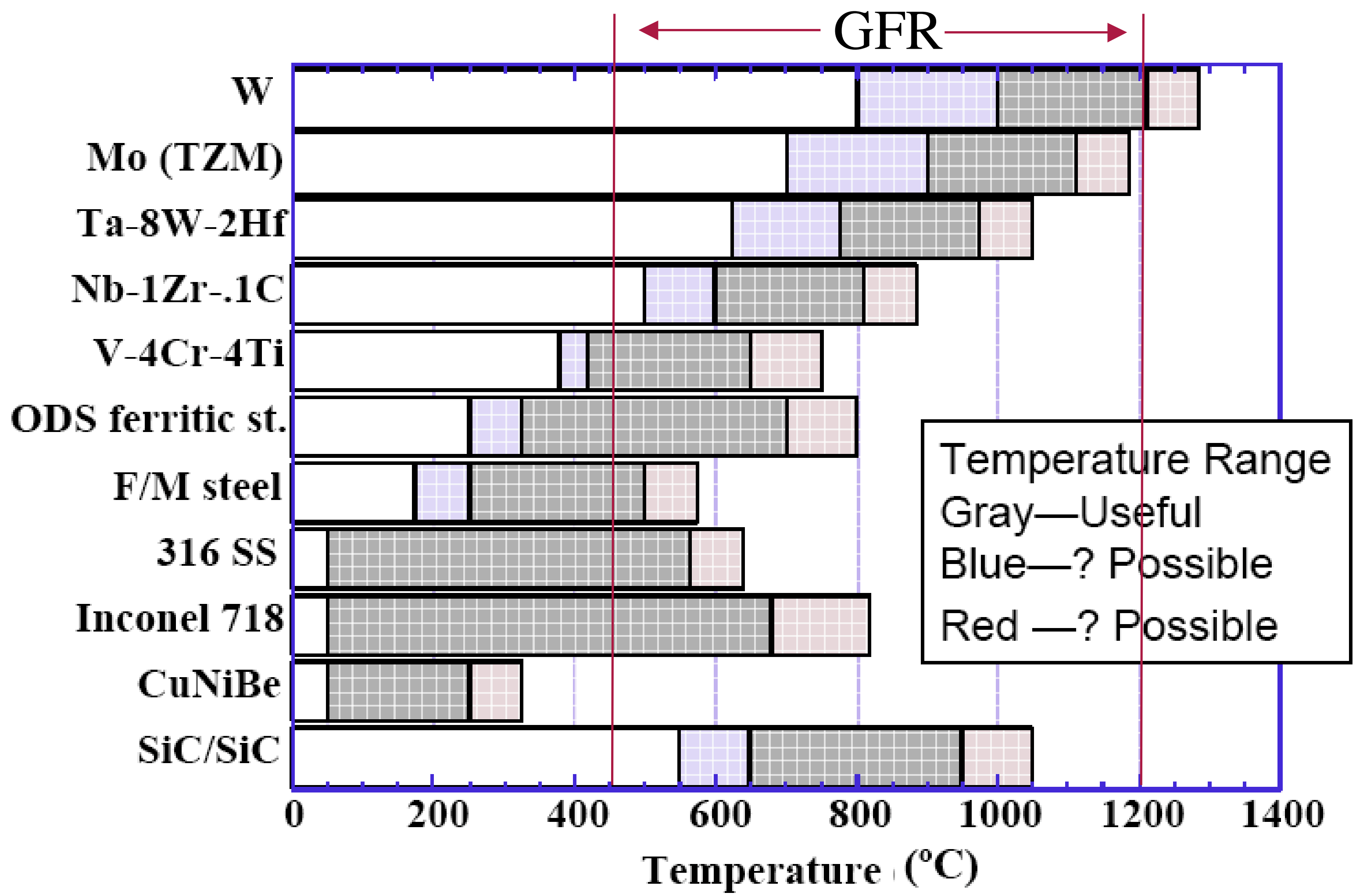

- S. J. Zinkle & N. M. Ghoniem, Fusion Engineering & Design, 51-52 (2000), 55”

GFR-Ceramics, first selection

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T melt < 2000°, redhibitory neutronic absorption, too low thermal conductivity

	Matériau	T fusion T décomp (°C)
carbures	**SiC (□+□)**	**2972**
	ZrC	**3400**
	TiC	**3100**
	VC	**2810**
	~~TaC~~	~~3800~~
	~~WC~~	~~2900~~
	~~HfC~~	~~3800~~
nitrures	**ZrN**	**2952**
	TiN	**2950**
	AlN	**2227**
	~~TaN~~	~~3087~~
	~~Si3N4~~	~~1827~~

	Matériau	T fusion T décomp (°C)
oxydes	~~Al_2O_3~~	~~2050~~
	~~MgO~~	~~2832~~
	~~$MgAl_2O_4$~~	~~2135~~
	~~ZrO_2~~	~~2370~~
	~~Y_2O_3~~	~~2427~~
	~~SiO_2~~	~~1470~~
siliciures	$MoSi_2$	2050
	~~$TaSi_2$~~	~~2200~~
	~~WSi_2~~	~~2165~~
	~~$TiSi_2$~~	~~1540~~
	~~$ZrSi_2$~~	~~1520~~
	~~$HfSi_2$~~	~~1750~~
	~~VSi_2~~	~~1660~~
	~~$CrSi_2$~~	~~1550~~

Supercritical-Water-Cooled Reactor (SCWR)

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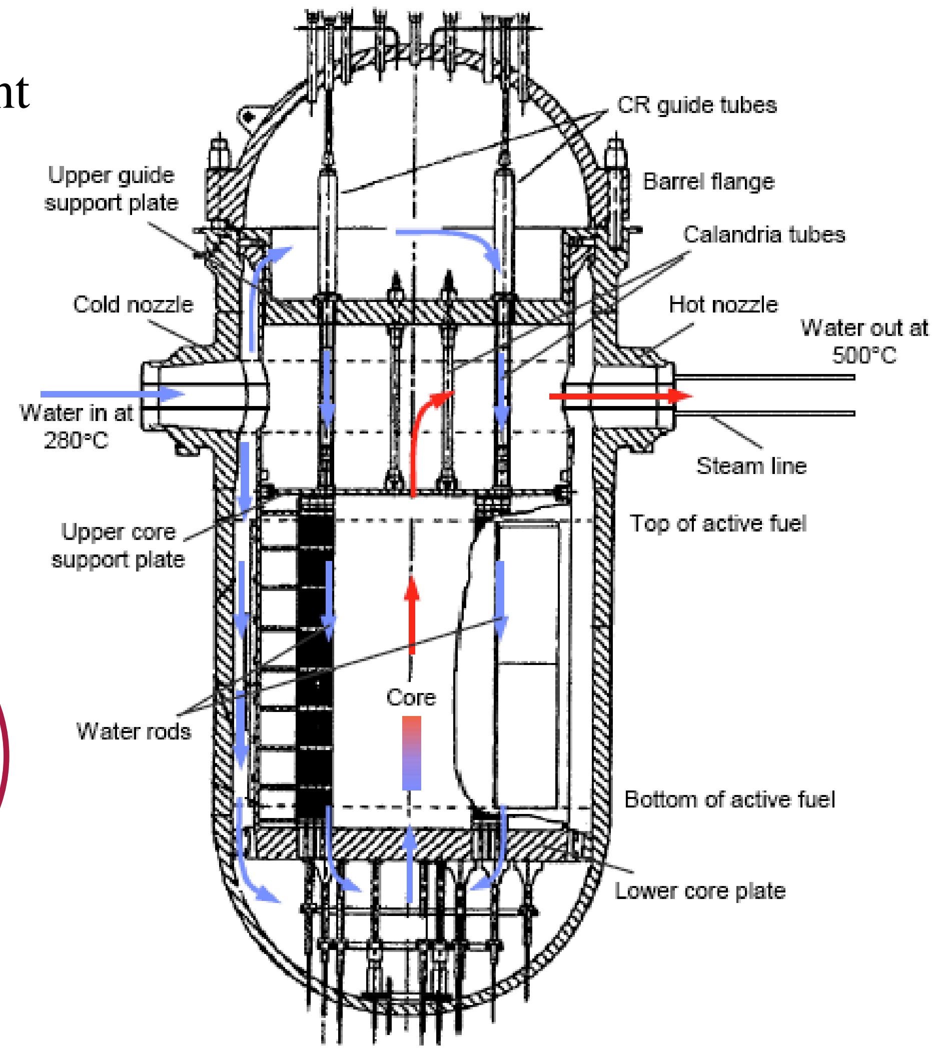
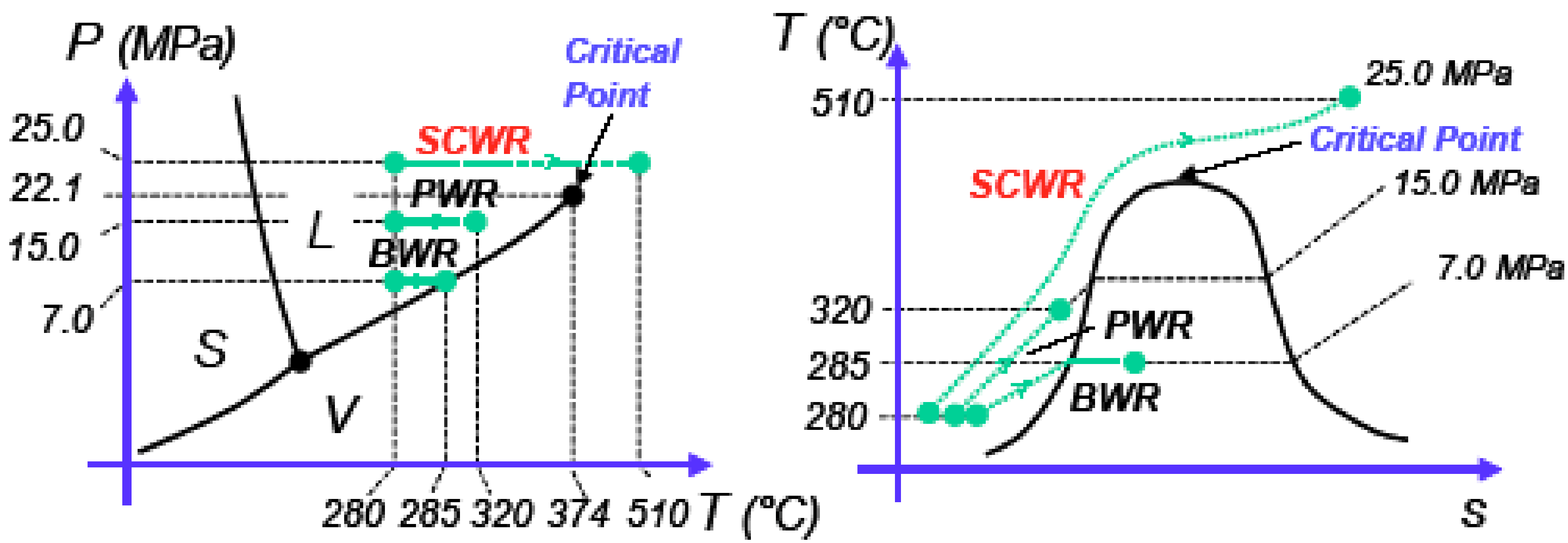
Benefits

- Efficiency near 45% with excellent economics
- *Thermal* or fast neutron spectrum

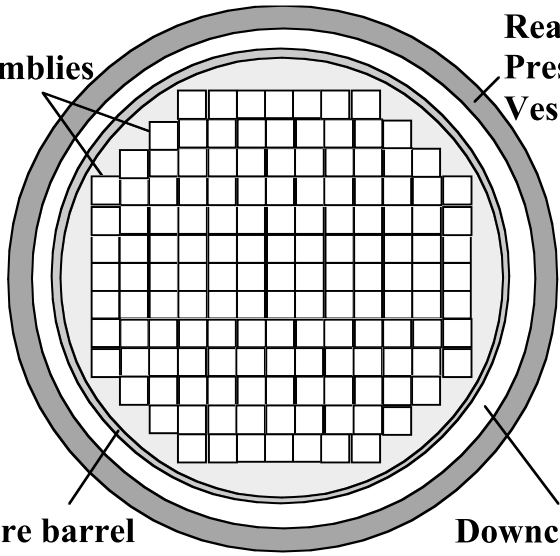
Parameter	Value
Thermal power	3575 MWth
Net electric power	1600 MWe
Net thermal efficiency	44.8%
Operating pressure	25 MPa
Reactor inlet temperature	280 °C
Reactor outlet temperature	500 °C
Reactor flow rate	1843 kg/s

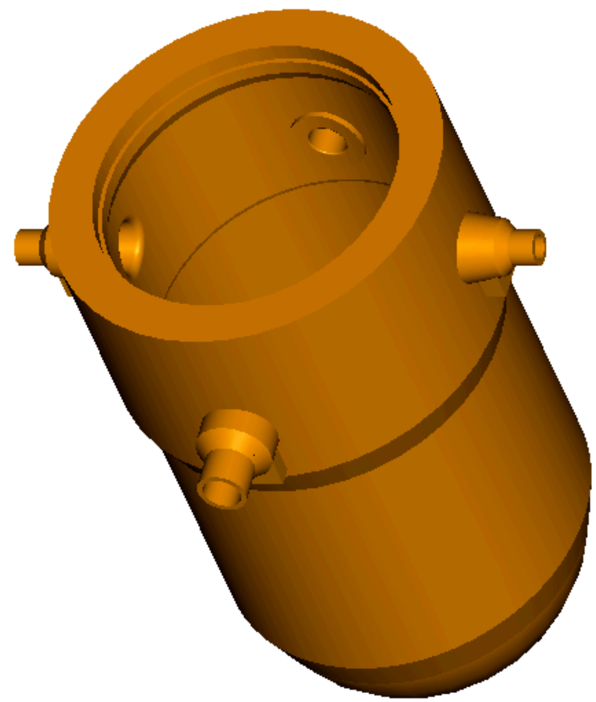


Supercritical-Water-Cooled Reactor (SCWR)



SCWR Components



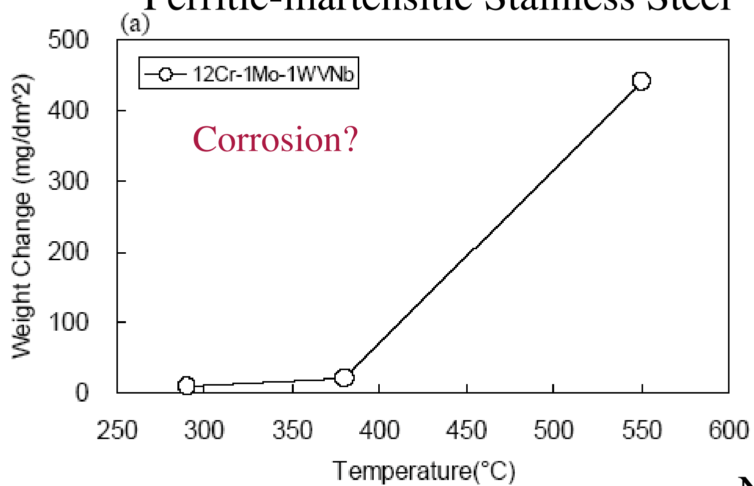


- **Temperature Range-**280-500°C Normal, Up to 840°C Transient (<30 sec)
- **Pressure**-25MPa
- **Irradiation Dose-**15 dpa removable components, 67 dpa core barrel*

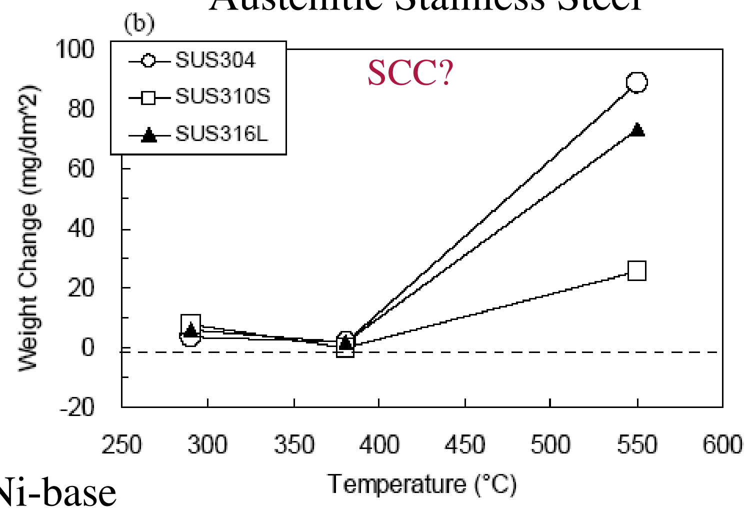
Through-thickness properties in the much thicker vessel sections required for the SCWR

Supercritical-Water-Cooled Reactor (SCWR) Materials Choices

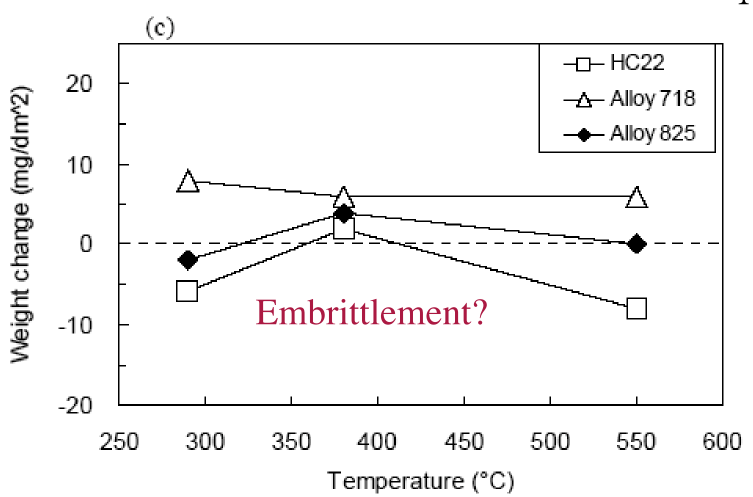
Ferritic-martensitic Stainless Steel

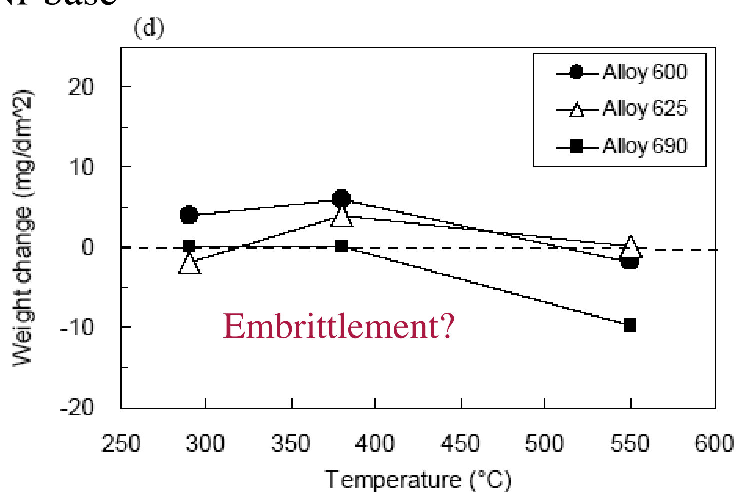


Austenitic Stainless Steel



Ni-base





S. Kasahara et al., GENES4/ANP2003, Sep. 15-19, 2003, Kyoto, JAPAN, Paper 1132

Lead-Cooled Fast Reactor (LFR)

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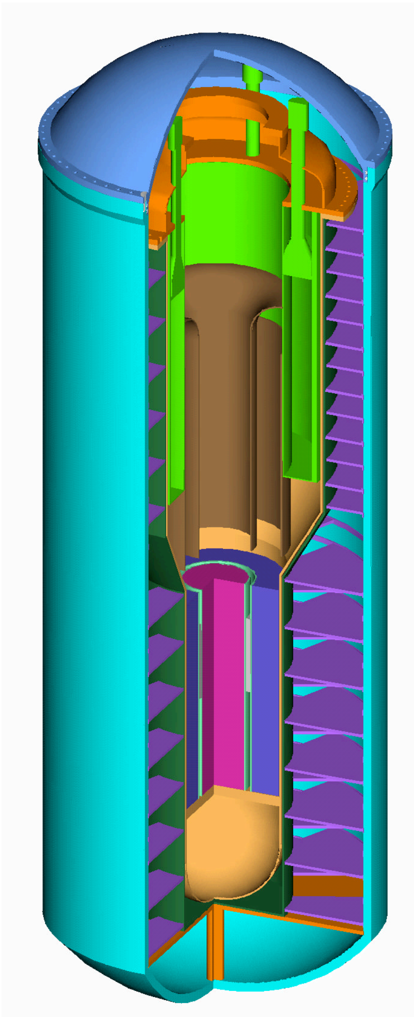
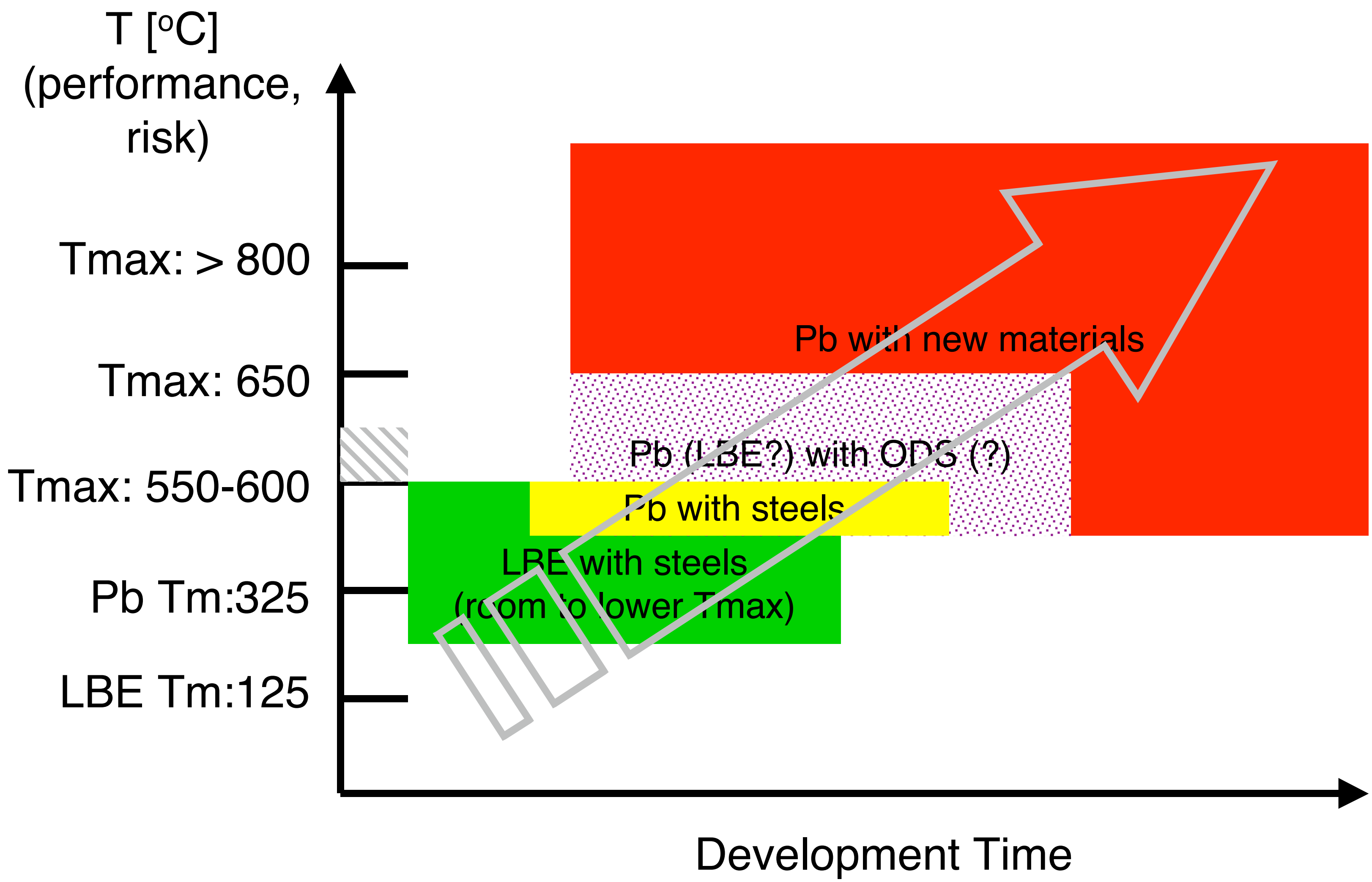


	Pb-Bi coolant, (nearer-term)	Pb coolant, (far-term)
Outlet Temperature (ºC)	~∏550	750–800
Pressure (Atmospheres)	1	1
Rating (MWe)	50–150	150-400
Fuel	Metal Alloy or Nitride	Nitride
Cladding	Ferritic Steel	Ceramic, coatings, or refractory alloys
Power conversion	Rankine or supercritical carbon dioxide Brayton cycle	Rankine or supercritical carbon dioxide Brayton cycle
Other energy products		Hydrogen, Potable Water

LFR Conceptual Development Path



LFR High Temp Design Option - Key Reactor Environments

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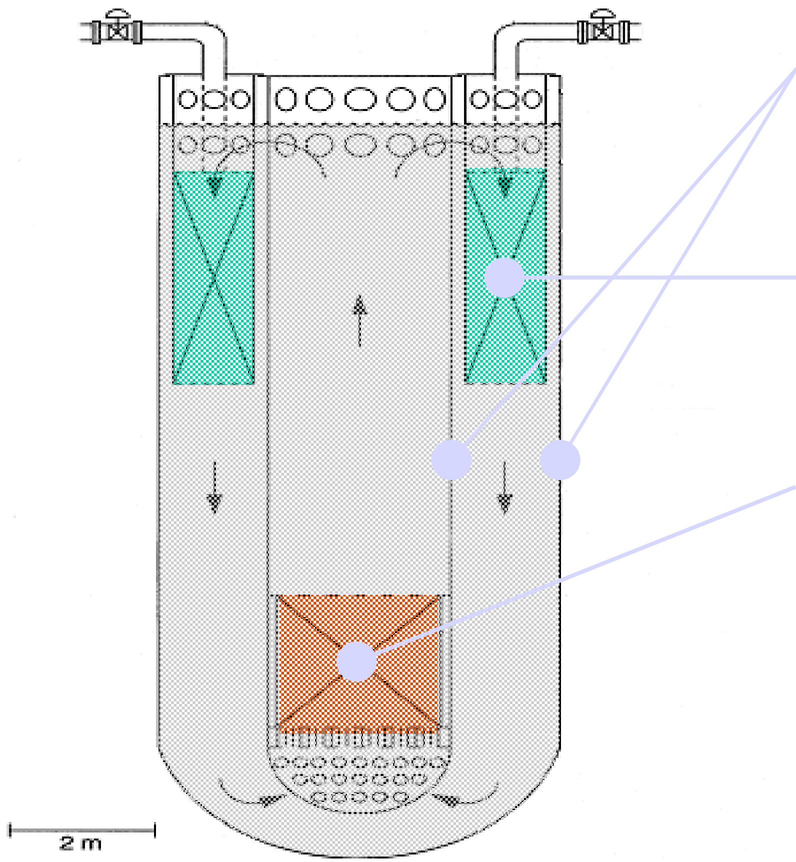

- **Reactor Vessel and Structures**
  - Molten lead @ 650°C to 850°C
  - High stress from mass of coolant
  - Moderate to high fluence (shielded by lead)~10 dpa on vessel
- **Heat Exchangers for Process Heat**
  - Molten lead @ 650°C to 850°C
  - Low Pressurized He
  - Low to moderate fluence
- **Reactor Core and Cladding**
  - Molten lead @ 650°C to 850°C
  - Highest fluence~200 dpa
  - Fuel/clad interactions with evolving stress situation (fission gas and swelling)
- **Material Choices to Avoid Need for Exquisite Coolant Chemistry Control**
  - Very low O_2 partial pressure

Comparative Environments

Reactor Type	Inlet Temp (°C)	Outlet Temp (°C)	Maximum Dose (dpa)	Pressure (Mpa)	Coolant
PWR	290	320	100	16	Water
SCWR	290	500	15-67	25	Water
VHTR	600	1000	1-10	7	Helium
SFR*	370	550	200	0.1	Sodium
LFR*	600	800	200	0.1	Lead
GFR*	450	850	80	7	Helium/ SC CO_2

Material Classes Proposed for Gen IV Systems

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System	STRUCTURAL MATERIALS: FERRITIC-MARTENSITIC STAINLESS STEEL ALLOYS	AUSTENITIC STAINLESS STEEL ALLOYS	OXIDE DISPERSION STRENGTHENED STEELS	NI-BASED ALLOYS	GRAPHITE	REFRACTORY ALLOYS	CERAMICS
GFR	P	P	P	P		P	P
LFR	P	P	S			S	S
MSR				P	P	S	S
SFR	P	P	P				
SCWR-Thermal Spectrum	P	P	S	S			
SCWR-Fast Spectrum	P	P	S	S			
VHTR	S			P	P	S	P

P=Primary, S=Secondary

Generation IV Materials Challenges

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- **Higher Temperature/Larger Temperature Ranges**
  - Examples
    - *VHTR coolant outlet temperature near 1000°C*
    - *GFR transient temps to 1600-1800°C, gradient across core of ~400°C*
    - *LFR to 800°C steady-state outlet*
  - Issues
    - *Creep*
    - *Fatigue*
    - *Toughness*
    - *Corrosion/SCC*

- ***Must drive modeling toward a predictive capability of materials properties in complex alloys across a wide temperature range***

Generation IV Materials Challenges

- **High Fluence/dose**
  - Examples
    - *LFR, SFR Cladding*
    - *SCWR Core Barrel*
    - *GFR Matrix*
  - Issues
    - *Swelling*
    - *Creep, stress relaxation*

- ***Must drive modeling toward a predictive capability of materials properties in complex alloys to large radiation dose***

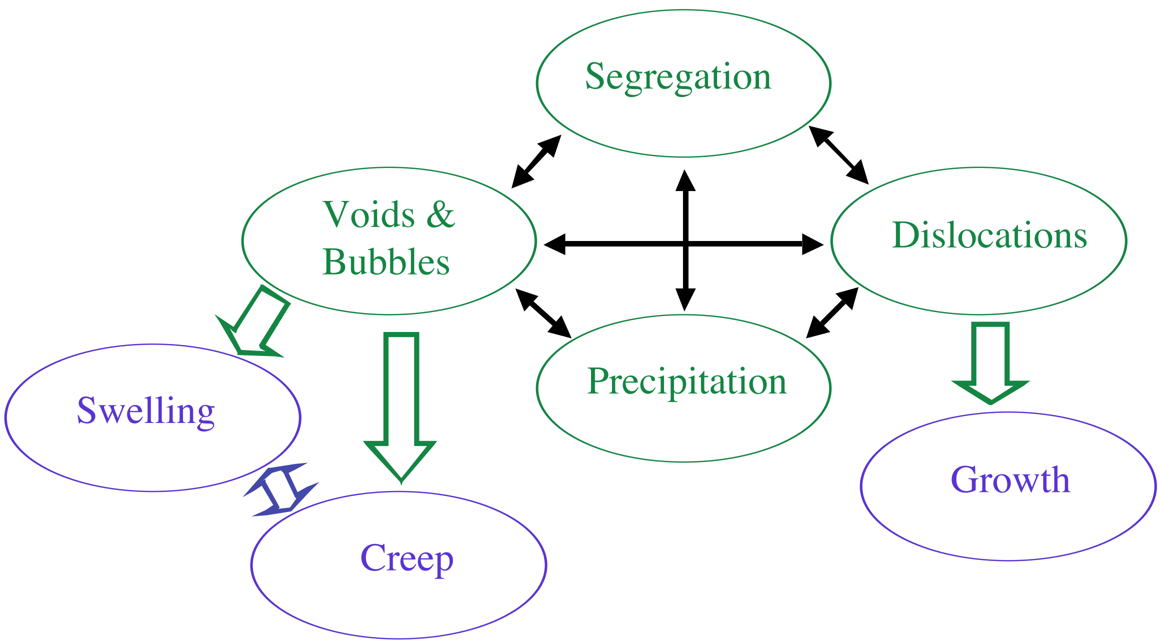
Generation IV Materials Challenges

- **Unique Chemical Environments**
  - Examples
    - *Pb and Pb-Bi Eutectic*
    - *Supercritical Water*
    - *High temperature oxidation in gas-cooled systems*
    - *Molten Salts*
  - Issues
    - *Corrosion*
    - *SCC/IASCC*
    - *Liquid Metal Embrittlement*

- ***Must drive modeling toward a predictive capability of chemical interactions in complex alloys to large radiation dose***

Fundamental issues

- *The co-evolution of all components of the microstructure, and their roles in the macroscopic response in terms of swelling, anisotropic growth, irradiation creep, and radiation-induced phase transformations should be studied within the of the science of complex systems.*



Summary

- *Six concepts have been identified with the potential to meet the Generation IV Goals*
- *Concepts operate in more challenging environments than current LWRs and significant material development challenges must be met for any of the Generation IV systems to be viable.*
- *Experimental programs cannot cover the breadth of materials and irradiation conditions for the proposed Gen IV reactor designs*
- *Modeling and microstructural analysis can provide the basis for a material selection that is performed based on an incomplete experimental database and that requires considerable judgment to carry out the necessary interpolation and extrapolation*