Worldwide Development of Degradation Resistant Nuclear Materials Triggered by the Fukushima Nuclear Accident

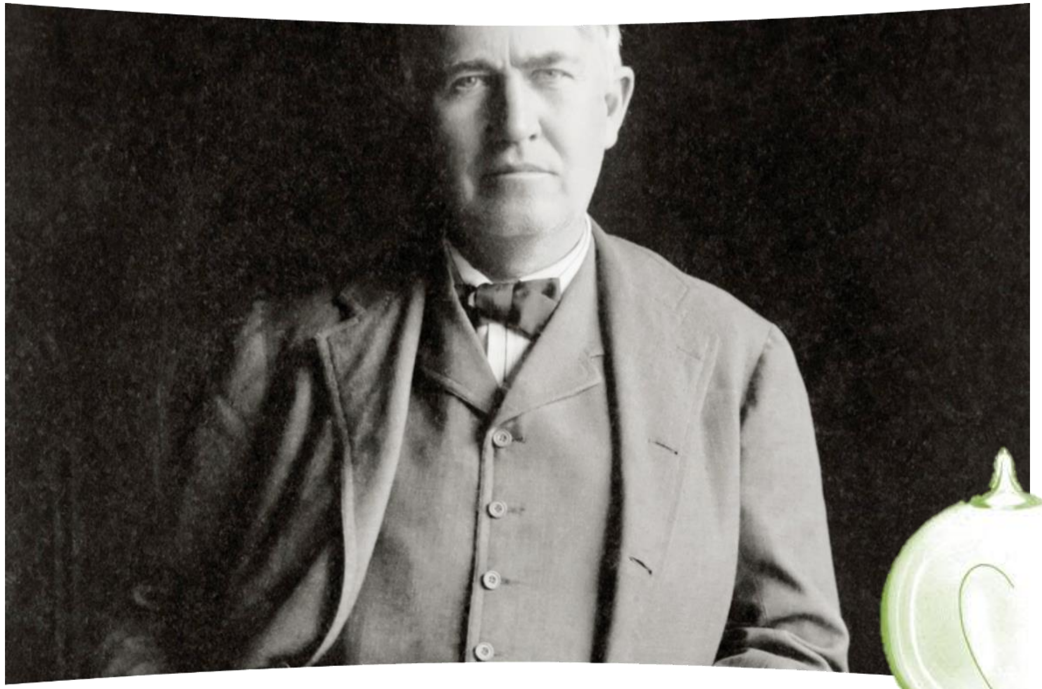
NACE International San Francisco Bay Section
08-January-2019

Raul B. Rebak, GE Global Research, Schenectady, NY, USA

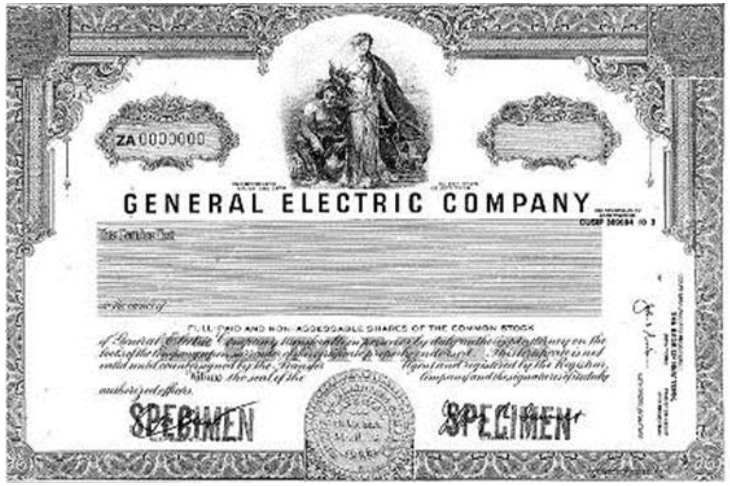
NACE INTERNATIONAL SAN FRANCISCO SECTION

Imagination at work.

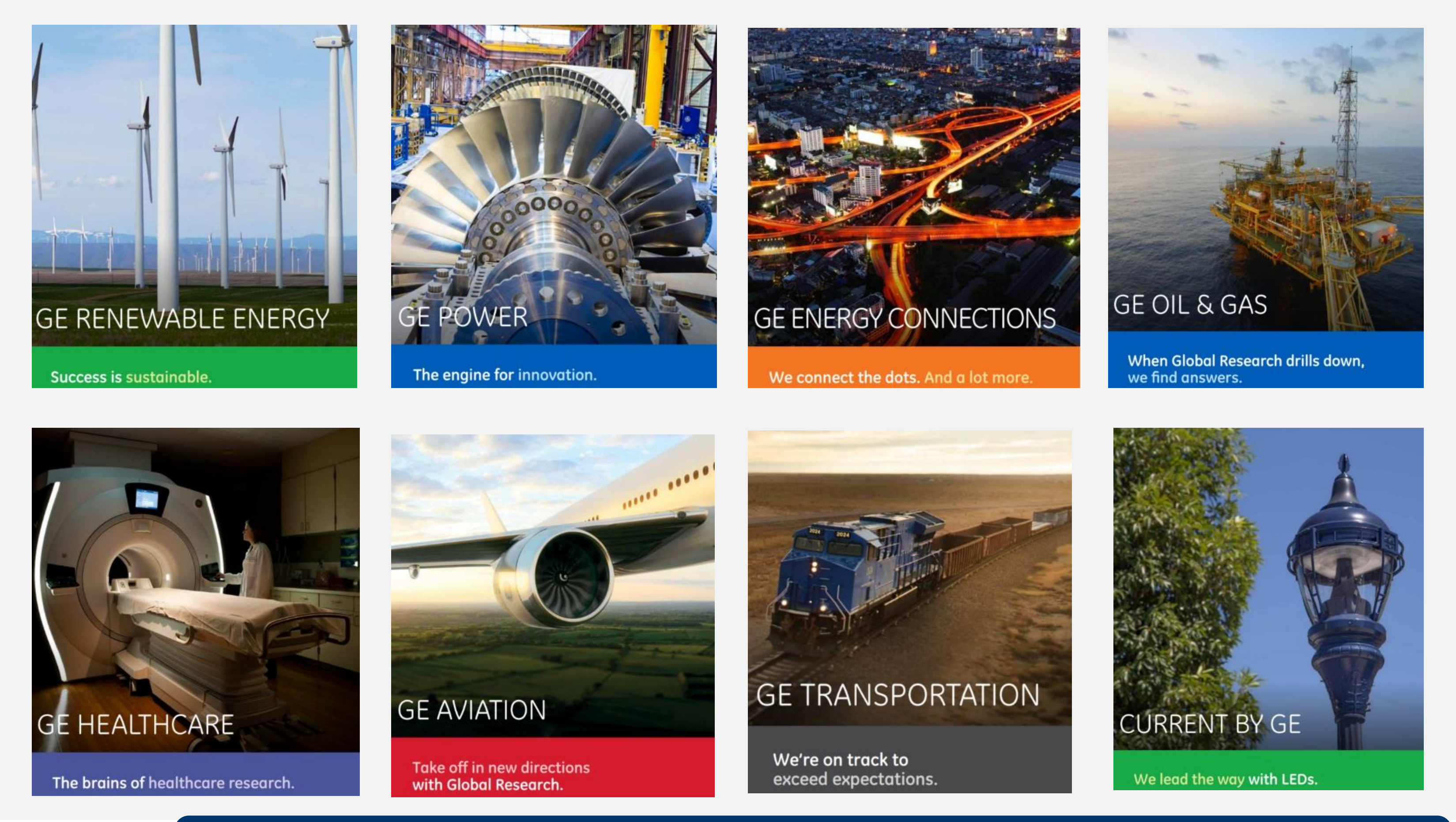
General Electric



1) Started in Schenectady, NY in 1892
2) Founded by Thomas A. Edison
3) Operates in 180 countries in the world
   - Known by Aviation, Power, Oil & Gas, Healthcare, etc.
4) GE Global Research Center in Schenectady, a unique research center in the world. Started in 1900.
5) 1100 engineers (685 PhDs)



GE Today



Spending $5+B per year on innovation

Driving technology advantages across our businesses

GE Global Research

The technology development arm for GE

- First U.S. industrial lab
- Market-focused R&D
- One of the world's most diversified industrial research organizations
- Leading a team of ~50K world-class engineers

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Accelerating innovation through collaboration

1

The accident and the opportunities

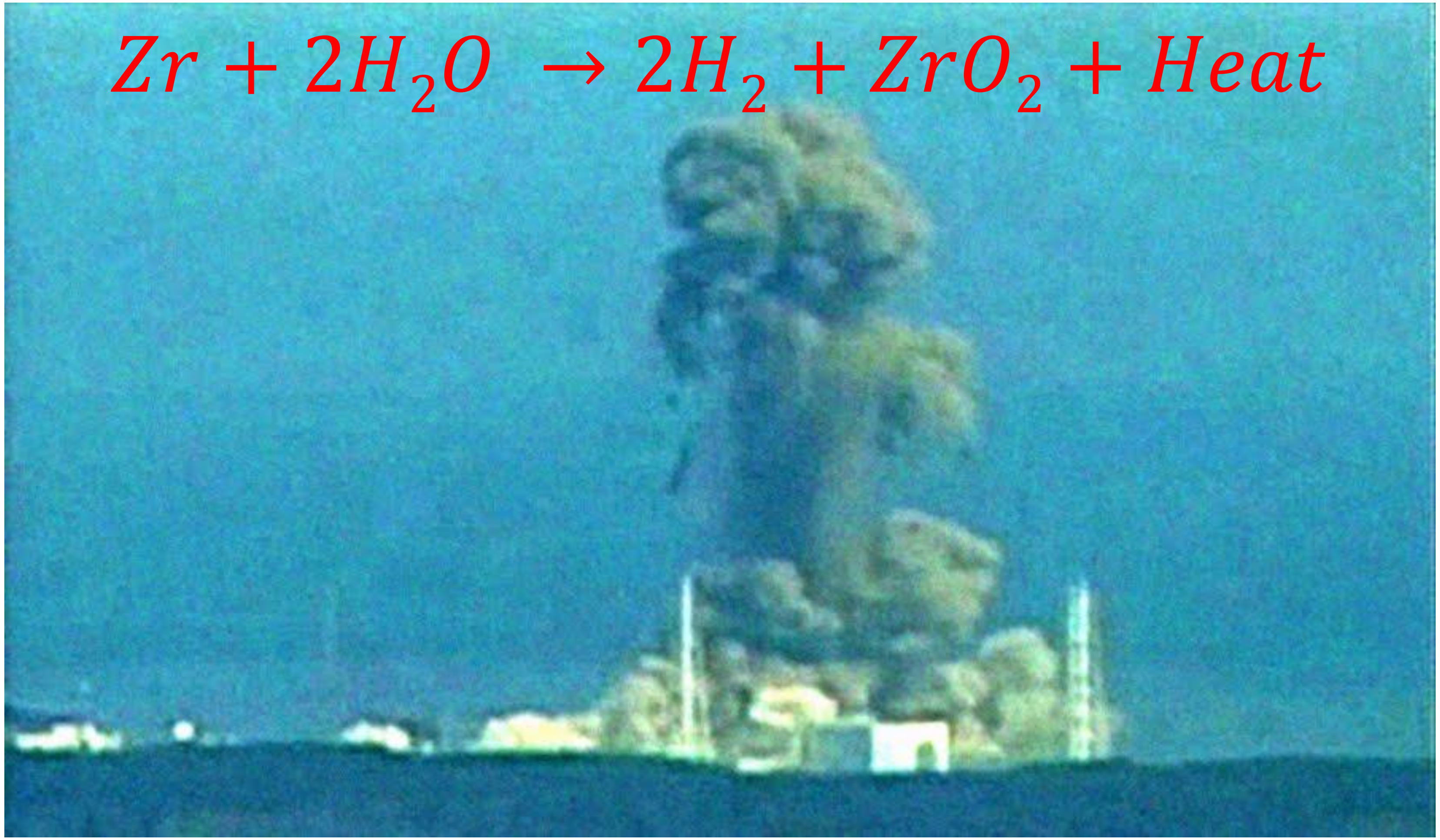
11-March-2011, Tsunami at Fukushima Nuclear Site

- The second wave 15 m (50 ft) high hit the turbine buildings, destroying the diesel generators in the first floor and in the basement.
- Plant black out. No coolant for the fuel rods in the reactor or the spent fuel in the pools.

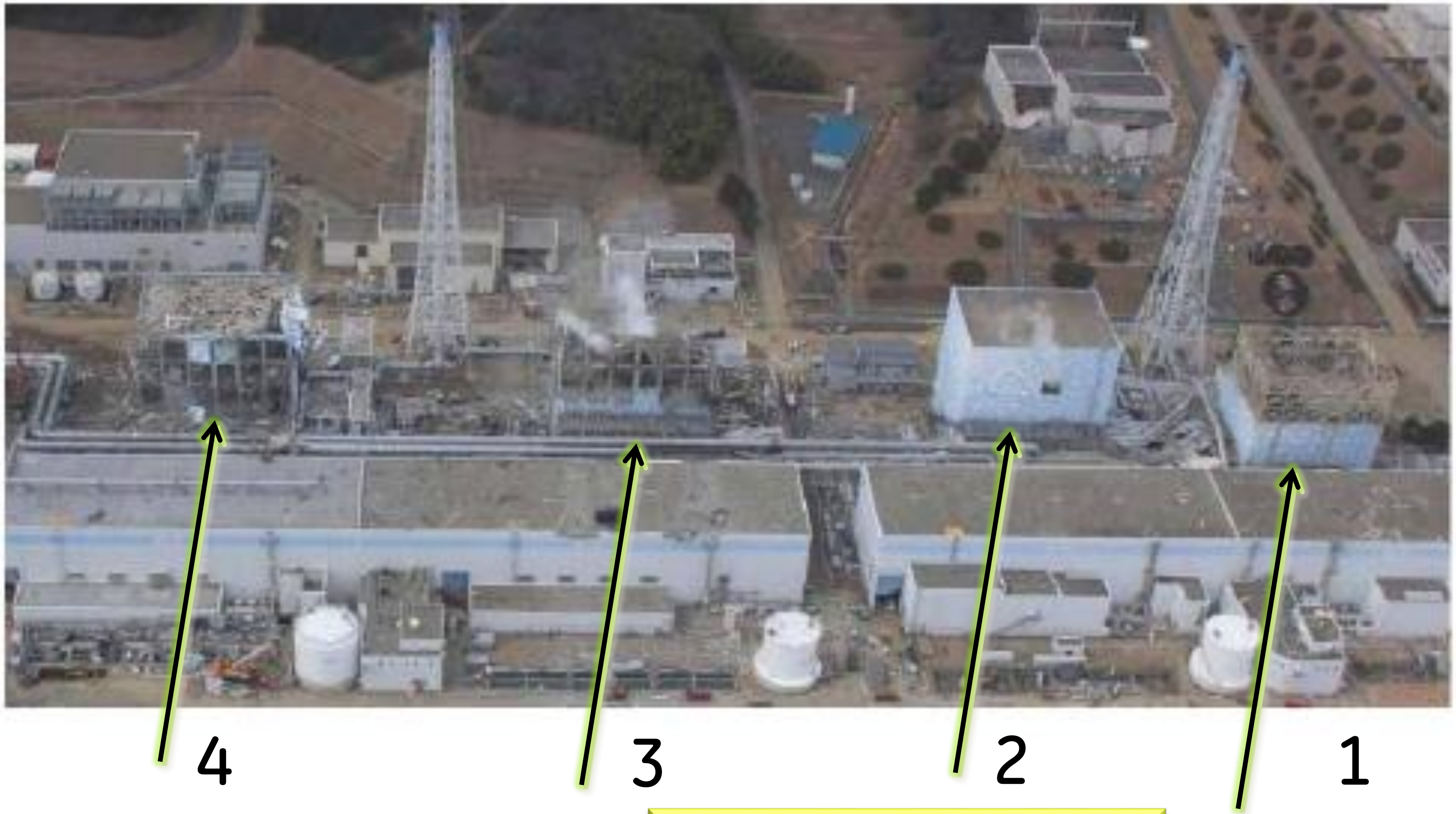
The second wave, 11 March 2011

Building explosions due to the ignition of accumulated hydrogen gas

$$Zr + 2H_2O \rightarrow 2H_2 + ZrO_2 + Heat$$



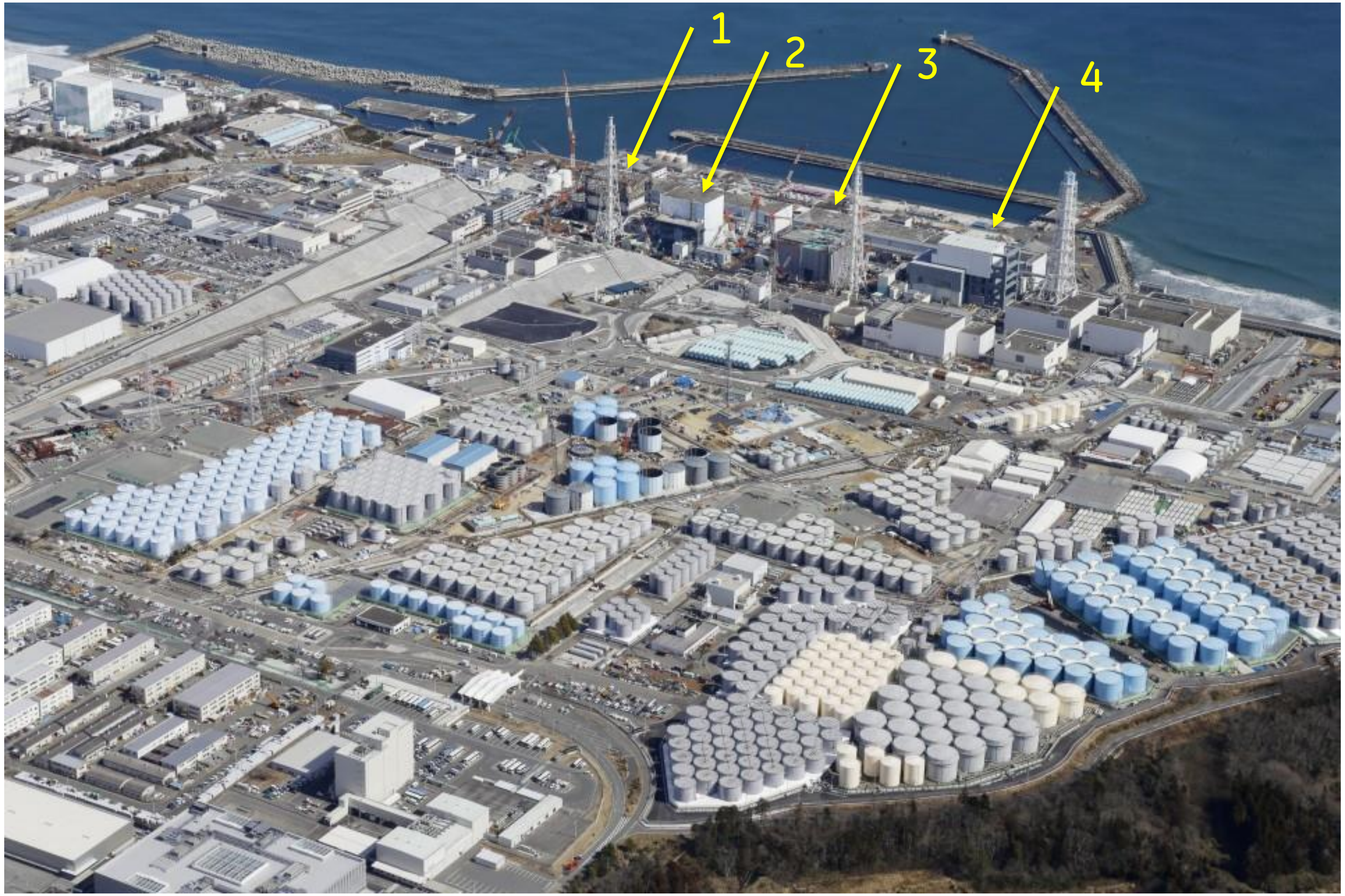
Fukushima Daiichi Reactors after the Explosions



View from the Sea

Fukushima Daiichi – Pre Tsunami.

Fukushima Daiichi Recent View



In Chinese, **Crisis** = wēi jī

Danger 危 + 机 Incipient moment; crucial point, when something begins or changes.

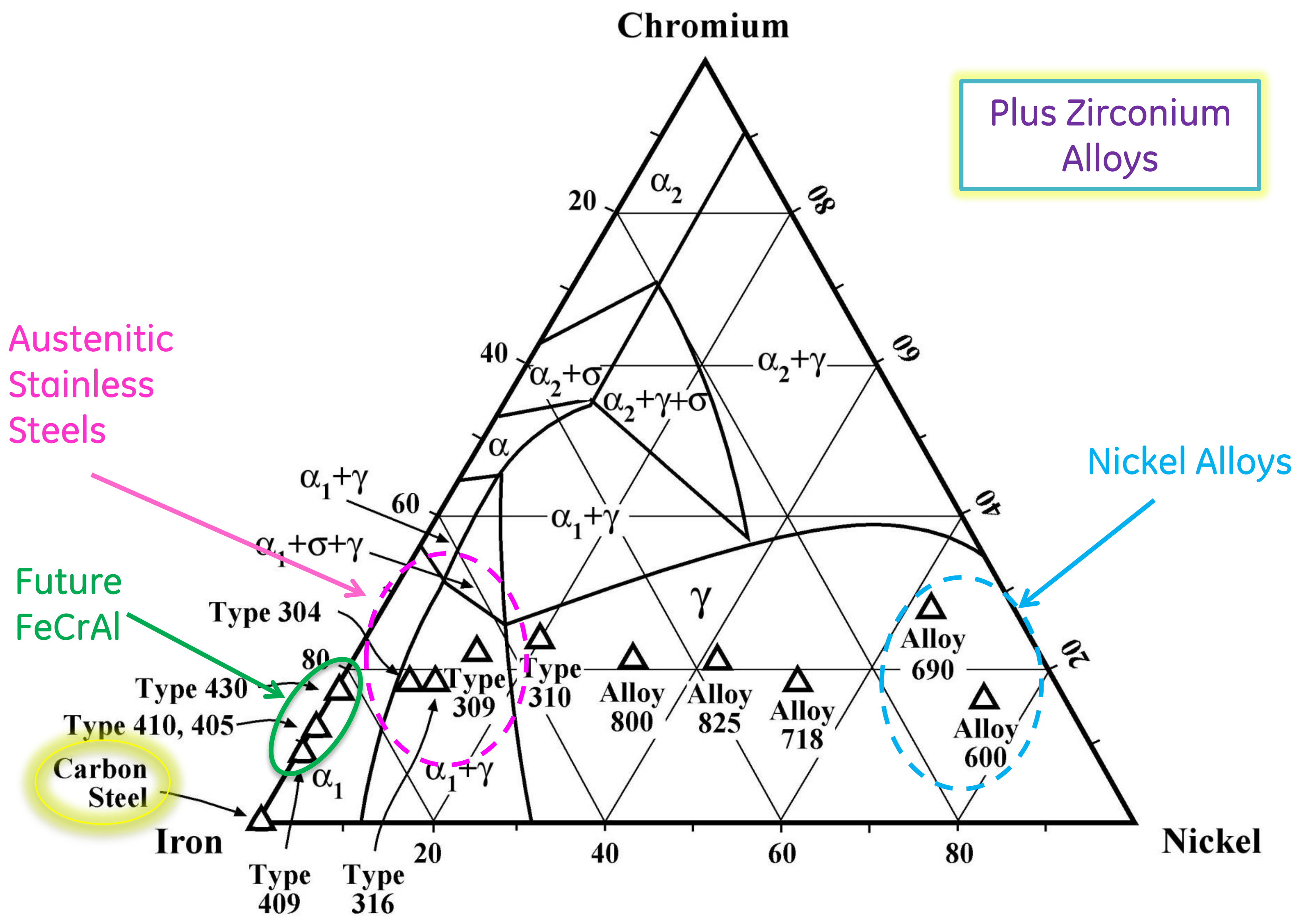
Character wēi

Character jī

2

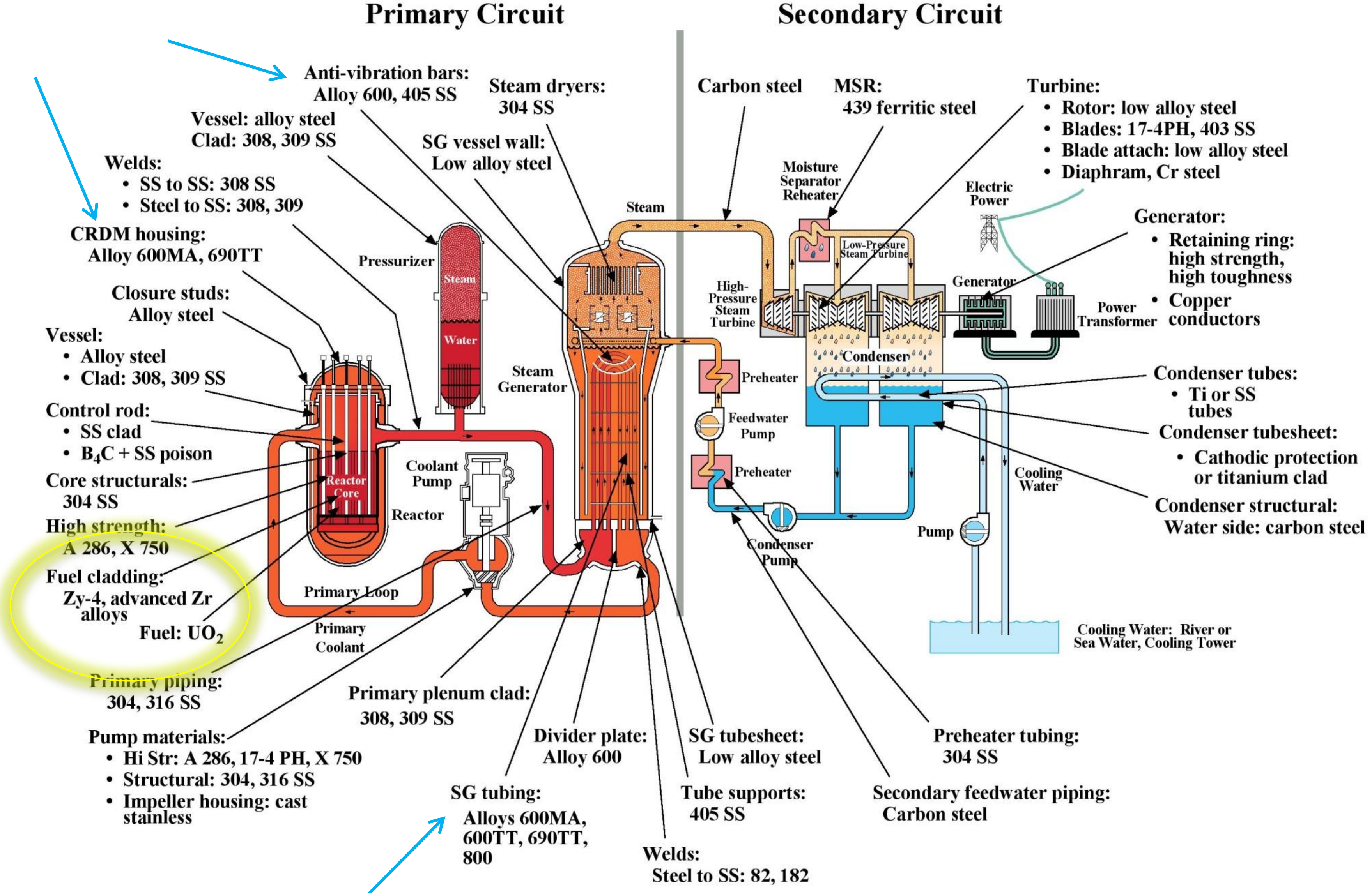
Materials in Nuclear Power

Structural Materials in the Nuclear Power Industry



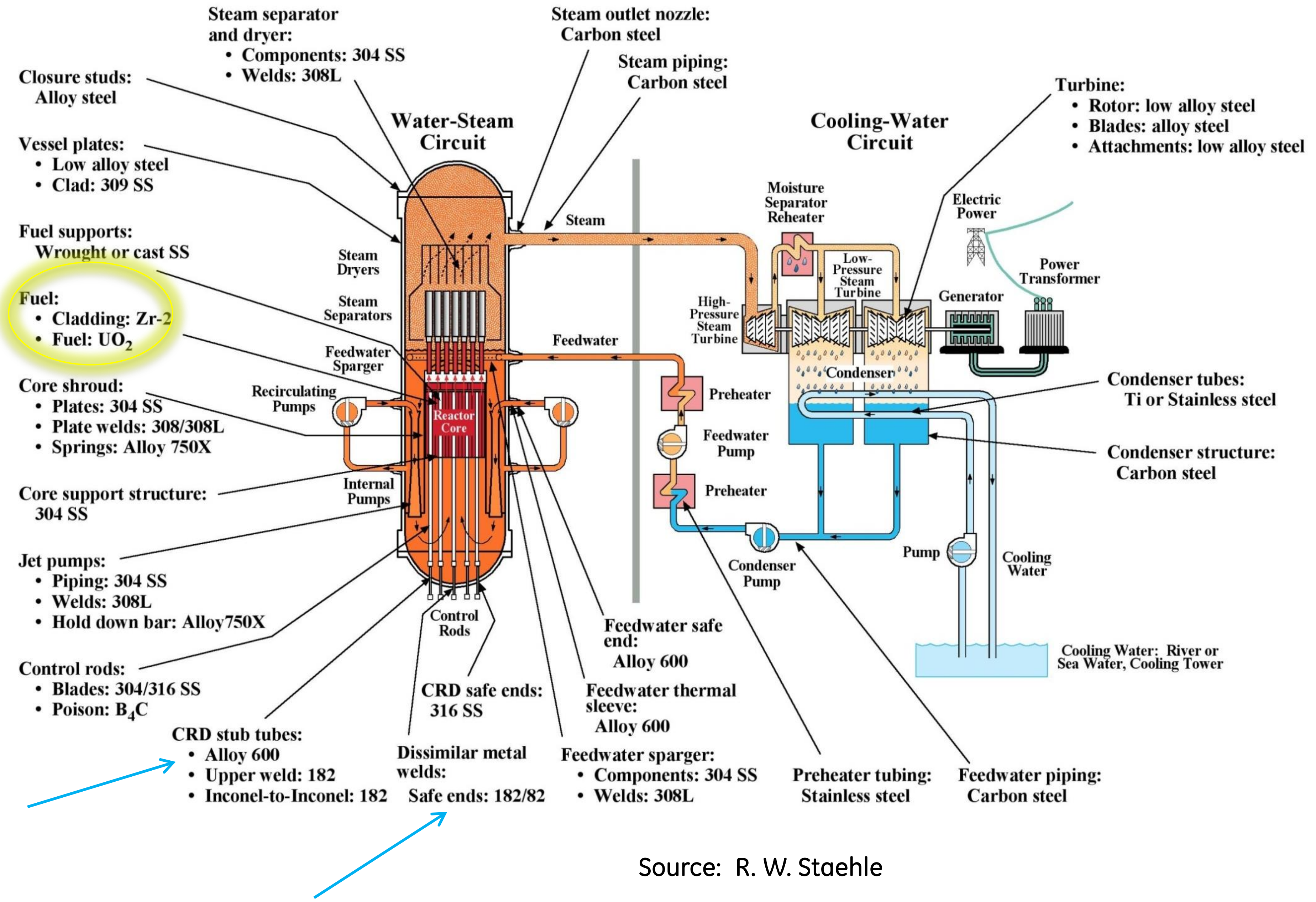
Source: R. W. Staehle

Materials and Components in PWRs



Source: R W Staehle

Materials and Components in BWRs

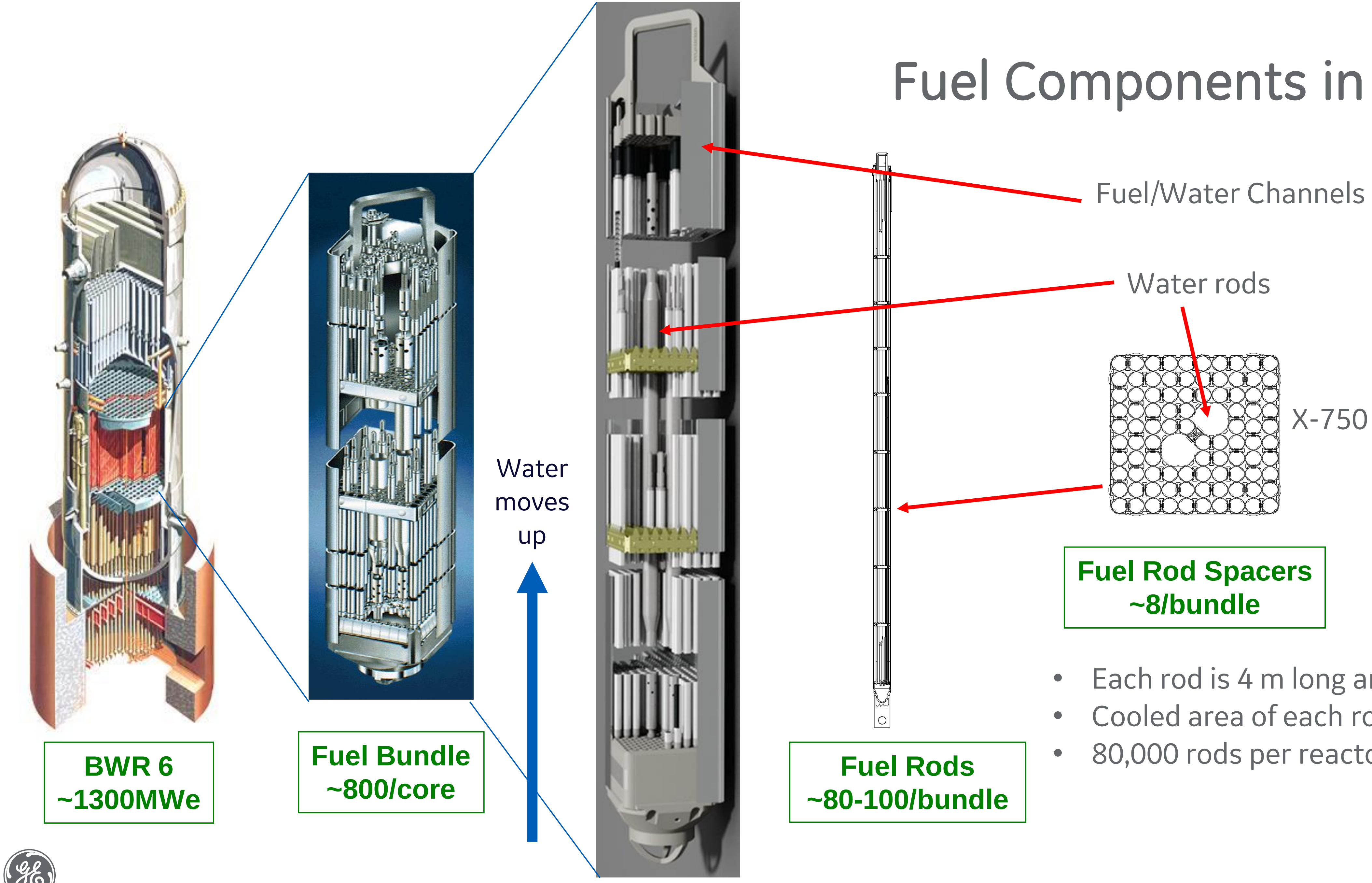


Source: R. W. Staehle

3

Department of Energy Accident Tolerant Fuels

Fuel Components in BWR



- Each rod is 4 m long and 10 mm OD
- Cooled area of each rod is 1300cm².
- 80,000 rods per reactor

Accident Tolerant Fuels (ATF)
Advanced Technology Fuels (ATF)

Improved Reaction Kinetics with Steam
- Heat of oxidation
- Oxidation rate

Improved Fuel Properties
- Lower operation temperatures
- Clad internal oxidation
- Fuel densification/relocation
- Fuel melting

Accident Tolerant Fuel

Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

Improved Cladding Properties
- Clad fracture
- Dimension stability
- Thermal shock resistance
- Clad melting

Slower Hydrogen Generation Rate
- Hydrogen bubble
- Hydrogen explosion
- Hydrogen embrittlement of clad

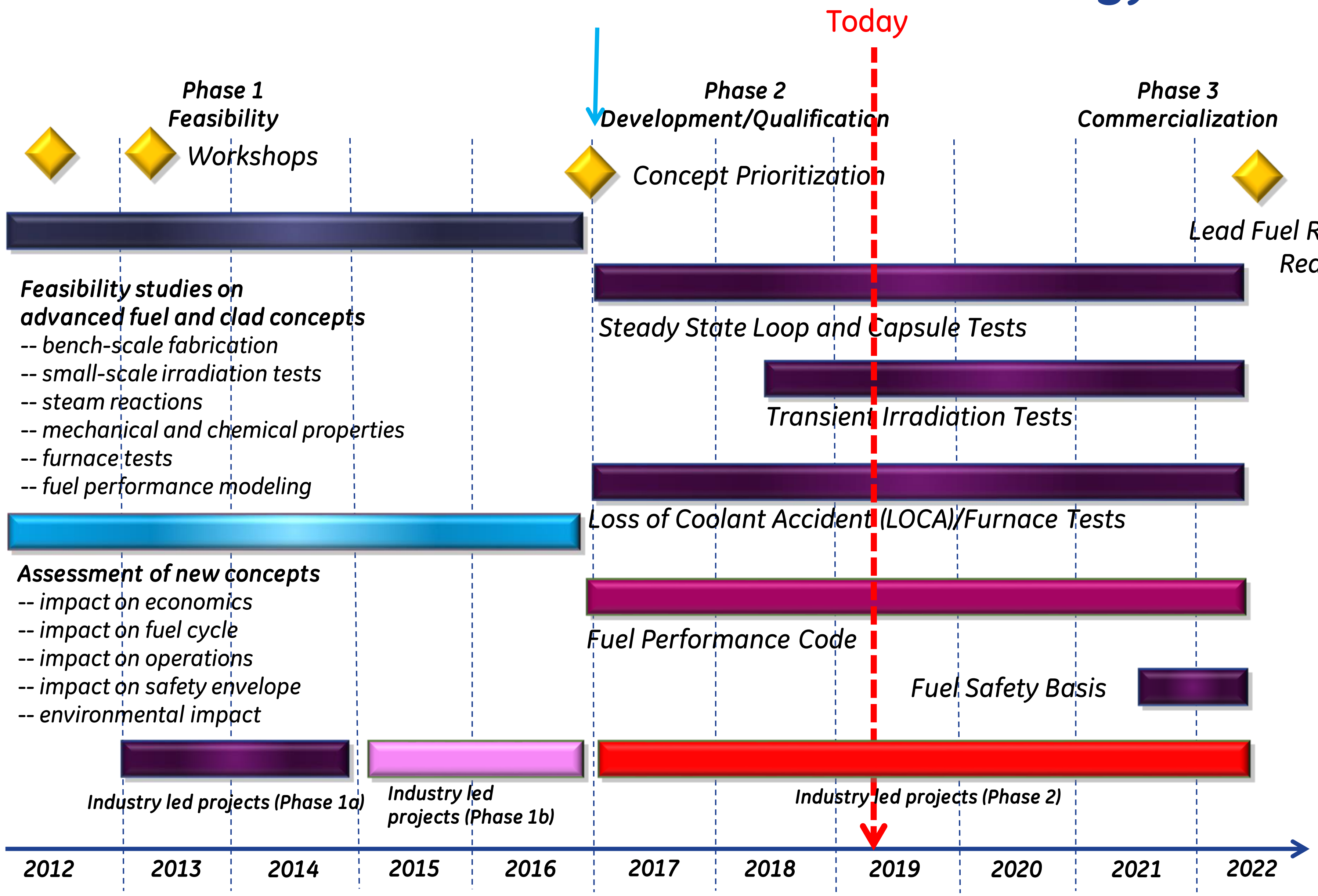
Department of Energy – Nuclear Energy

Since October 2012, DOE-NE has supported the research of newer materials for nuclear power plants providing cost shared funding.

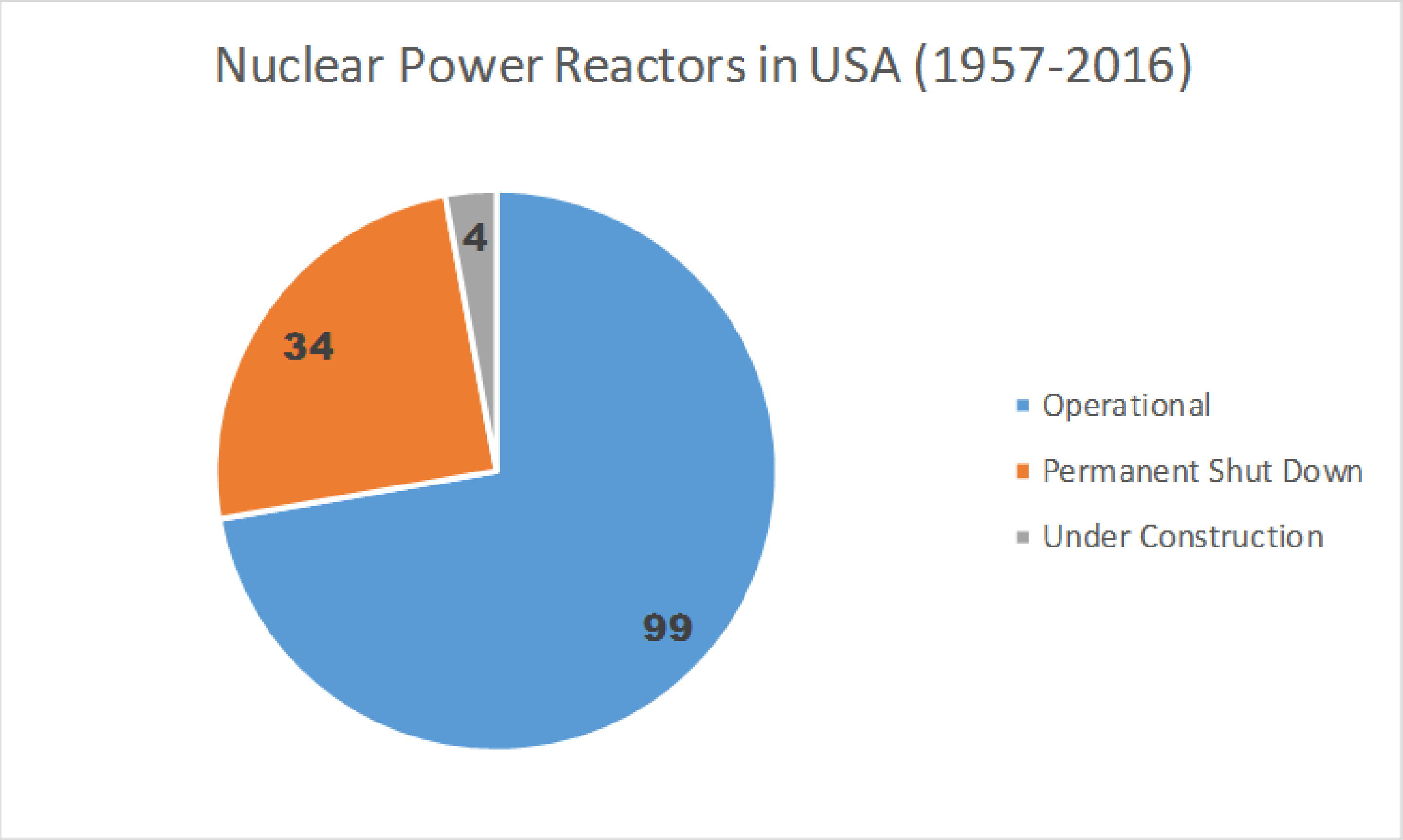
Companies supported include

1) Framatome – Coatings of Zircaloy
2) General Electric – FeCrAl cladding, SiC
3) Westinghouse – Coatings of Zircaloy, SiC

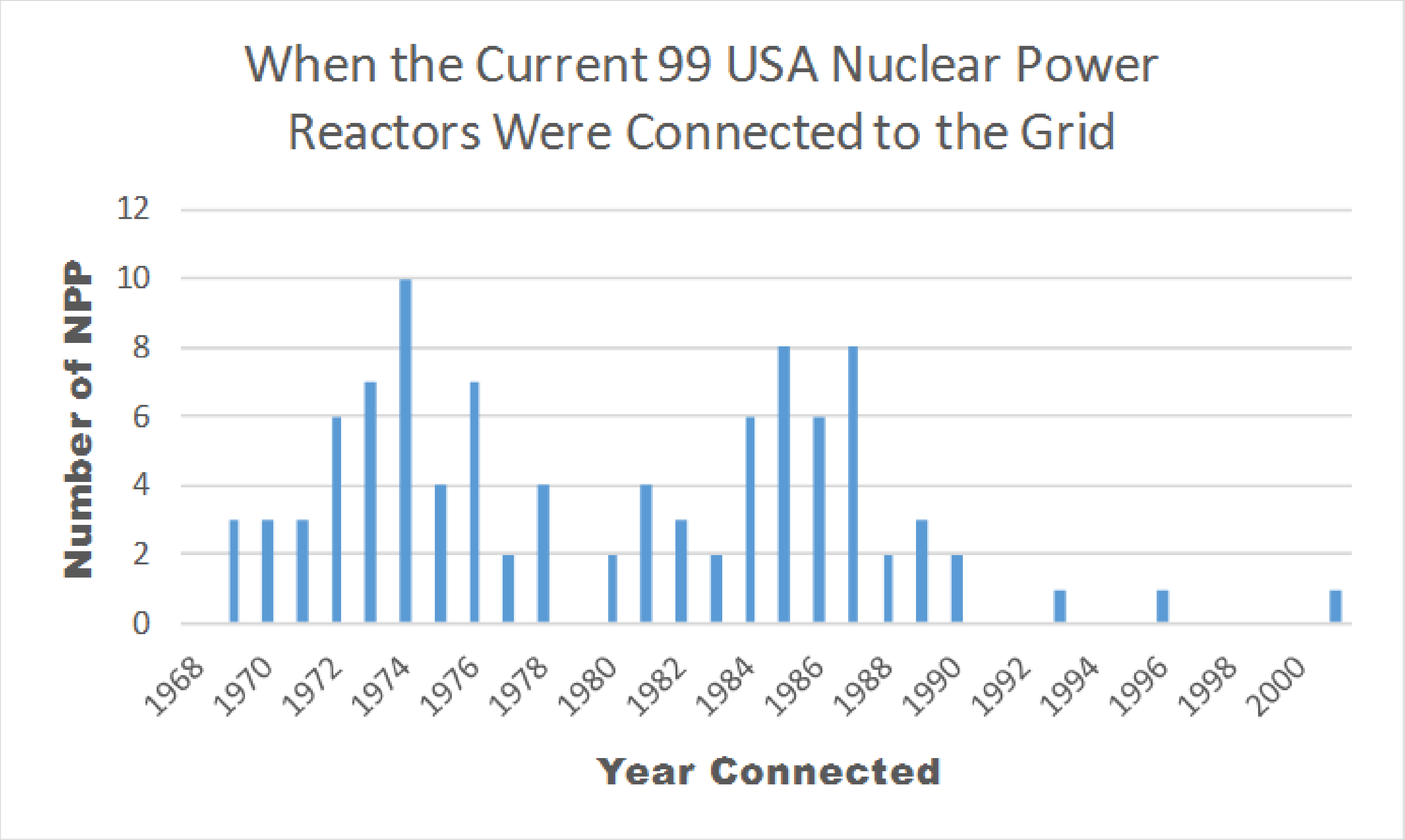
Ten-Year ATF Plan from DOE Nuclear Energy



Nuclear Power Reactors in the USA 1957-2016



89% of the Reactors are at least 30 years old



To implement Accident Tolerant Fuels in the current reactor fleet, it needs to be a concept with near term solution.

IronClad (FeCrAl) – GE/ORNL Effort, February 2018

Southern Nuclear Initial Installation – Plant Hatch, Unit 1 Cycle 29

U.S. DEPARTMENT OF ENERGY

News - Google Chrome

Hatch-unit-restarts-with-accident-tolerant-fuel

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Hatch unit restarts with accident-tolerant fuel

07 March 2018

Share

Unit 1 of the Edwin I Hatch nuclear power plant in the US state of Georgia has begun operating with test accident-tolerant fuel assemblies. The fuel, loaded during a recent outage, is the first of its kind to be installed in a commercial nuclear reactor.

The twin-unit Hatch plant (Image: Southern Nuclear)

Southern Nuclear took the 876 MWe (net) boiling water reactor (BWR) offline for a planned refueling and maintenance outage on 4 February. In addition to refueling the reactor and performing regular maintenance and testing, workers made upgrades to plant systems and components. During the outage, in collaboration with Global Nuclear Fuels (GNF), lead test assemblies of accident-tolerant fuel were installed. The reactor was restarted on 4 March.

Lead test assemblies using an iron-chromium-aluminium fuel cladding material, known as IronClad, and coated zirconium fuel cladding, known as ARMOR, were installed in Hatch 1.

IronClad material is designed to provide oxidation resistance and "excellent material behaviour" over a range of conditions, with low oxidation rates of at higher temperatures further improving safety limit margins, GNF says.

Two variants of IronClad material have been installed at unit 1 of the Hatch plant: one in a fuel rod form but not containing fuel, while the other is in the form of a solid bar segment.

The IronClad lead test assemblies are the first developed through the US Department of Energy's Enhanced

GE's Nuclear Fuel Designs Ready for Reactor Testing | Department of Energy - Google Chrome

https://www.energy.gov/ne/articles/ges-nuclear-fuel-designs-ready-reactor-testing

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Office of Nuclear Energy

GE's Nuclear Fuel Designs Ready for Reactor Testing

FEBRUARY 16, 2018

Home » GE's Nuclear Fuel Designs Ready for Reactor Testing

General Electric recently announced plans to test a pair of nuclear fuel designs in a commercial reactor later this month in Georgia.

This is big news for the U.S. nuclear industry as it continues to develop new technologies to further enhance the safety and performance of its nuclear fuels.

It's also an important milestone for the U.S Department of Energy (DOE).

GE's IronClad fuel design will be the first key component tested in a commercial nuclear reactor that was developed through DOE's accident tolerant fuels program.

This is an important accomplishment made possible by a great collaboration between the government, our labs and industry partners. It's also what we refer to as a win-win for industry and the nation.

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US accident tolerant fuels to begin tests

15 February 2018

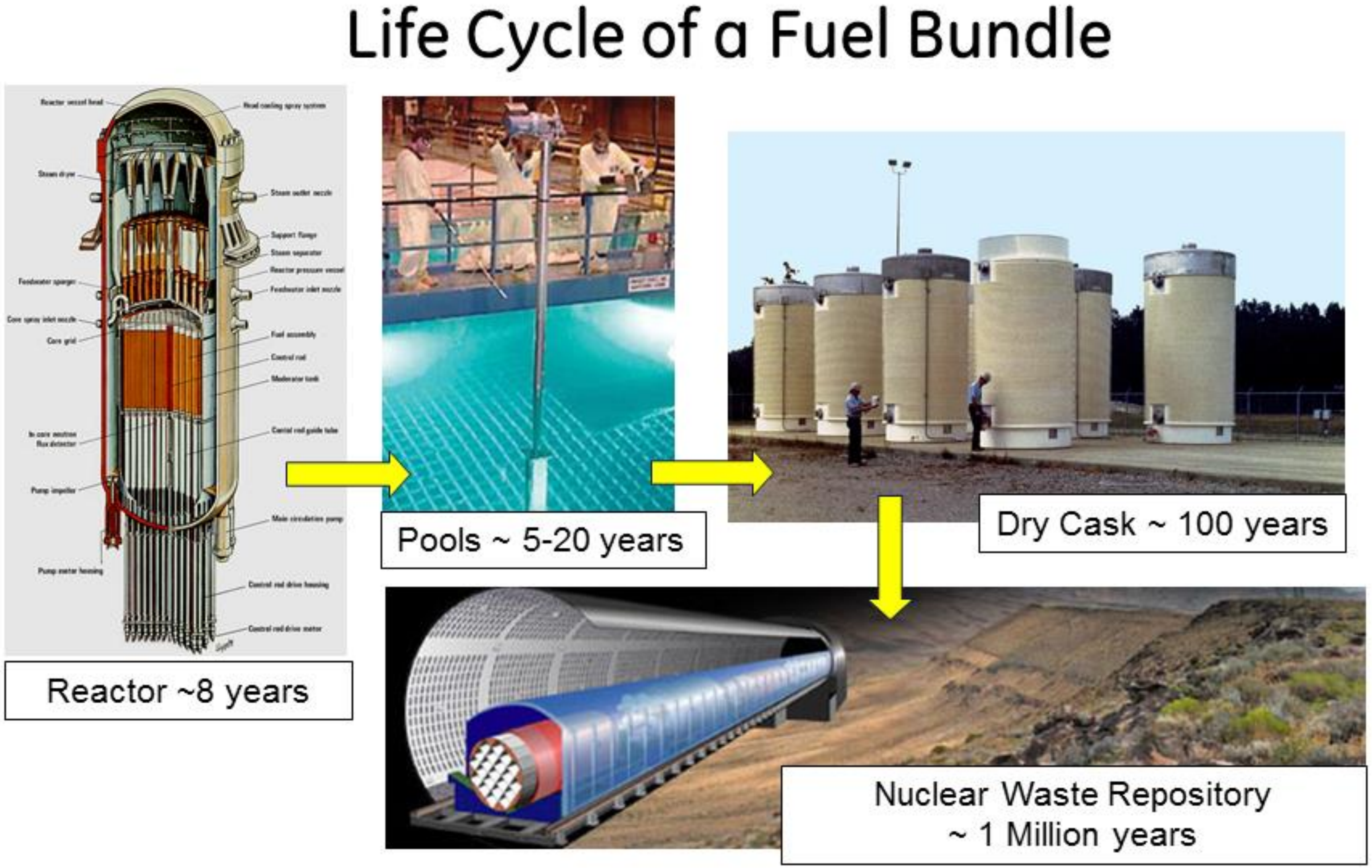
Print | Email

US-based Global Nuclear Fuel (GNF) said on 8 February that it had manufactured and shipped batches of test assemblies of its IronClad and Armor accident tolerant fuels (ATFs) for installation at Southern Nuclear Operating Company's two-unit Hatch nuclear plant in early 2018. The lead test assemblies were engineered and manufactured at GNF's facility in Wilmington, North Carolina.

GNF, a GE-led joint venture with Hitachi Ltd, is working with both Southern Nuclear and Exelon Generation to insert lead test assemblies utilising an iron-chromium-aluminum fuel cladding material (IronClad) and coated zirconium fuel cladding (Armor) into several reactors over the next few years.

The IronClad lead test assemblies will be the first fuel developed through the US Department of Energy's (DOE's) Enhanced Accident Tolerant Fuel programme to be installed in a commercial nuclear reactor. "We are exploring many technologies for our advanced fuel portfolio but believe that our expertise and experience with ferritic steel and coated zirconium cladding will enable us to put this enhanced solution to work more quickly for our customers," said GNF CEO Amir Vexler. GNF developed the Armor coating, which is applied to a standard zirconium fuel rod, to provide debris resistance and more oxidation resistance than conventional zirconium cladding.

The Fuel Cycle



The GE Accident Tolerant Fuel Team

GE Global Research

HITACHI

Exelon

GNF
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Oak Ridge National Laboratory

Southern Company

SANDVIK

Brookhaven National Laboratory

University of Idaho

INL
Idaho National Laboratory

University of Michigan

Los Alamos National Laboratory

Why FeCrAl Alloys for Cladding?

Development of High Performance FeCrAl Fuel Cladding for Light Water Power Reactors

FeCrAl cladding concept:

Fe + 10/22 Cr + 4/6 Al (+ 3 Mo, Hf, Y, Zr, etc.)

APMT = Powder Metallurgy

C26M = Traditional Melting

NFD ODS = Powder Metallurgy from Japan

Near term solution for enhanced safety of current light water reactors.

1. Superior oxidation resistance in the event of a severe accident.
2. Excellent environmental characteristics under normal operation both for BWR and PWR coolants
3. Eliminates common current fuel failure mechanisms
4. No change in fuel type (Utilizes current UO_2 fuel)

Needed Cladding Performance for

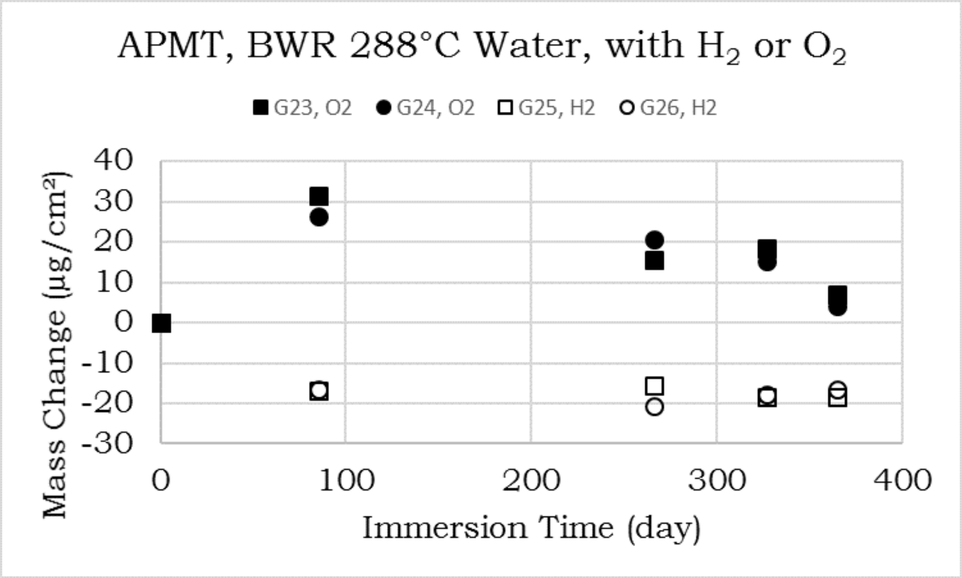
Normal Operation Conditions

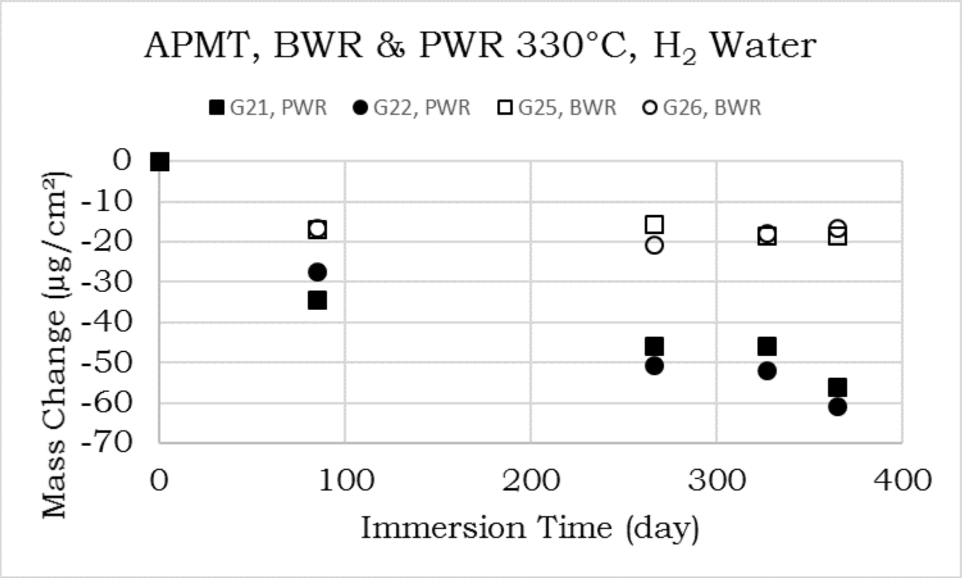
- Boiling Water Reactors, 288°C, water + hydrogen or oxidants
- Pressurized Water Reactor, 330°C, water + hydrogen

Severe Accident Conditions

- Loss of Coolant Accident
- Steam or steam + air at T > 1200°C

Low general corrosion under normal operation conditions.





Normal Operation Electrochemical Behavior

Element	Zircaloy-2 hcp	304SS austenitic	X-750 austenitic	C26M ferritic	APMT ferritic
Zr	~98	--	--	--	--
Fe	0.07-0.2	~70	7	~80	~70
Ni	0.03-0.08	8	~72	--	--
Cr	0.05-0.15	19	15	12	22
Al	--	--	0.7	6	5
Mo	--	--	--	2	3
Si	--	0.75 max	0.5 max	0.2	0.7 max
Mn	--	2 max	1 max	--	0.4 max
C	--	0.08 max	0.08 max	0.01 max	0.08 max
Other	1.5Sn	--	2.5Ti, 1Nb	0.05Y	Y, Hf

Corrosion potential vs. immersion time in pure water at 288°C, containing either 0.3 ppm hydrogen or 1 ppm oxygen.

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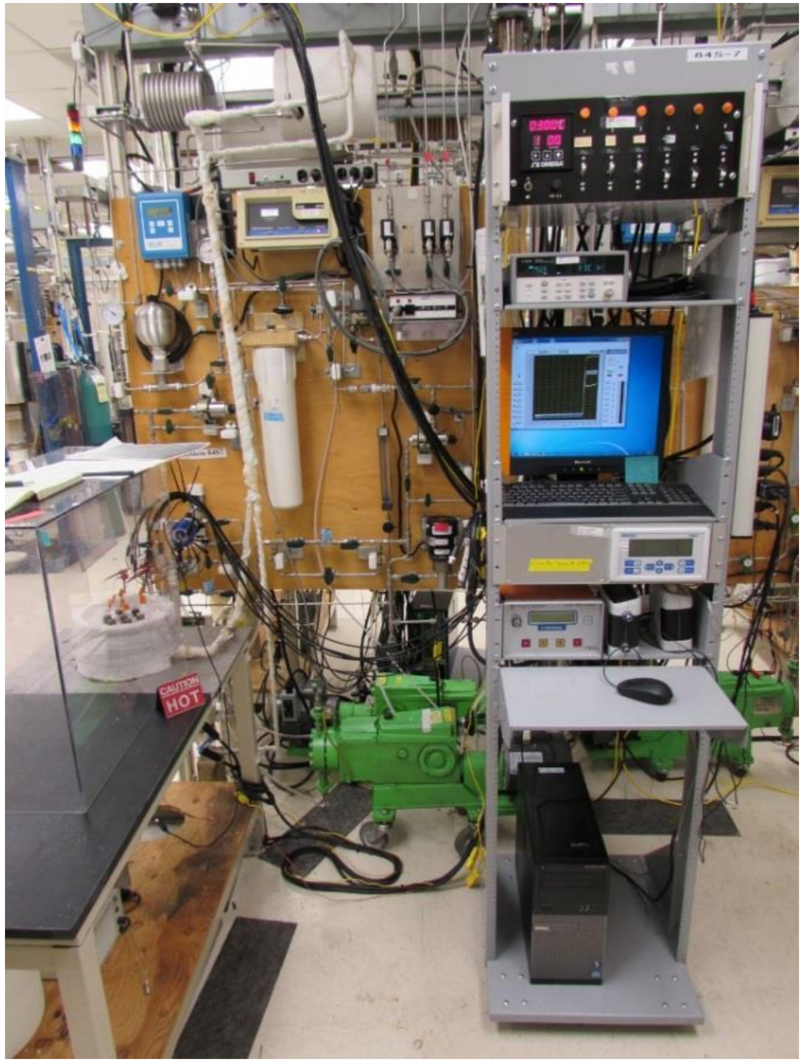
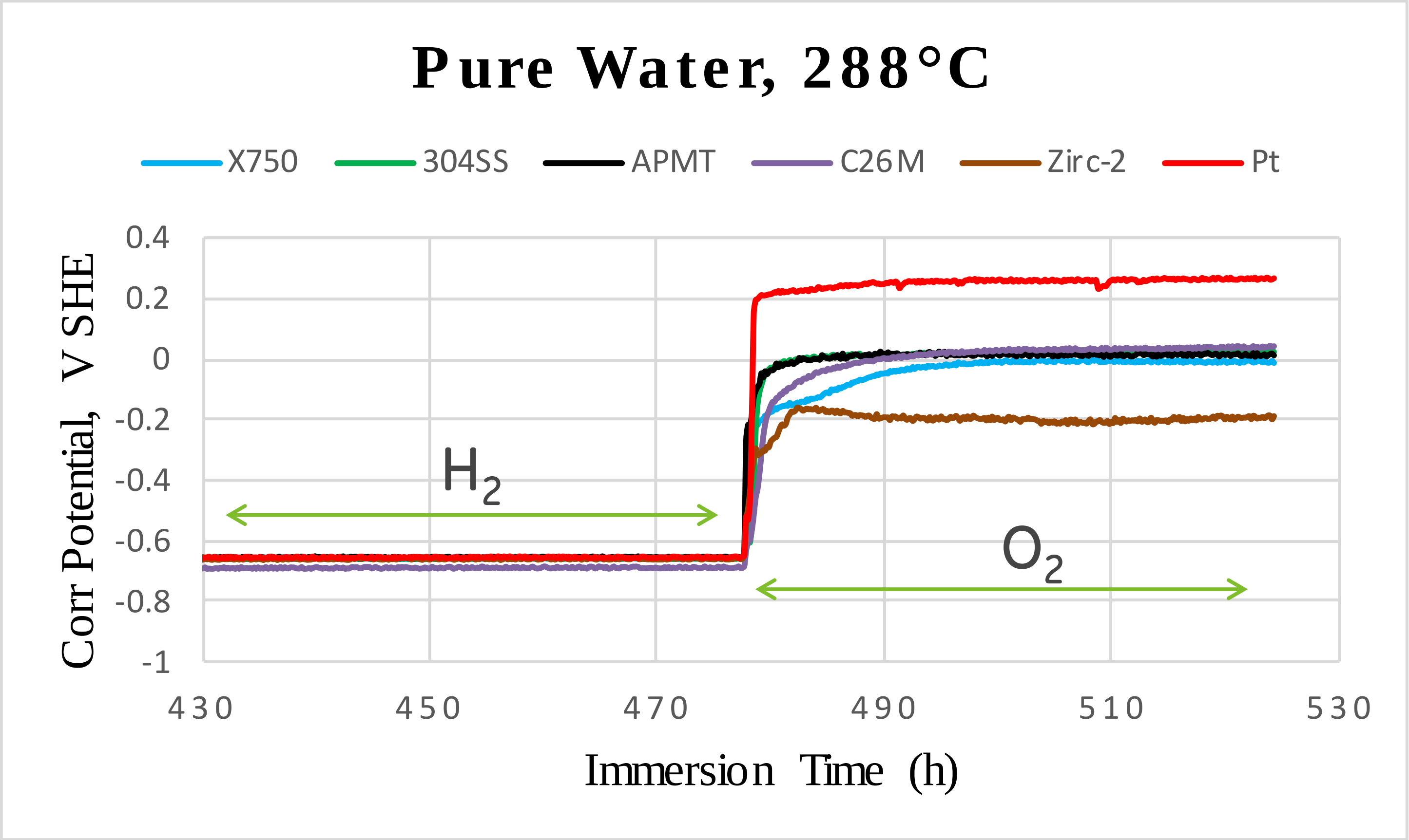
Electrochemical Testing in 288°C Water



Normal Operation Electrochemical Behavior



Corrosion potential vs. immersion time in pure water at 288C. In the first period the water contained 0.3 ppm hydrogen and in the last, 1 ppm oxygen.

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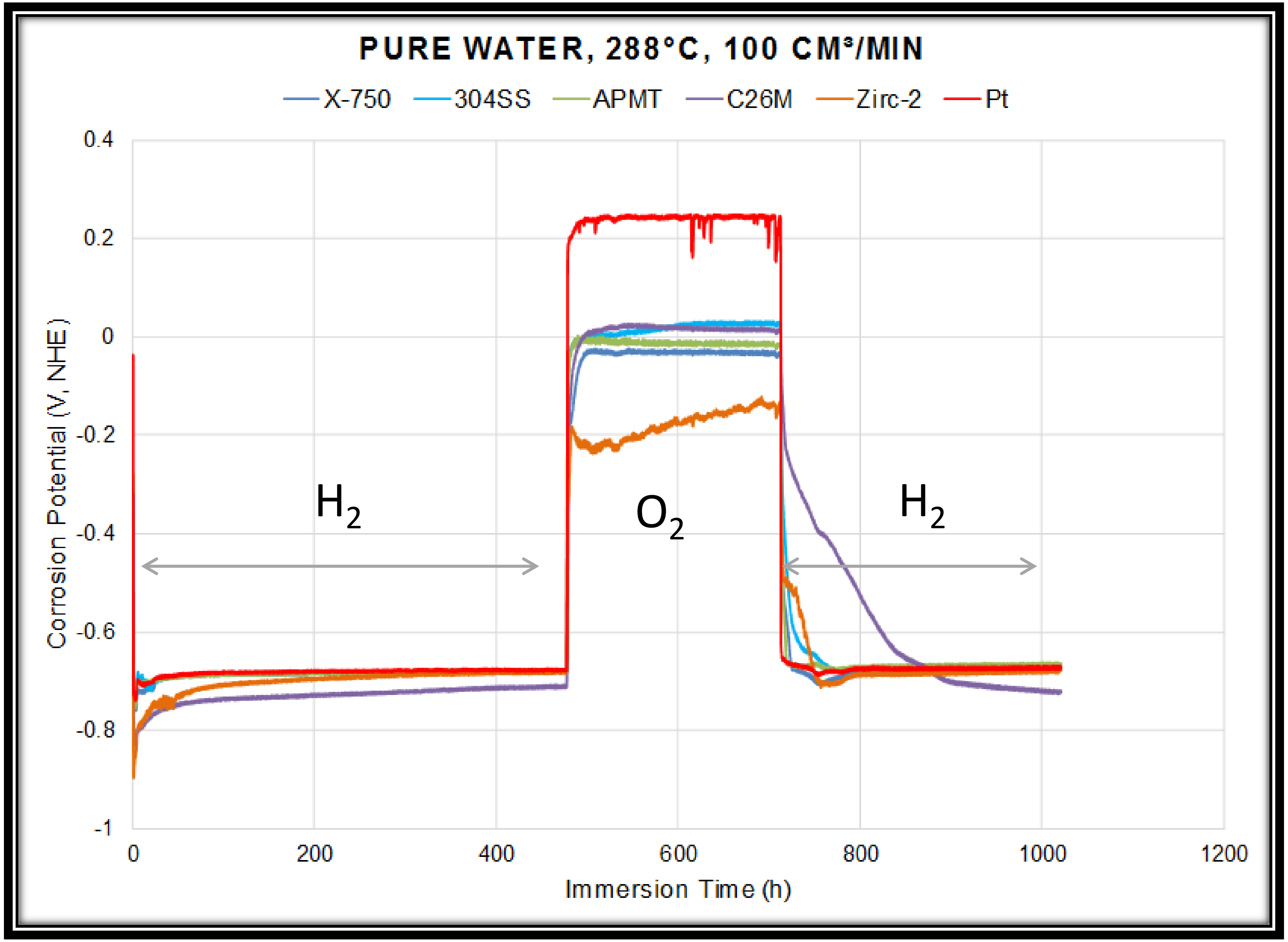
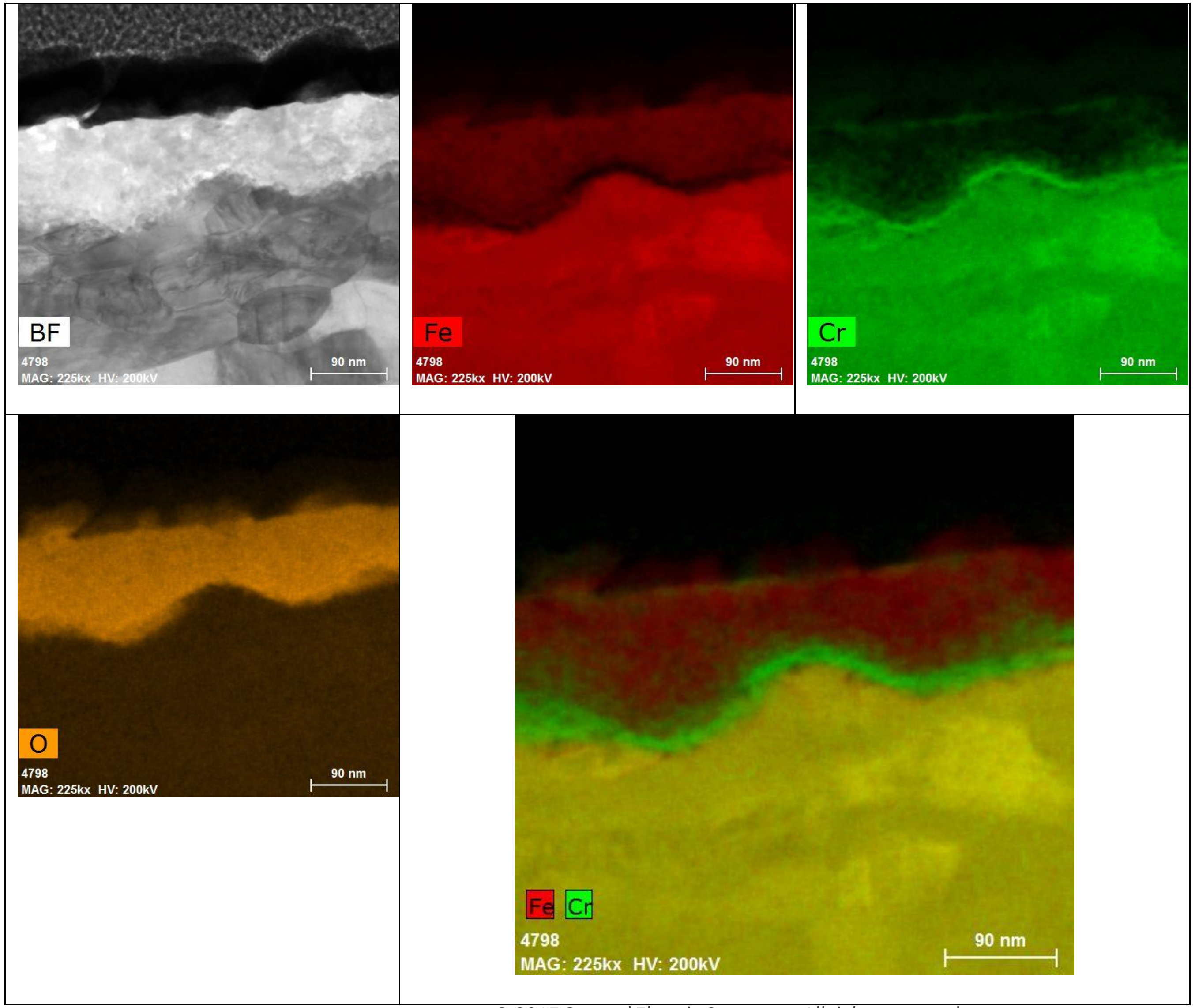
Electrochemical Behavior Normal Operation



Corrosion potential vs. immersion time in pure water at 288C. In the first period the water contained 0.3 ppm hydrogen and in the last, 1 ppm oxygen.

Normal Operation with Protective Oxide

Surface & cross-section of the oxide formed on APMT coupon exposed for 1 year to



BWR, pure water + 1 ppm O_2 at 288°C

Dual Layer Oxide

A ~10 nm thick inner layer of Cr_2O_3

No Mo or Al in the oxides.

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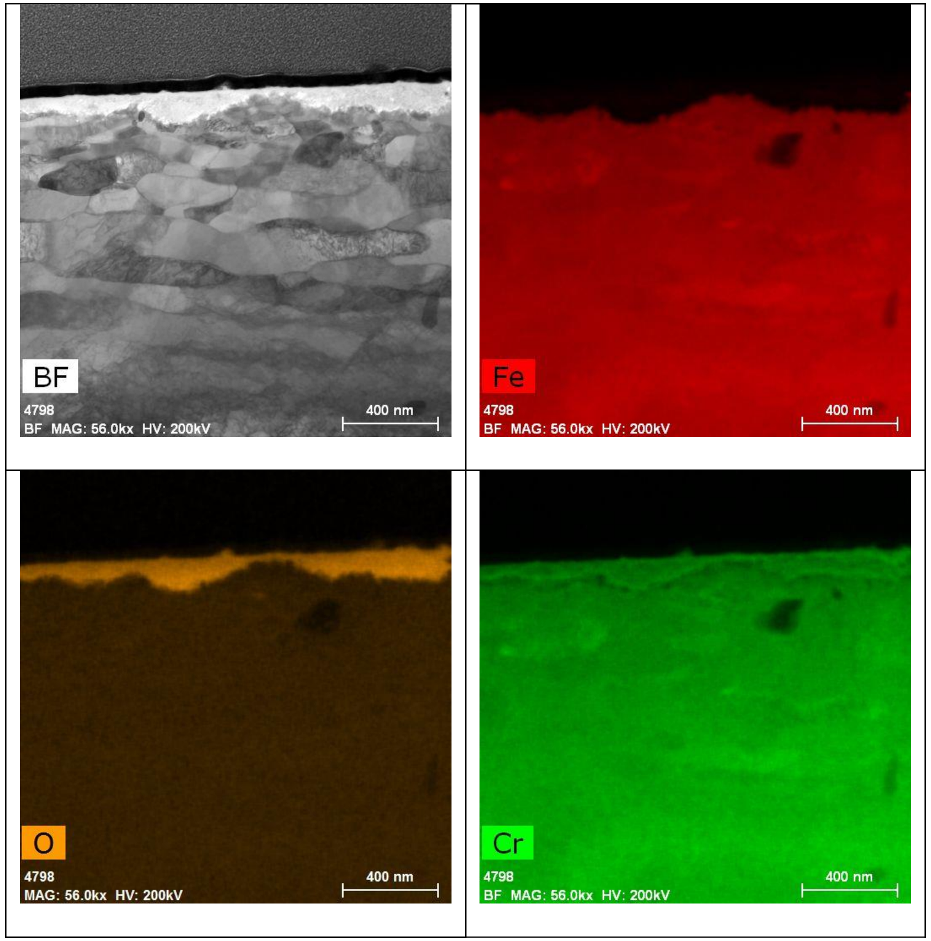
Normal Operation PWR Condition, Protective Oxide

Surface & cross-section of the oxide formed on APMT coupon exposed for 1 year to



PWR, pure water + 3.75 ppm H_2 at 330°C

A single layer oxide rich in Cr

No Fe, Mo or Al in the oxide.

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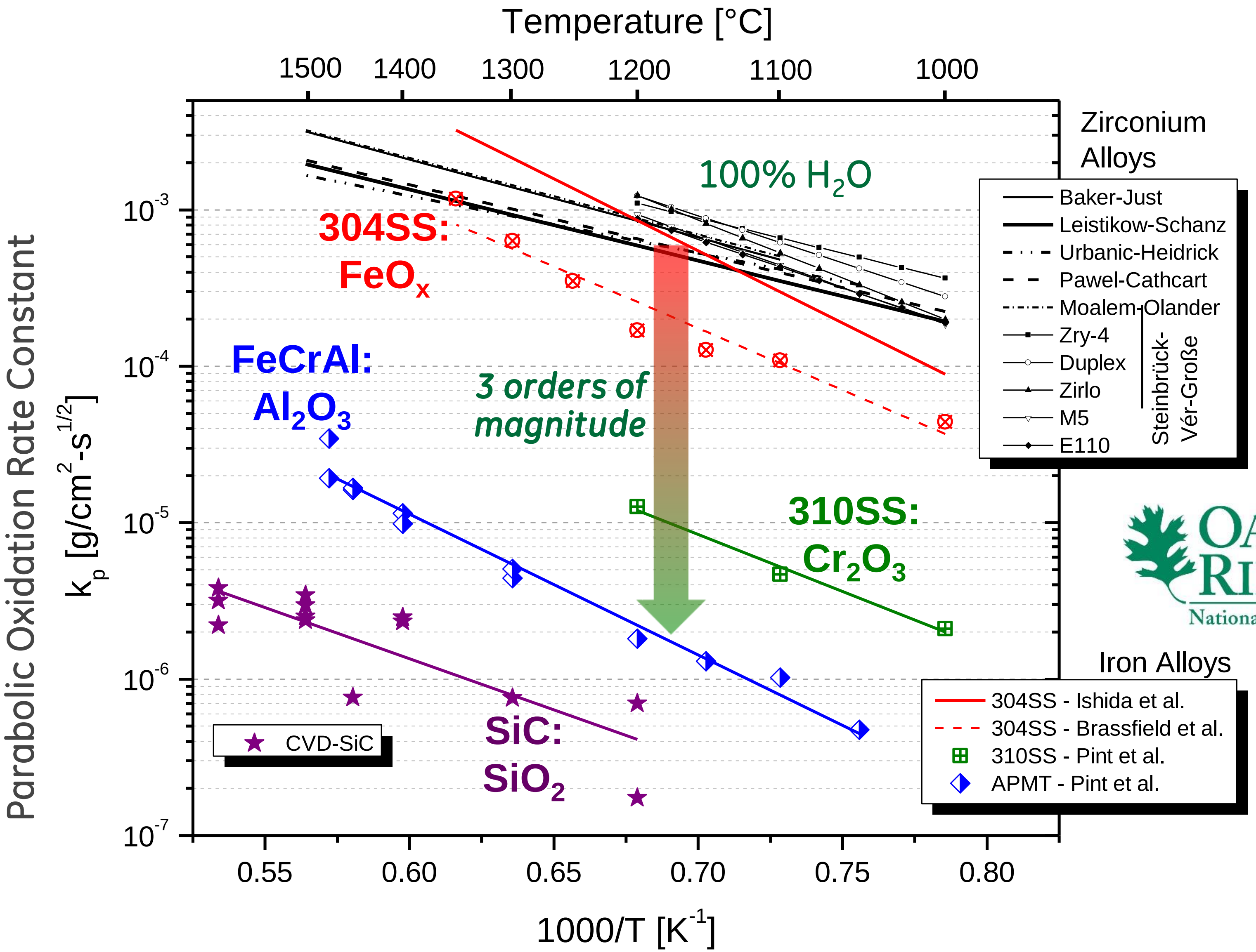
Comparison on Sperheated Steam Oxidation Rate

K.A. Terrani, S.J. Zinkle, L.L. Snead, "Advanced oxidation-resistant iron-based alloys for LWR fuel cladding," *J. Nucl. Mater.*, **448**, (2014) 420.

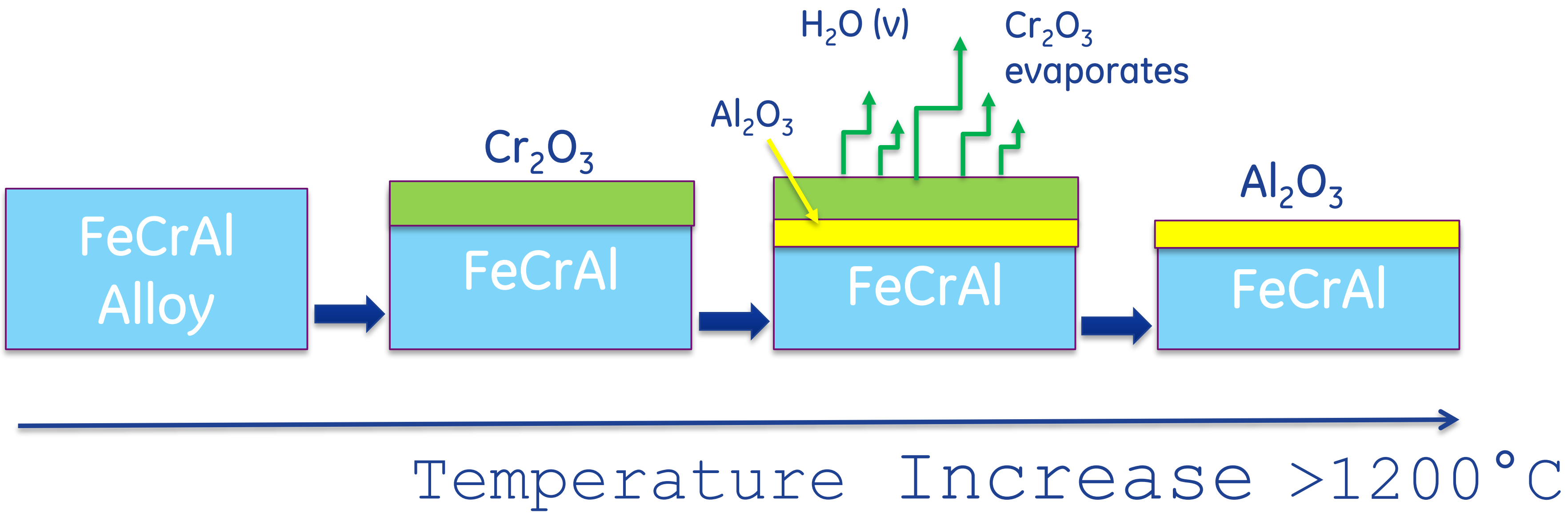


OAK RIDGE National Laboratory

Three orders of magnitude reduction in oxidation rates

High temperature oxidation of Fe-Cr-Al alloys.

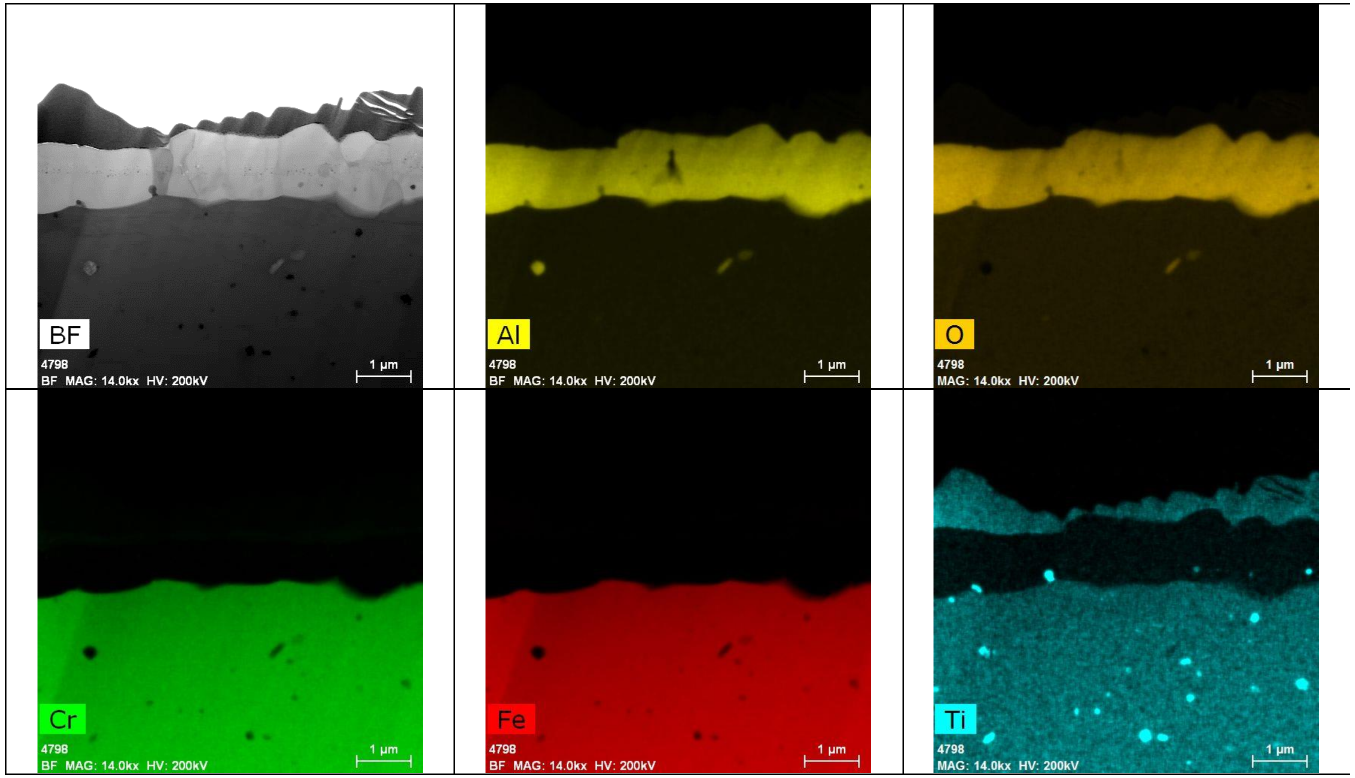
- Outstanding resistance to oxidation in steam at temperatures higher than 1000°C



a) Up to near 1000°C, Cr_2O_3 protects the material from further oxidation
b) At 1200°C and higher steam temperatures, FeCrAl protected by an alumina layer

Alumina layer forms on the surface of APMT Tube, 0.8 mm wall thickness and 9.5 mm OD after exposure to 100% steam at 1200°C for 4 h

~1 μm thick Alumina Layer



~70Fe + 21Cr + 5Al + 3Mo

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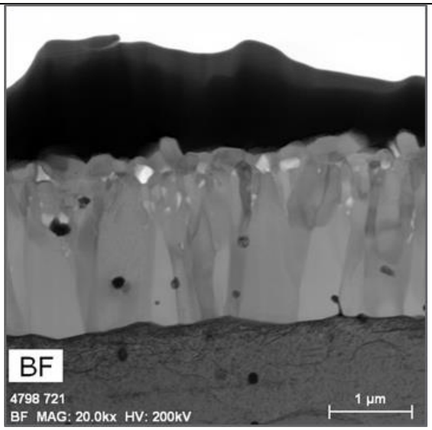
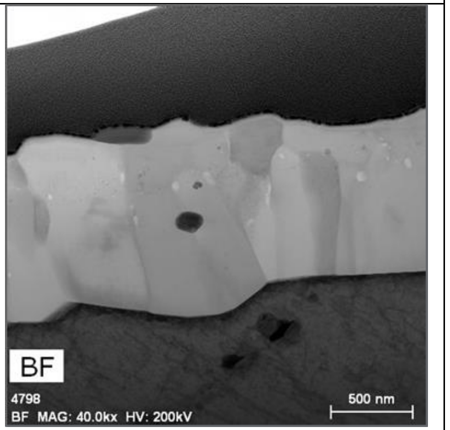
At 1200°C, the oxide was thinner in steam than in air.

<table>
<tr><th></th><th>1200°C, air, 4h</th><th>1200°C, steam, 4h</th></tr>
<tr><td>APMT</td><td>
</td><td>
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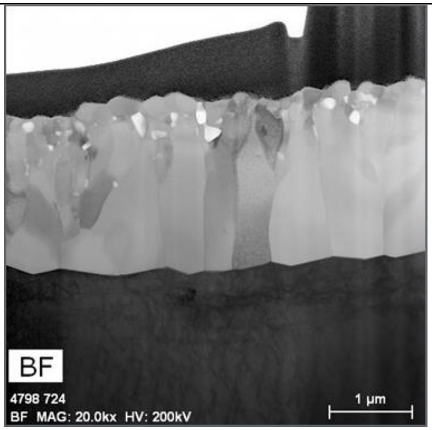
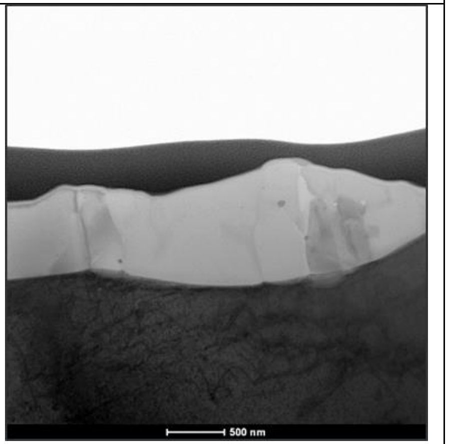
<tr><td>C26M</td><td>
</td><td>
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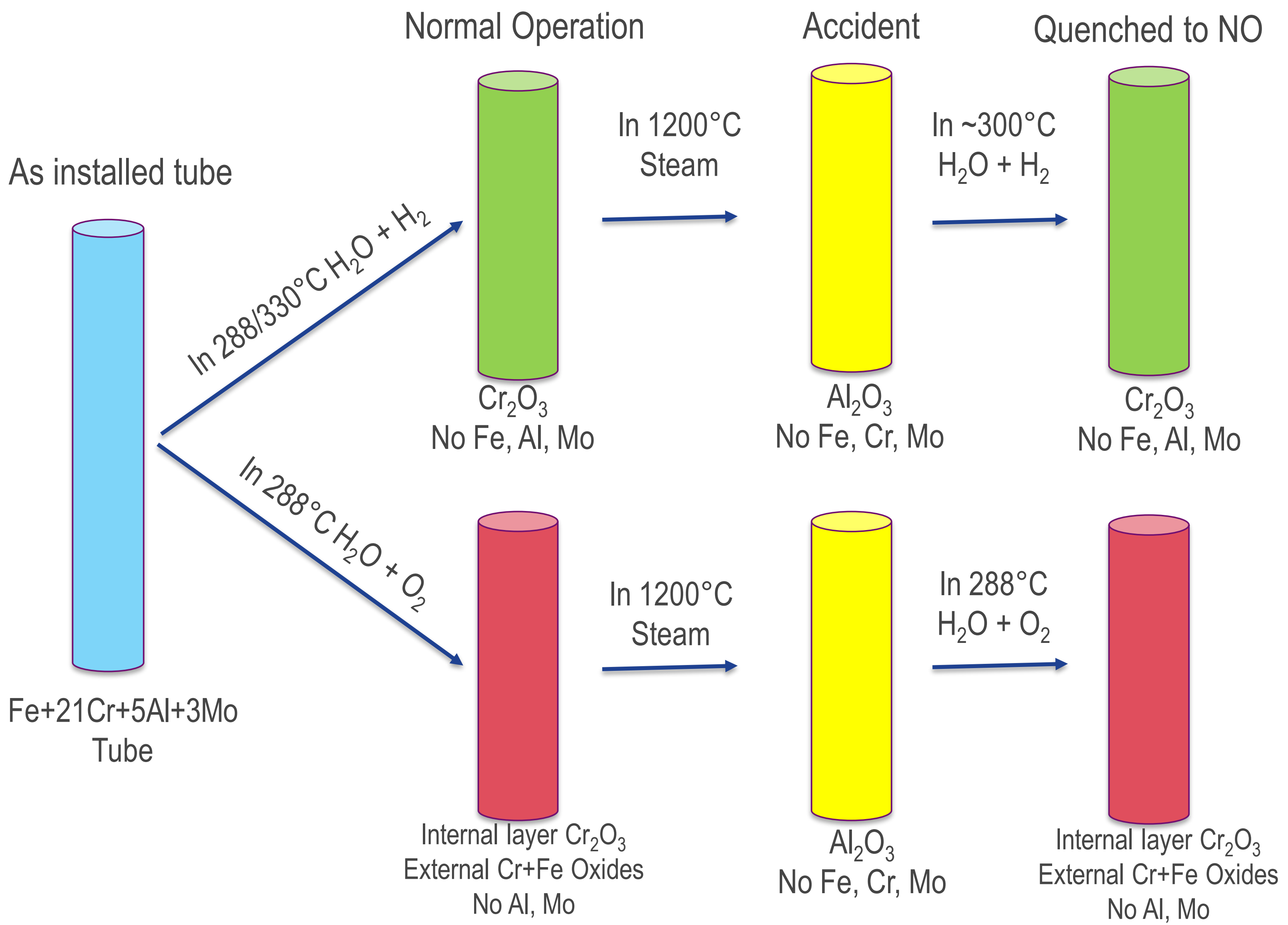
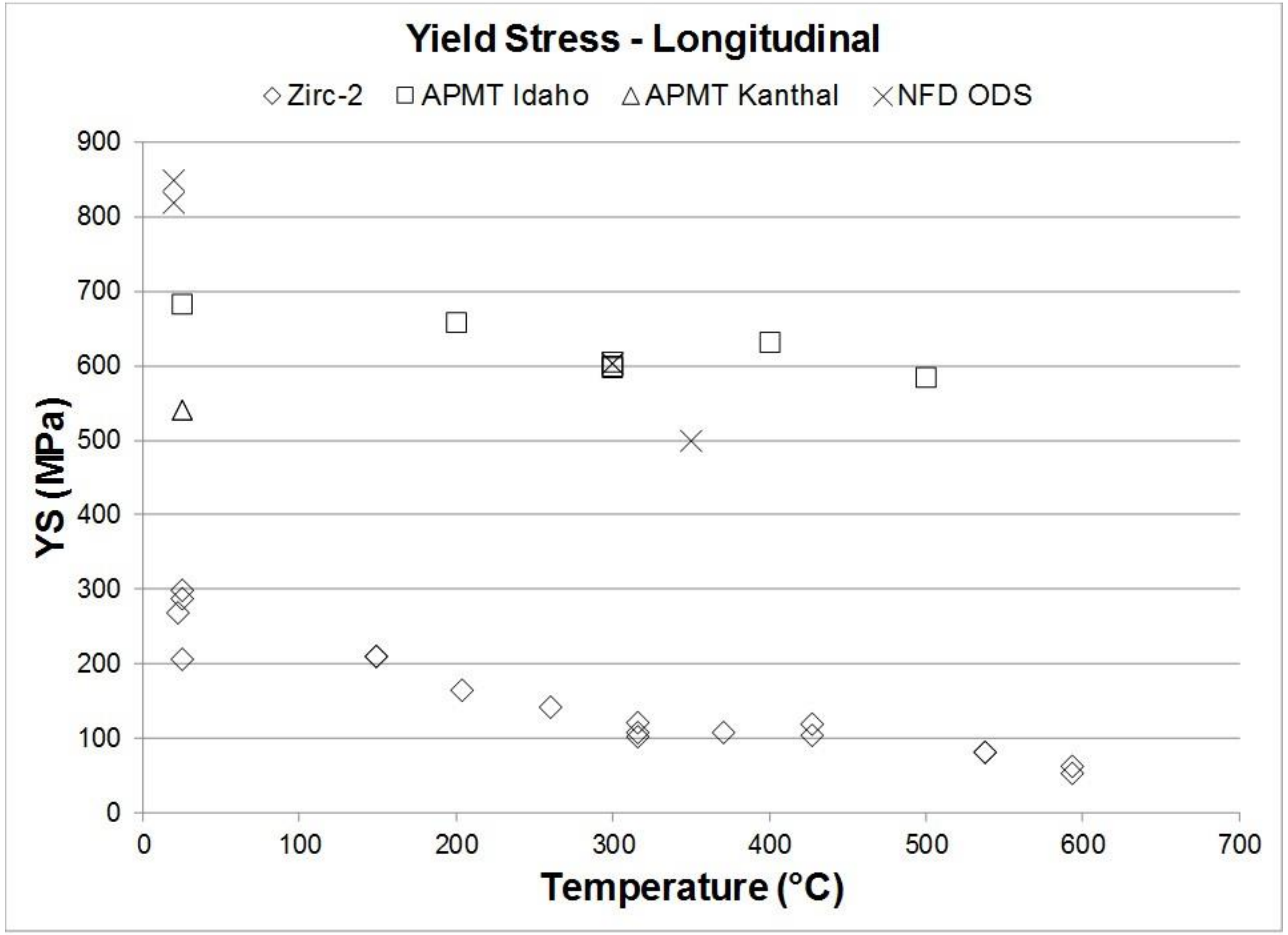
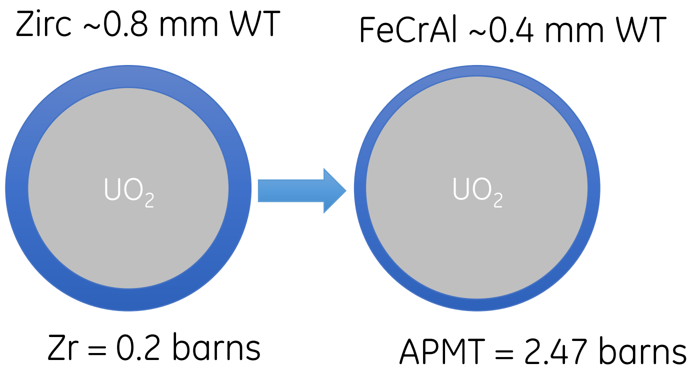
Surface Oxide Evolution on APMT FeCrAl



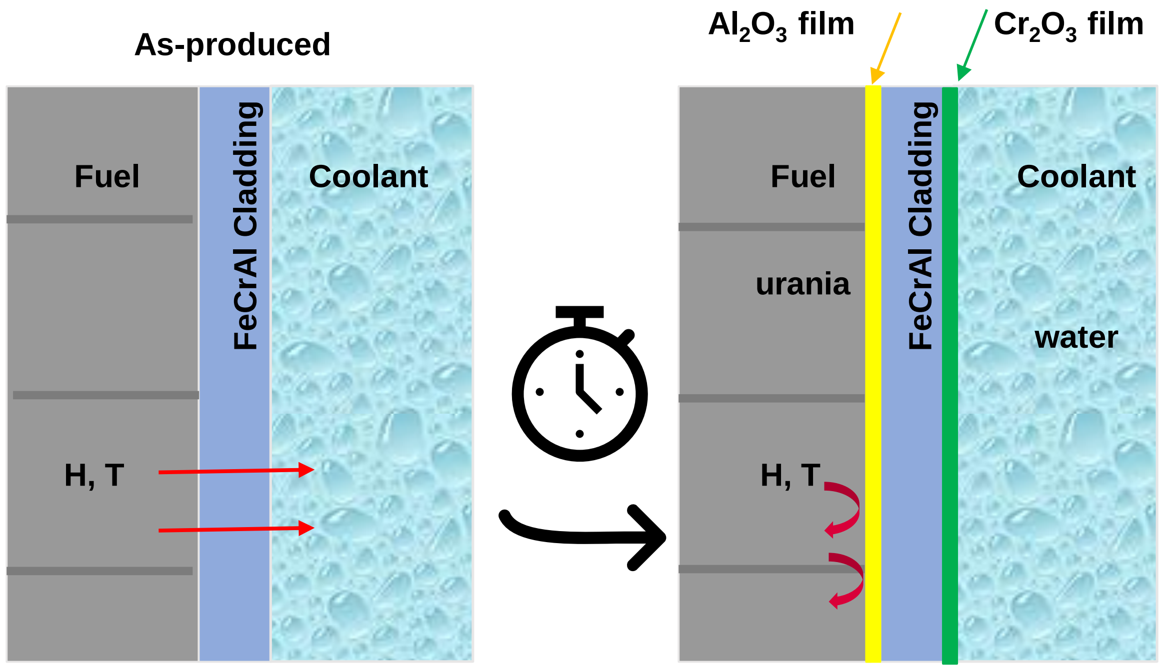
Non-Irradiated Mechanical Properties up to 600°C





Higher initial IronClad strength favorable for fuel performance allows for thinner wall of the cladding.

Radioactive Hydrogen forms in the Fuel and May Migrate through the Cladding Wall into the Coolant.



FeCrAl is ferritic, atomic hydrogen permeates through the wall.
Hydrogen do not form stable hydrides with any of the elements of the cladding.
Surface oxides will minimize hydrogen permeation through the cladding wall.

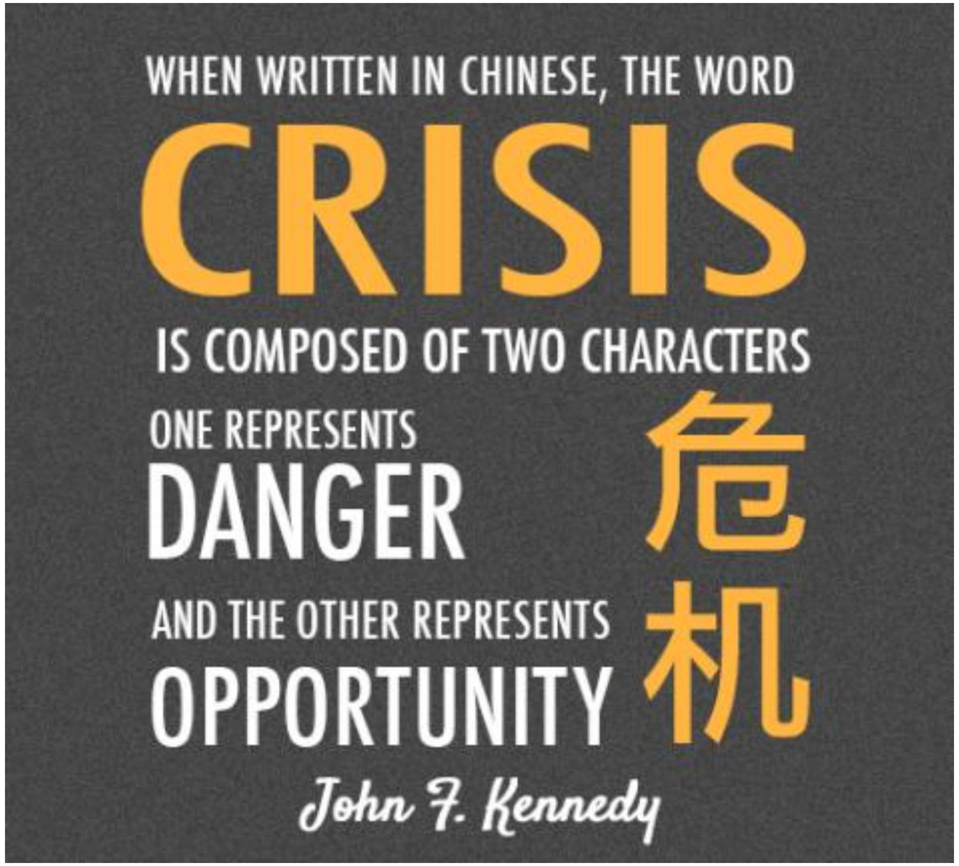
4

Conclusions

Summary and Conclusions

1) The Fukushima Daiichi accident in March 2011 was an unfortunate event; however it re-energized the materials development for nuclear power plants.
2) General Electric (GE) and Oak Ridge National Laboratory (ORNL) are pursuing an accident tolerant fuel (ATF) design concept named IronClad which utilized FeCrAl material for cladding and uranium dioxide (UO_2) fuel pellets.
3) The use of IronClad will greatly improve the safety of plant operation by putting a sturdier primary barrier between the radioactive elements in the fuel and the coolant.
4) The use of IronClad cladding is an advanced ATF concept, which could be implemented in the current fleet of the light water power reactors.
5) GE/GNF and Southern Nuclear completed in February 2018 the first ATF installation of non-fueled rods in a commercial reactor (Hatch-1) for the entire DOE program.

Crisis = Danger & Opportunities



[The word] "crisis" (wēijī) consists of two syllables that are written with two separate characters, wēi and jī.
While it is true that wēijī does indeed mean "crisis" and that the wēi syllable of wēijī does convey the notion of "danger," the jī syllable of wēijī most definitely does not signify "opportunity."
The jī of wēijī, in fact, means something like "incipient moment; crucial point (when something begins or changes)."