Accident Tolerant Fuel Cladding: In Progress

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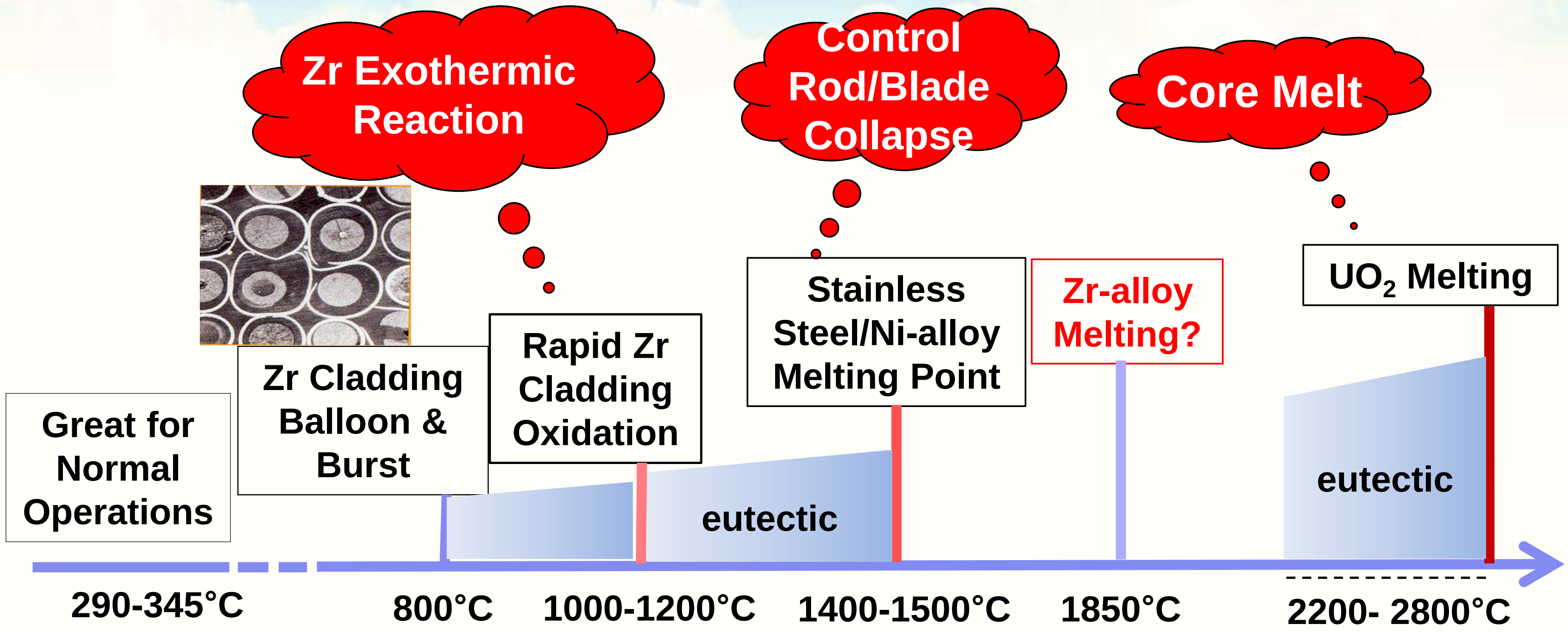
Behavior of Fuel and Core Materials in Severe Accidents



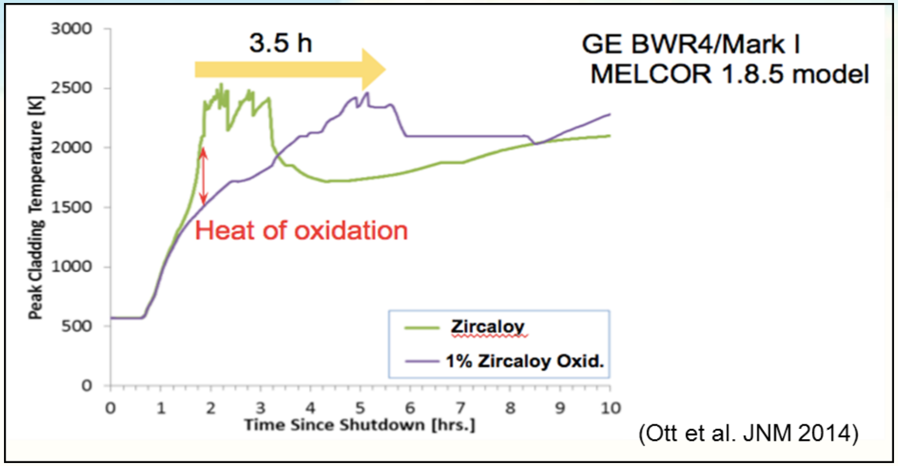
Issues with Zr-alloy cladding under severe accidents:

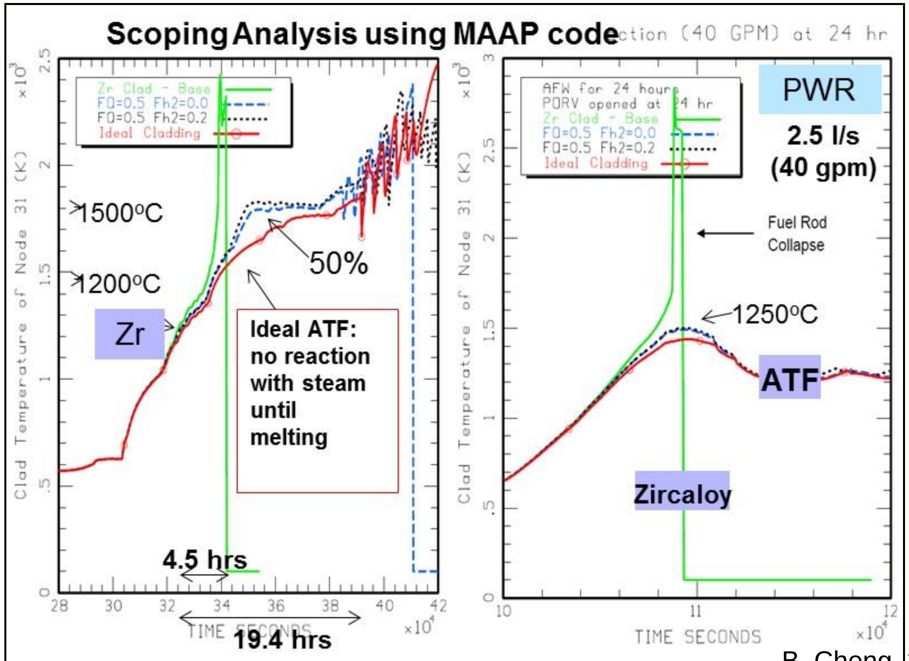
- **Rod integrity and core coolability at T>~800°C**
- **Rapid hydrogen and heat generations at T>800-1000°C**
- **Fission product dispersion (Cs, I, CsI…)**

B. Cheng, 2014

Objectives of ATF Cladding Development

- Provide additional “coping time” for operator to restore cooling system
- Explore possibility of stabilizing fuel rods with a combination of ATF cladding and injection of small volume of water
- To gain meaningful “coping time”, ATF cladding needs to survive at 1200-1500°C
  - Has mechanical strength to maintain fuel/core in coolable geometry
  - Has resistance to steam oxidation to reduce hydrogen generation





B. Cheng, 2015

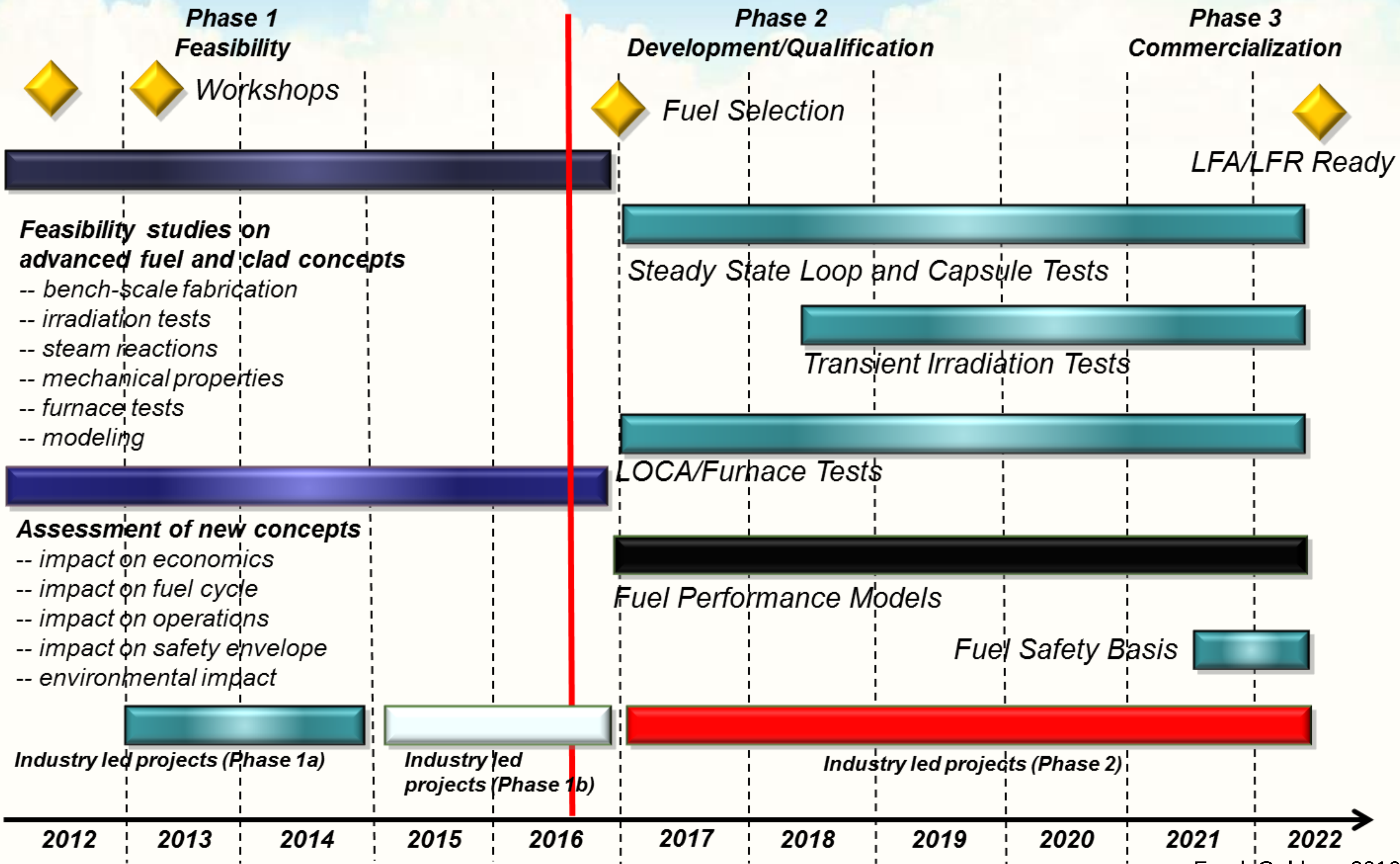
Desired Attributes of ATF Cladding

- **Good high temperature properties (1200-1500°C)**
  - Oxidation resistance to steam (vs. Zr)
    - Reduce hydrogen production and decay heat
  - High tensile and creep strength to maintain fuel rod integrity and core coolability
- **Compatible with current fuel/core designs**
- **Meet regulatory and operational requirements**
  - Licensing
  - Fuel reliability
  - Corrosion resistance, irradiation embrittlement resistance
  - Fuel economics

References

2013-2017 EPRI/INL/DOE Joint Workshop on Accident Tolerant Fuel

DOE R&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal



Frank Goldner, 2016

AFC ATF program is supported by a large part of the U.S. nuclear complex

National Laboratories

- INL Idaho National Laboratory
- Oak Ridge National Laboratory
- Brookhaven National Laboratory
- Argonne National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory

Universities

- UF University of Florida – The Foundation for The Gator Nation
- University of Illinois – Urbana-Champaign · Chicago · Springfield
- UT The University of Tennessee – Knoxville, Chattanooga, Martin, Tullahoma, Memphis
- Texas A&M University
- Georgia Tech
- MIT
- W (University of Wisconsin)
- M (University of Michigan)

Nuclear Industry

- GE imagination at work
- Westinghouse
- AREVA
- Duke Energy
- TVA
- Southern Company
- EPRI Electric Power Research Institute

Frank Goldner, 2017

Bilateral International Collaboration (Significant ATF Development)

France
- ***Advanced core materials***
- ***Joint support of Halden collaborative irradiations***

European Union
- ***Three general INERIs currently underway with JRC-ITU***

UK
- ***Active partners in ATF FOAs and IRPs***
- ***Joint participation in ATF OECD/NEA***
- ***Basic material properties of high density fuels***

Russian Federation (currently on hold)
- ***Advanced LWR fuels and ATF***
- ***Exchange of attributes and metrics***

China
- ***Attributes and metrics***
- ***Information exchange on R&D facilities***
- ***Assessment of ATF Performance***
- ***Collaborative testing opportunities***

Korea
- ***Advanced LWR fuels and ATF***
- ***Collaboration for Halden irradiation test***

Japan
- ***Definition of attributes and metrics***
- ***Coordination of technology R&D***
- ***Coordination of facilities used for R&D***

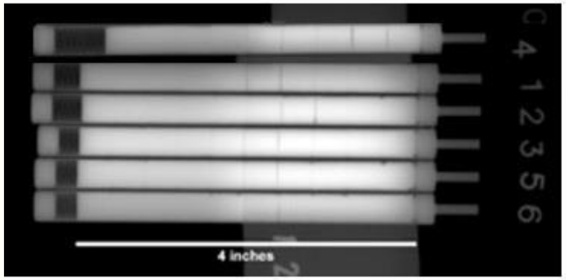
Others
- ***OECD/NEA Expert Group***
- ***IAEA Expert Group***

Jon Carmack, 2016

USA Industry Teams for DOE ATF Cladding Program (2012 – present)

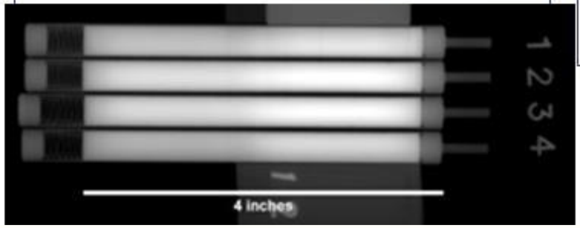
AREVA

- ***Cr coated Zr***
- ***Increased fuel conductivity***
- *Additives*
  - *SiC powder or whiskers*
  - *Diamond*
  - *Chromia dopant*



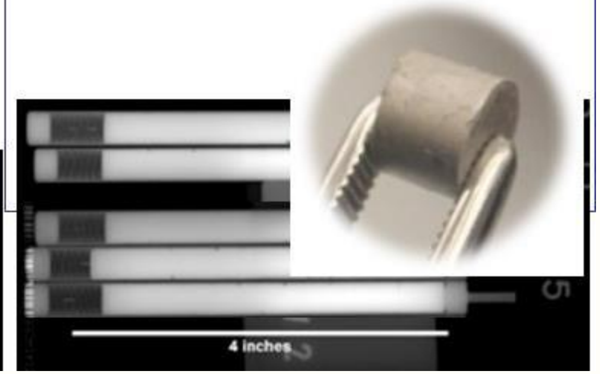
GE

- *Develop advanced **ferritic/martensitic steel alloys (e.g., Fe-Cr-Al) for fuel cladding** to improve behavior under severe accident scenarios*
- *Objectives:*
  - *Characterize candidate steels*
  - *Study tube fabrication methods, neutronics, fuel economy, thermo-hydraulic calculations, regulatory approval path*
  - *Initiate ATR testing with UO_2 and two cladding materials.*



Westinghouse

- ***Cladding** concepts:*
  *- **SiC** and SiC ceramic matrix composites;*
  *- **coated Zr alloys***
- ***High density/high thermal conductivity fuel pellets***
- *First batch of U_3Si_2 pellets were sintered using finely ground powder*
- *Pellets were pressed using pressures of 6,000-10,000 psi and sintered at temperatures of 1400 °C*



U_3Si_2 Pellet

Jon Carmack, 2016

Worldwide ATF Cladding Projects

<table>
<tr><th colspan="6">USA DOE Funded Programs</th></tr>
<tr><td>Organization</td><td>Areva</td><td>GE</td><td colspan="2">Westinghouse</td></tr>
<tr><td>Base Alloy</td><td>Zr alloy</td><td>FeCrAl</td><td>Zr alloy</td><td>SiC composite</td></tr>
<tr><td>Coating Material</td><td>Cr</td><td rowspan="2">N/A</td><td>Cr, Cr+Mo, FeCrAl</td><td rowspan="2">N/A</td></tr>
<tr><td>Coating Process</td><td>PVD</td><td>Cold spray</td></tr>
</table>

<table>
<tr><th colspan="9">International Activities</th></tr>
<tr><td>Organization</td><td>EPRI</td><td colspan="2">KAERI</td><td>METI</td><td>Toshiba</td><td colspan="2">ORNL</td><td>China</td></tr>
<tr><td>Base Alloy</td><td>Mo, Mo+L2O3</td><td>Zr alloy</td><td>SiC composite</td><td rowspan="3">ODS-FeCrAl
SiC composite</td><td>SiC fiber braid</td><td>FeCrAl</td><td>SiC composite</td><td>SiC fiber</td></tr>
<tr><td>Coating Material</td><td>Zry, Nb</td><td>CrAl, FeCrAl.Cr</td><td rowspan="2">N/A</td><td>SiC</td><td rowspan="2">N/A</td><td>Cr, CrN</td><td>SiC</td></tr>
<tr><td>Coating Process</td><td>PVD</td><td>3D laser</td><td>CVI, CVD</td><td>PVD</td><td>CVI, CVD</td></tr>
</table>

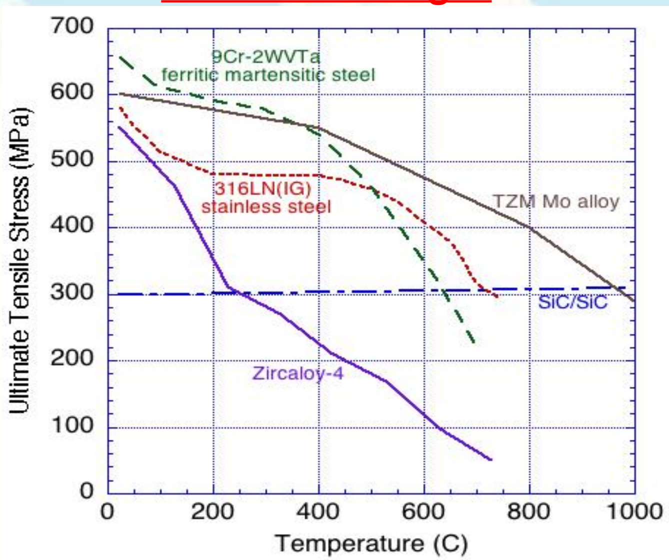
Comparison of Candidates ATF Cladding

Material	Neutron Cross Section, barns	Melting Temp. ^{o}C	Eutectic Temp. ^{o}C	Phase Transition Temp. ^{o}C	Volatility, ^{o}C
Zr	0.184	~1800	~950 with Fe-Ni	~872	
Steel (Fe)	2.56	~1500	1160 with Fe-B	~912	
Mo	2.26	2623	1578 with Zr	None	
SiC	0.171	2730		None	2000
UO2		~2200-2600			

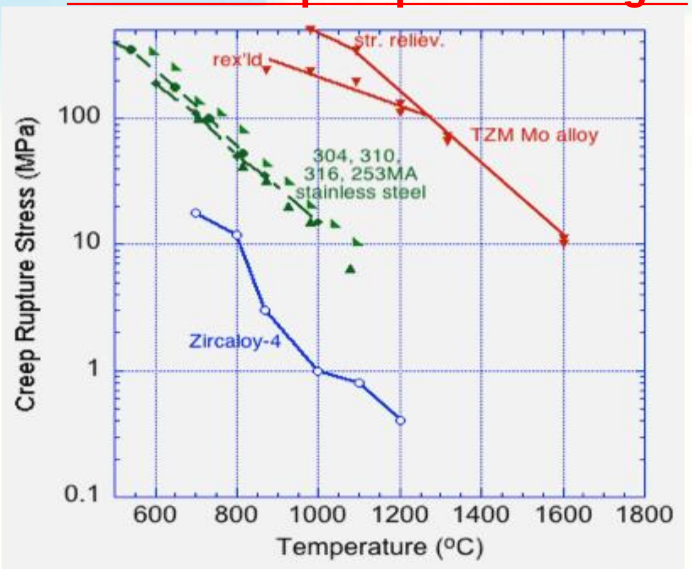
- Neutron cross section
- Mechanical strength at >1000^{o}C limits to refractory metals and ceramics
  - Maybe achievable with Mo, SiC, and maybe FeCrAl-ODS?
- High temperature oxidation resistance to steam or steam + H_2
  - Need surface protection from $(Al,Cr)_2O_3$, SiO_2, ZrO_2
- Fabricability and normal performance requirements

Mechanical Property of Material

Tensile Strength



100 hr Creep Rupture Strength



	Lose Strength, °C
Zr	>~800
Steel	>900-1200
Mo	>1300-1900
SiC	Stable (Ceramic)

Material	300°C	1000°C
Zircaloy-4	270	nil
Stainless Steel 304	475	<10
Ferritic Martensitic Steel	480	<10
SiC/SiC Composite	300	300
Molybdenum alloys	400-570	200-300

Only Mo-alloy and SiC suitable as candidates for structure designs for temperatures >1200°C?

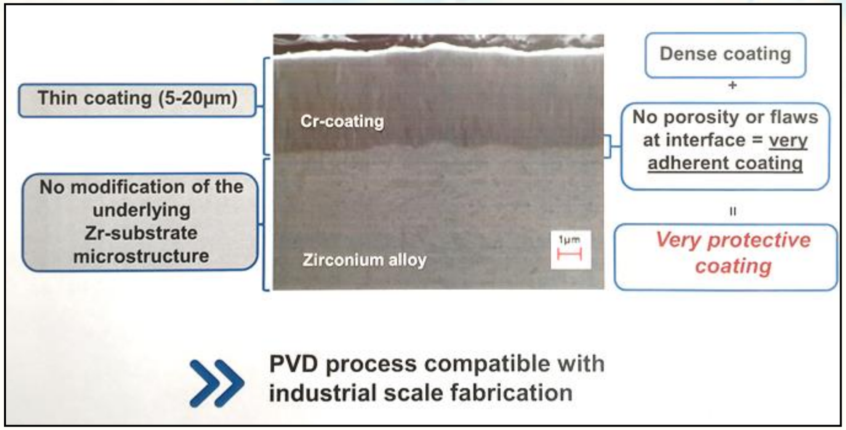
B. Cheng, 2014

Corrosion/Oxidation Property of Ferric Steel, Mo, & SiC

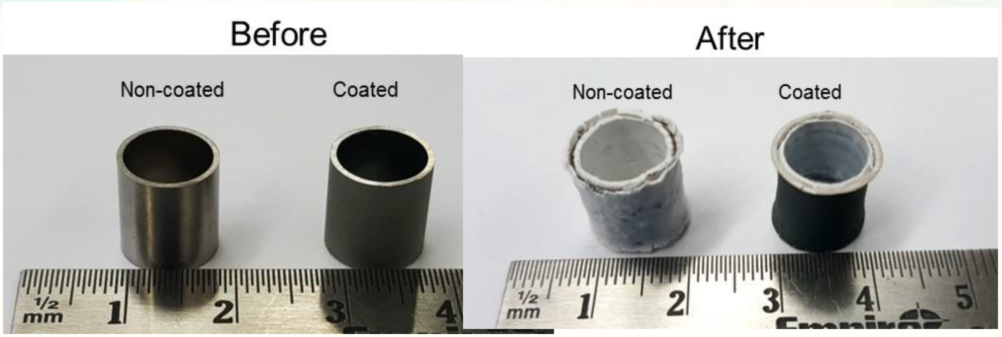
- **Ferritic Steel (FeCrAl)**
  - Loss of mechanical strength at ~1050^{o}C
  - Instability of Cr oxide at >900^{o}C
  - Cr soluble in oxidizing HT water
  - High solubility of Al_2O_3 in HT water
- **Mo**
  - Formation of Mo oxides at ~250^{o}C & vaporizes slowly at ~400^{o}C
  - Fast diffusion of O and Mo through the oxides at >600^{o}C and vaporizes rapidly
  - A protective layer needed for high temperature application
- **SiC Composites**
  - Oxidation in HT water to form SiO_2
    - $SiC + 2H_2O = SiO_2 + CH_4$
    - $SiC + 2O_2 + 2H_2O = Si(OH)_4 + CO_2$
  - High solubility of SiO_2 in the LWR coolant
    - $SiO_2 + 2H_2O = SiO(OH)^{-}_3 + H^+$
  - Necessity of a protective layer

Coated Zr Cladding

Areva: Cr coating by PVD

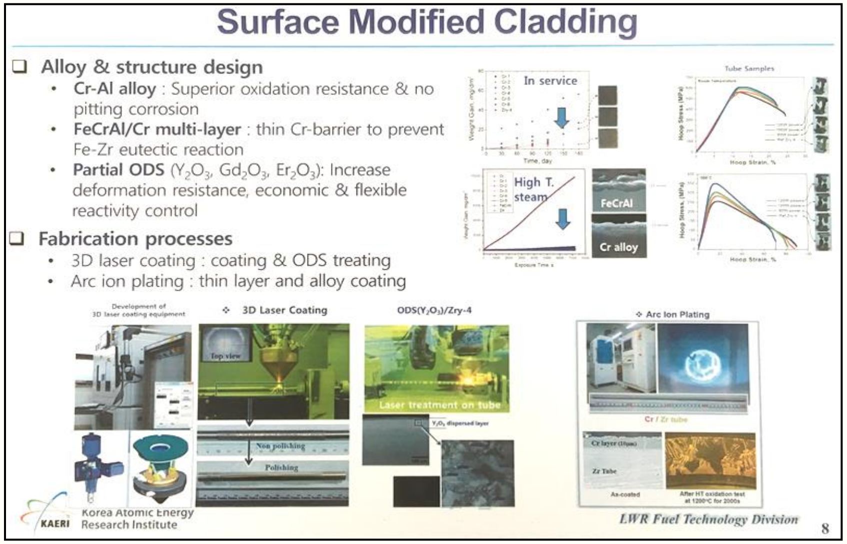


Westinghouse: Cr, Cr/Mo, & FeCrAl coating by cold spray



(Before/after air oxidation at 1200°C for 20 minutes)

KAERI: Cr, Cr/Al & ODS-FeCrAl coating by 3D laser



Cr Coating

- Dense coating layer
- Interdiffusion of Zr into Cr layer
- Joining/welding at coated area?
- Cr oxide
  - Stable in LWR-H_2 water, not in LWR-O_2 water
  - Instability at >900°C

FeCrAl Coating

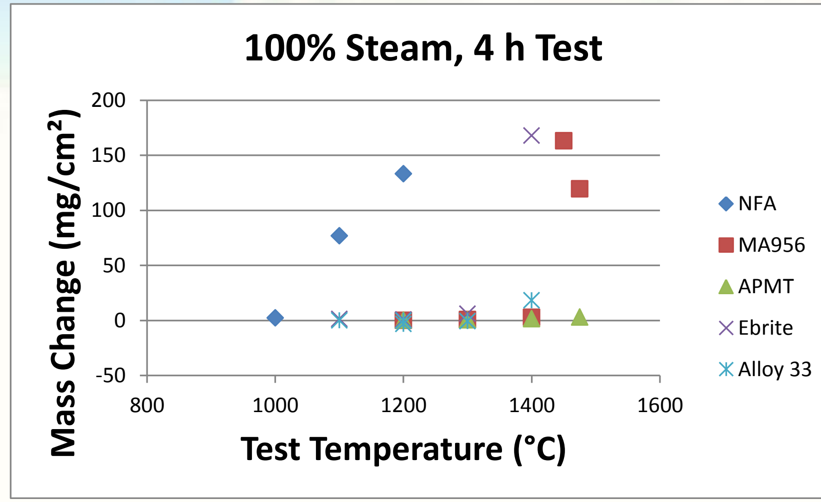
- Porous coating layer
- Difficulty for optimum FeCrAl alloying contents on coating layer
- Joining/welding at coated area

Ferritic Steel Alloys (FeCrAl)

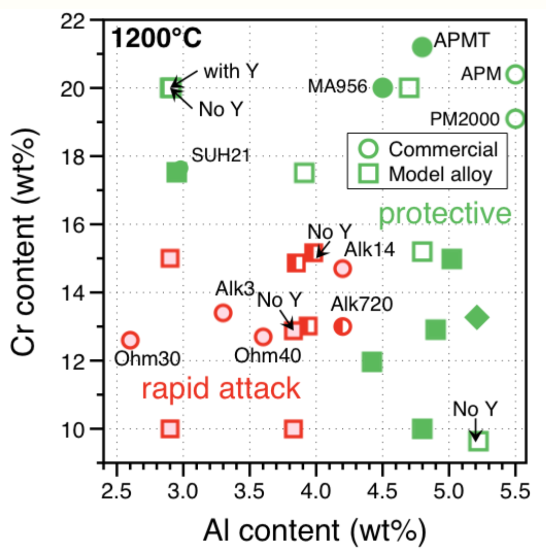
(Need to optimize the concentrations of Cr/Al)

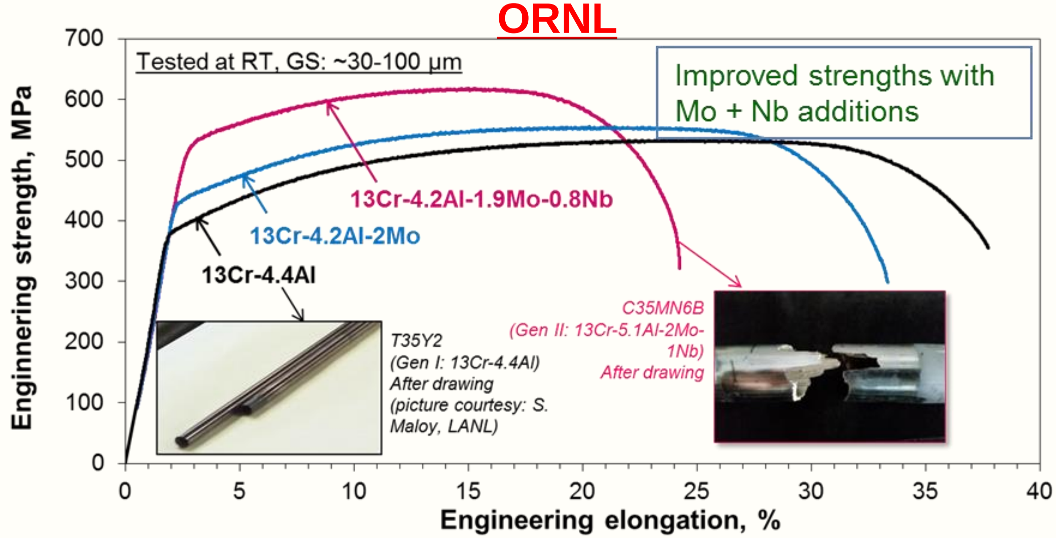
GE-GNF

	Alloy	Nominal Composition
A	**Zirc-2** UNS R60802	Zr + 1.2-1.7 Sn + 0.07-0.2 Fe + 0.05-0.15 Cr + 0.03-0.08 Ni
B	Ferritic steel **T91** K909 01	Fe + 9 Cr + 1 Mo + 0.2 V
C	Ferritic steel **HT9** S421 00	Fe + 12 Cr + 1 Mo + 0.5 Ni + 0.5 W + 0.3 V
D	Nano ferritic alloys -**N FA**	e.g. 14YWT; Fe + 14 Cr + 0.4 Ti + 3 W + 0.25 Y_2O_3
E	**MA956** or UNS S6795 6	Fe + 18.5-21.5 Cr + 3.75-5.75 Al + 0.2-0.6 Ti + 0.3-0.7 Y_2O_3
G	**APMT**	**Fe + 22 Cr + 5 Al + 3 Mo**
H	High Cr **Ebrite** S4462 7	Fe + 25-27.5 Cr + 1 Mo + 0.17 (Ni + Cu)
J	**Alloy 33** – UNS R2003 3	33 Cr + 32 Fe + 31 Ni + 1.6 Mo + 0.6Cu + 0.4 N



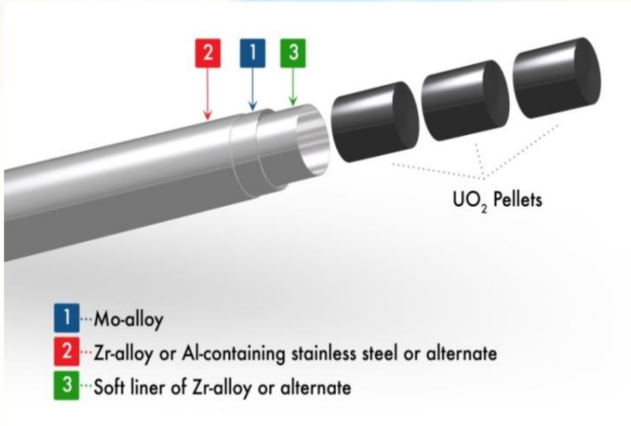
ORNL



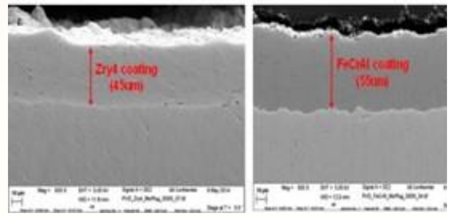


Lined Mo: EPRI

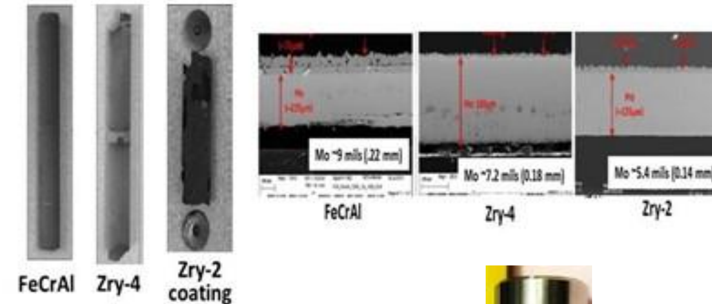
(Need a protective layer)

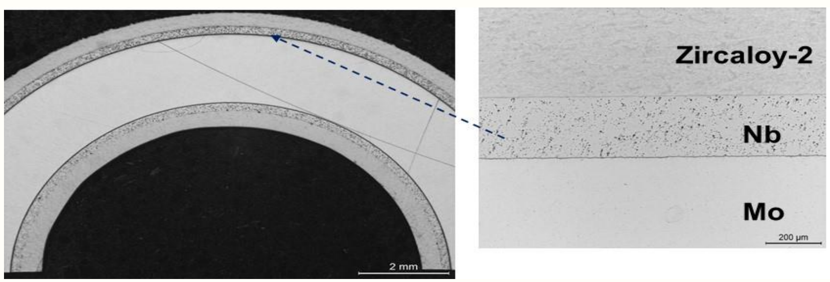


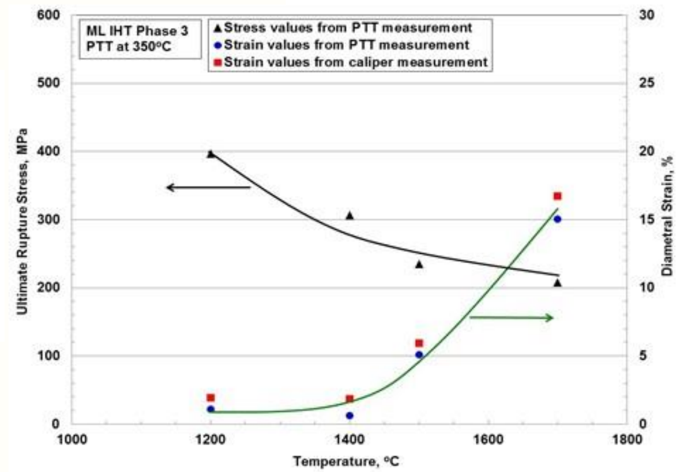
Coatings by PVD

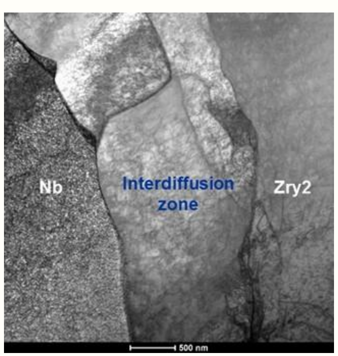


Oxidation:1200°C steam/24 hours









Hot Isostatic Pressing (HIP)

Electron beam (EB) weld Zr endcap to Zr-lined Mo tube (0.014” wall)

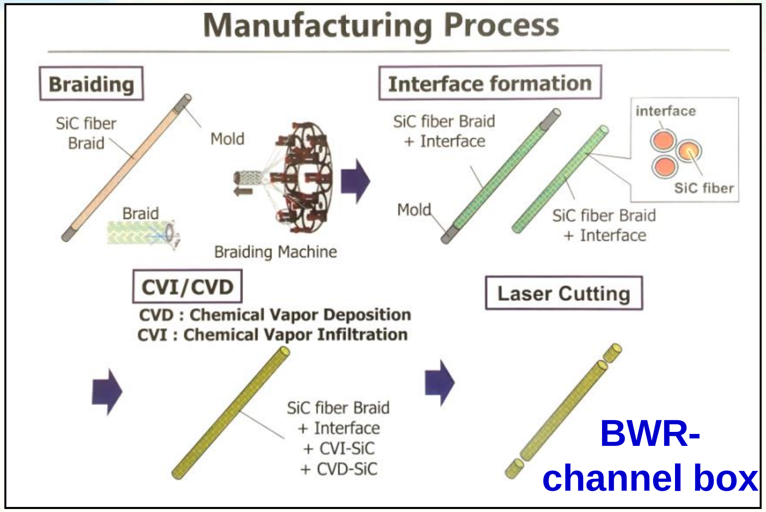
SiC Composite

(Soluble in LWR & need a protective layer)

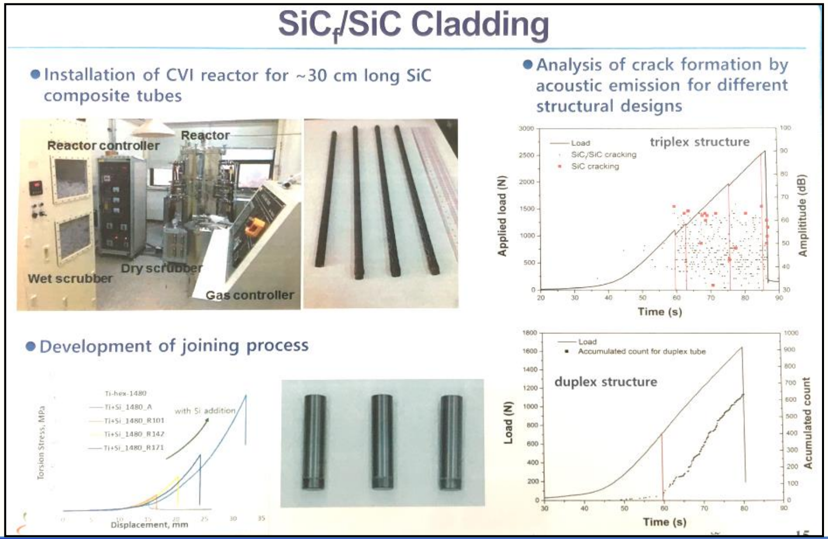
Westinghouse

Embrittlement of SiC-SiC composite after oxidation for 48 hours in 1400°C steam

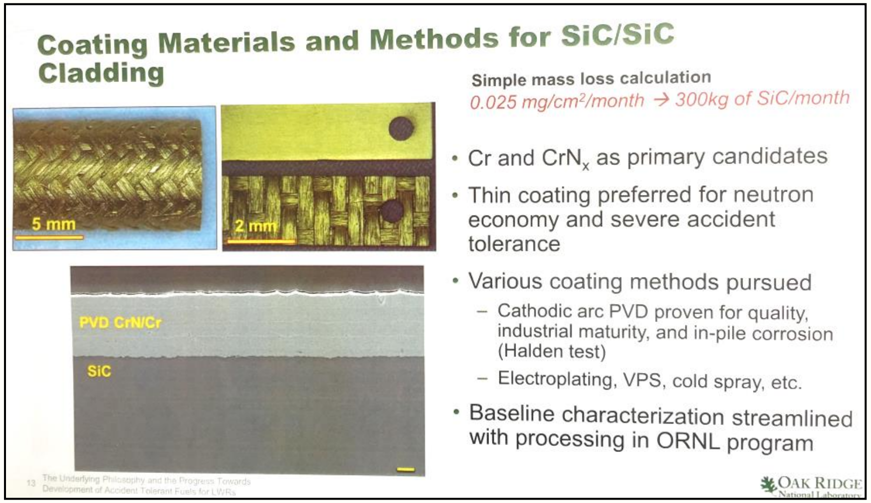
Toshiba/METI



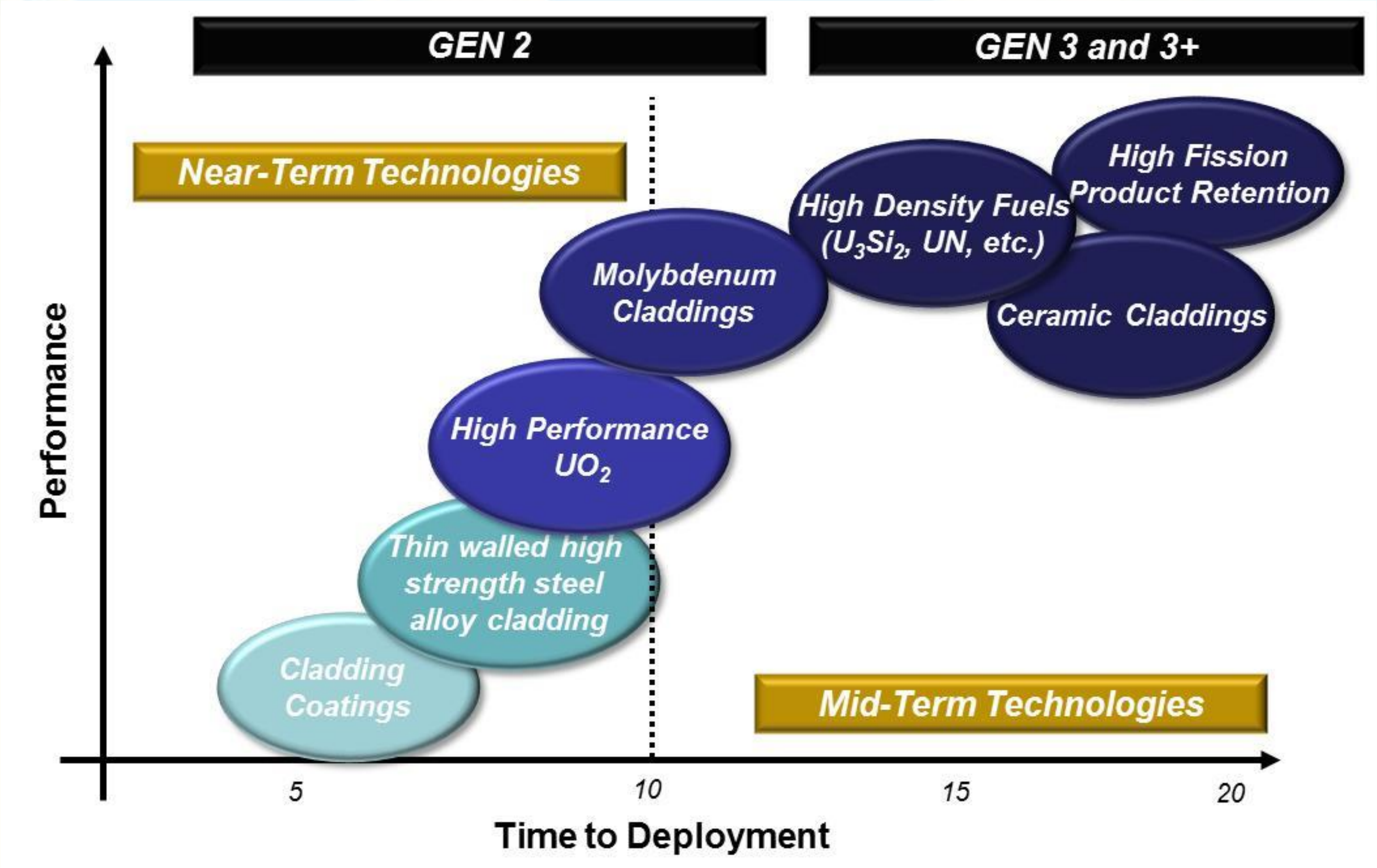
KAERI



ORNL



ATF Technologies



Summary

- **Product Development**
  - International ATF community is well coordinated on ATF cladding development and makes a good progress
  - A lot of technical difficulties on candidate ATF claddings need to be solved
- **Economic Benefit**
  - Commercial vendors need to optimize the best cladding for the cost benefit and no/low risk at operating LWR plants
- **Regulatory Issues**
  - Regulatory issues have to be identified and resolved before implementation at plants

THANK YOU

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