POWER UP

NAYGN CAROLINAS REGIONAL CONFERENCE

Plenary #2:

Accident Tolerant Fuel

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Westinghouse EnCore® Accident Tolerant Fuel (ATF) Program

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Duke Carolinas Regional NAYGN Conference

Charlotte, NC

July 25, 2019

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Outline

- Motivation
- Westinghouse ATF Technologies
  - Near Term Solutions
  - Long Term Solutions
  - Timeline for Development and Deployment
- Summary

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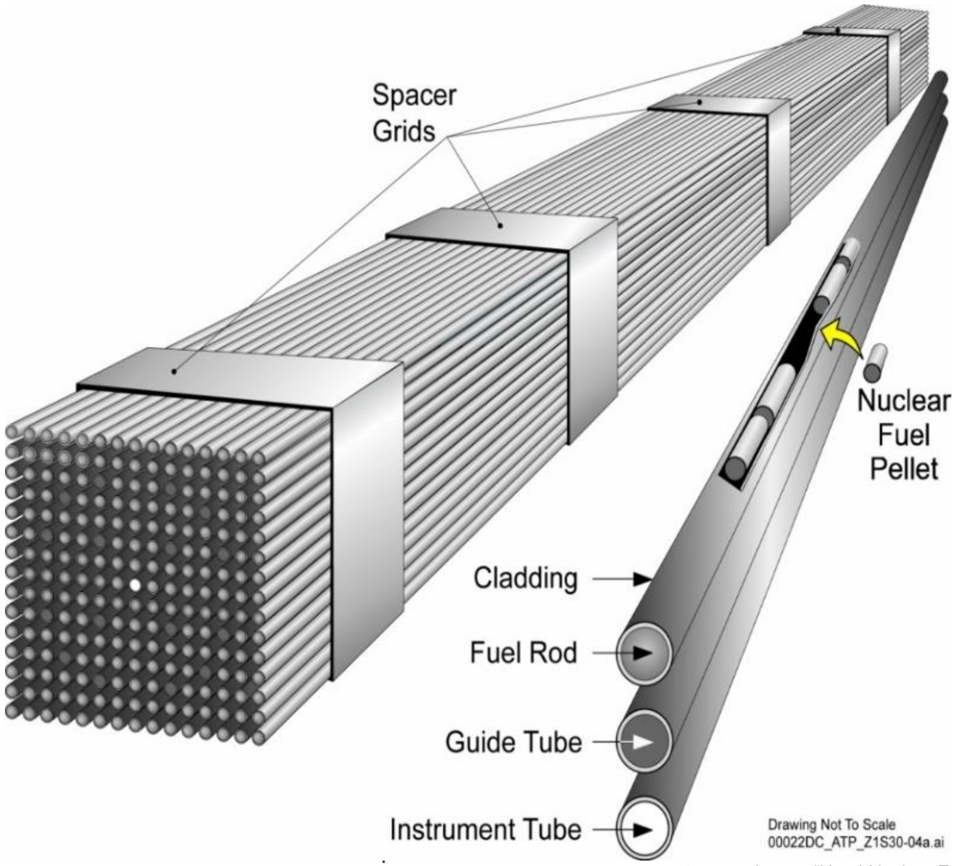
Background

- UO_2 pellets are contained within a Zr alloy cladding tube
- Cladding tubes are arranged in various grid designs
- Each PWR 4 loop reactor core contains 193 fuel assemblies



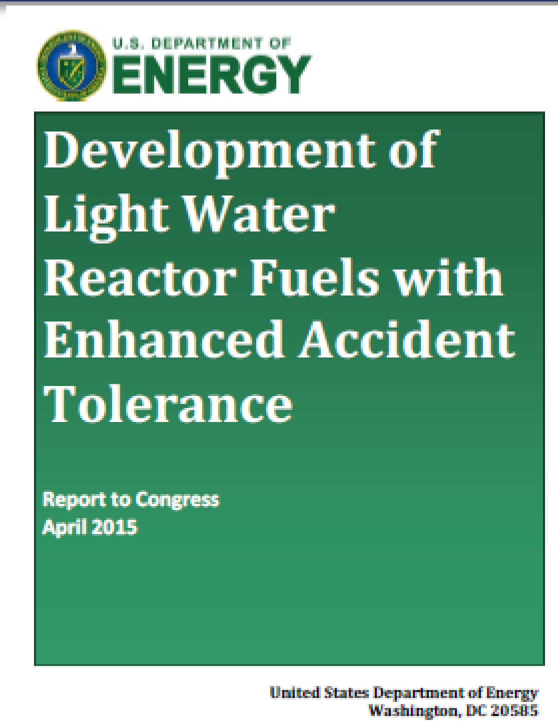
S. Marschman, "Used Nuclear Fuel Storage and Transportation Overview," Idaho National Laboratory, NEET ASI Review Meeting, September 17, 2014.

Motivation

- Highly exothermic reaction of Zr in steam:

$$Zr_{(s)} + 2H_2O_{(g)} \rightarrow ZrO_{2\,(s)} + 2H_{2\,(g)}$$

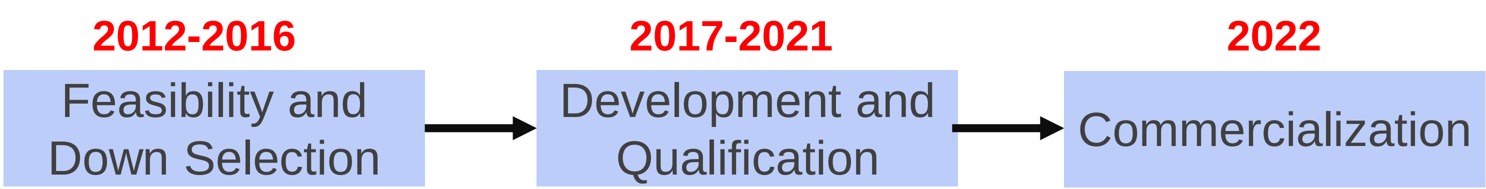
- Following the event at Fukushima Daiichi in 2011, U.S. DOE launched a program for accident tolerant fuel (ATF)
  - Fuels that can tolerate loss of cooling in the reactor core for considerably longer time periods compared to standard Zr-UO_2


U.S. DEPARTMENT OF ENERGY

Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

Report to Congress
April 2015

United States Department of Energy
Washington, DC 20585



Report to Congress, U.S. Department of Energy, "Development of Light Water Reactor Fuels with Enhanced Accident Tolerance," April 2015.

EnCore® Technology Roadmap

Near Term
Beginning
2019

- Continuous optimization and development of near term technologies to support future deployment
- Licensing of near term technologies
- LTR and LTA insertions

Medium Term
Beginning
2023

- Licensing updates of near term technologies and submittals of long term technologies
- Commercial region implementation of near term technologies

Long Term
Beginning
2027

- Commercial region implementation of long term technologies

LTR: lead test rod
LTA: lead test assembly

Westinghouse ATF Program

- Advanced Cladding
  - Chromium coated zirconium – provides oxidation and wear resistance
  - SiC – significantly increases maximum temperature and maintains cladding geometry

- Advanced Fuel
  - ADOPT™ fuel pellets – increase density and reduce pellet-cladding interactions
  - U_3Si_2 fuel pellets - increase thermal conductivity and improve fuel cycle economics

Near Term

Chromium Coated Cladding

ADOPT™ Fuel Pellets

Long Term

Silicon Carbide (SiC) Composite Cladding

Uranium Silicide (U_3Si_2) Pellets

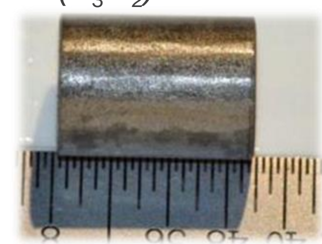


Photo courtesy of Idaho National Laboratory

Product Evolution

Development on track for LTR programs and future region implementation

Near Term Solutions

Chromium Coated Cladding

ADOPT Fuel Pellets

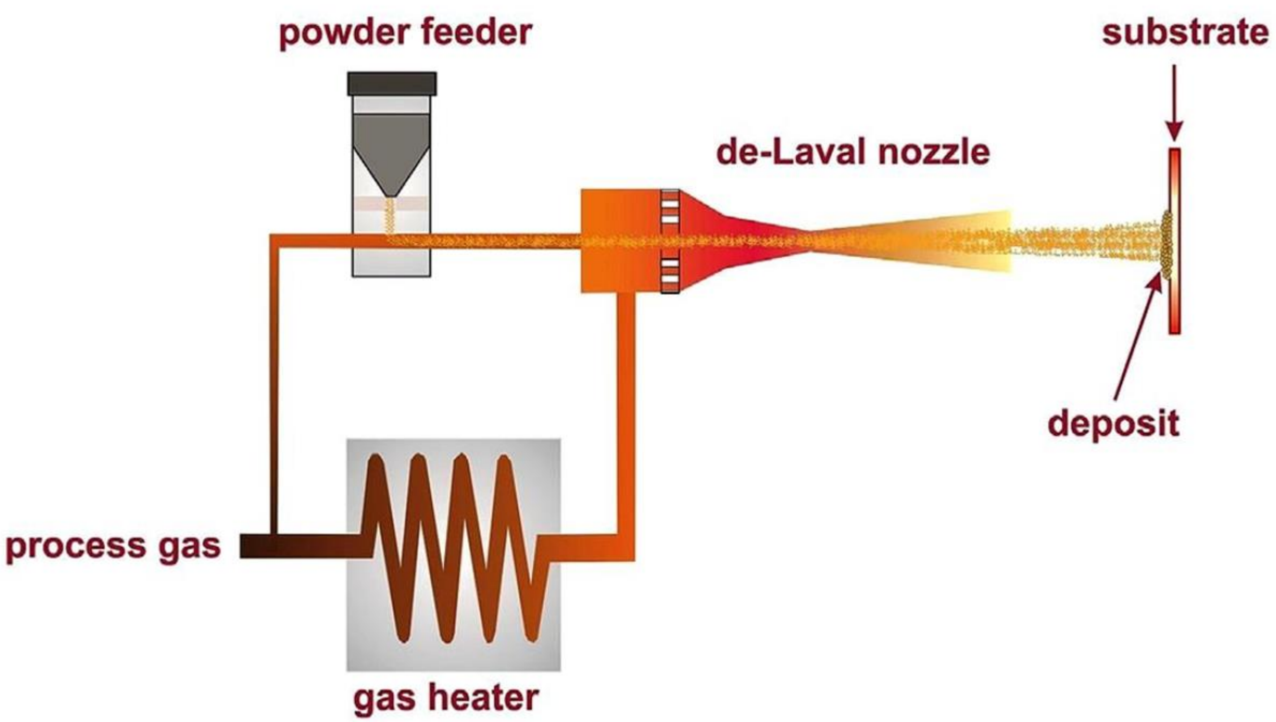
Benefits of Coated Cladding

A cold sprayed chromium coating has been developed to:

- Increase oxidation resistance under normal operating and accident conditions
- Reduce wear due to GTRF or damage due to debris
- Reduce ballooning and burst opening size in LOCA conditions

GTRF: Grid-to-rod fretting
LOCA: Loss of Coolant Accident

Coated Cladding - Cold Spray Process

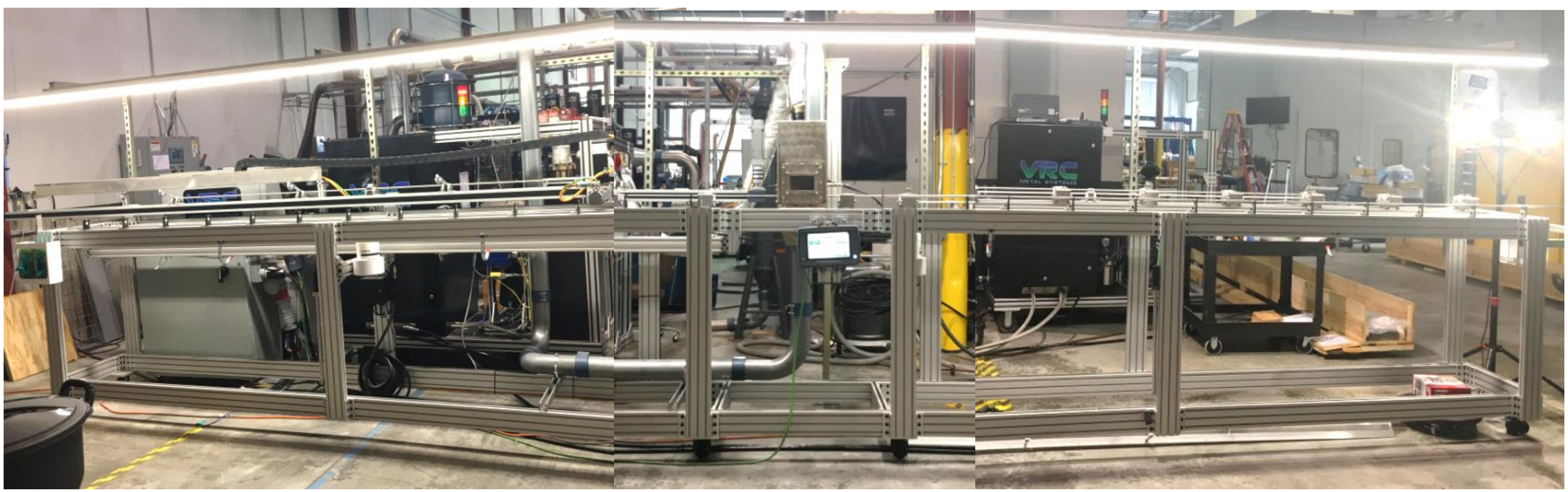


H. Assadi, H. Kreye, F. Gärtner, T. Klassen, "Cold Spraying – A Materials Perspective", Acta Materialia, 116 (2016) 382-407, 27 June 2016.

- Particles deposited in the solid state by a carrier gas of helium or nitrogen
- No need for substrate surface preparation or vacuum capabilities
- High deposition rates for a variety of materials on different substrate geometries

Coated Cladding - Scale-up

- Design and fabrication of scale-up equipment
  - Cladding tubes move relative to static cold spray nozzle
- Cold spraying of full length fuel cladding (~4m long)
  - Scale-up partner VRC Metal Systems
  - Qualification and certification complete



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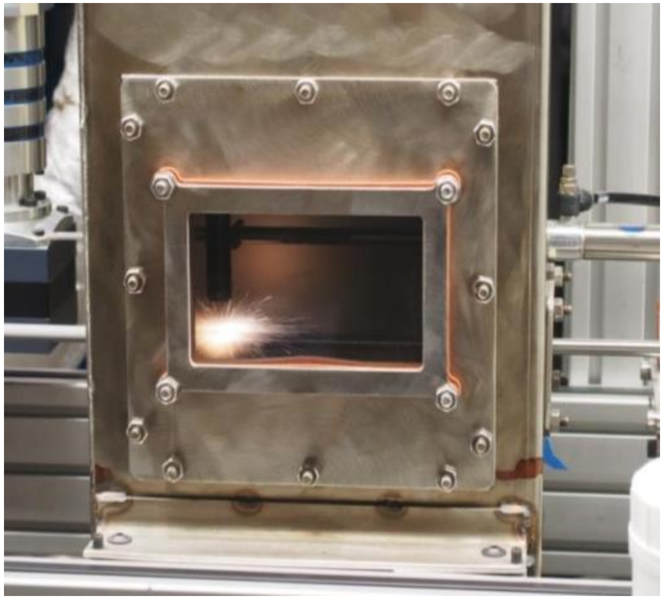
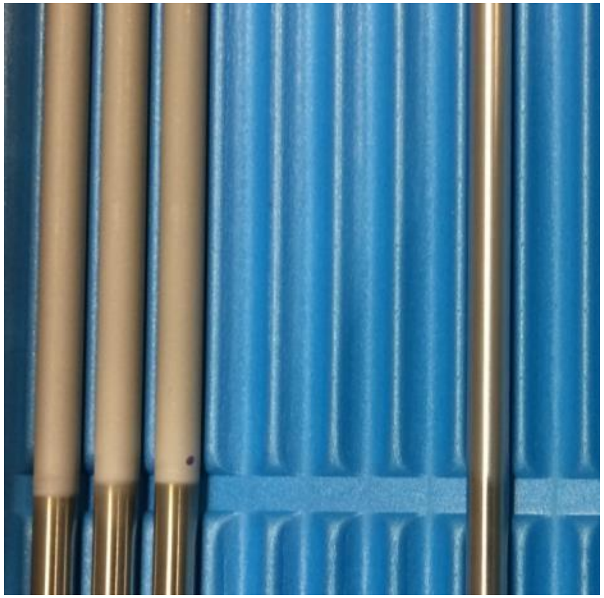
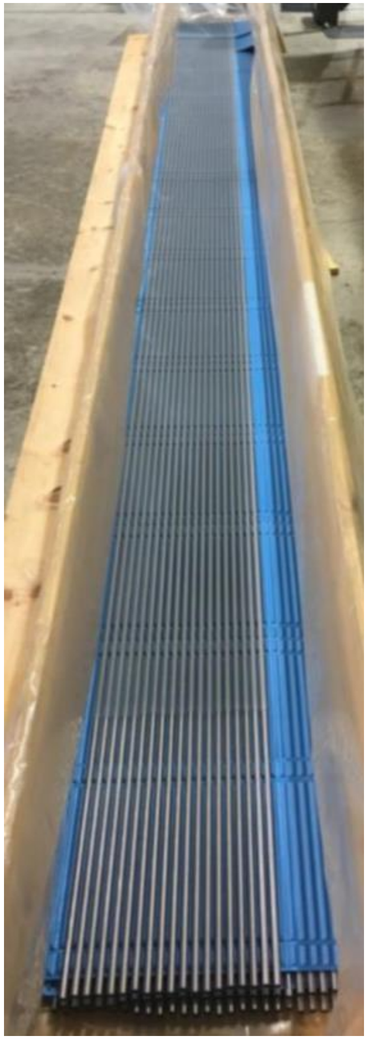
Coated Cladding – In-process Photos


Cold Spray of Full Length Tube


Coated Tubes Before and After Polishing


Lot of Coated Tubes

Successful scale-up process supported LTR insertion in Spring 2019

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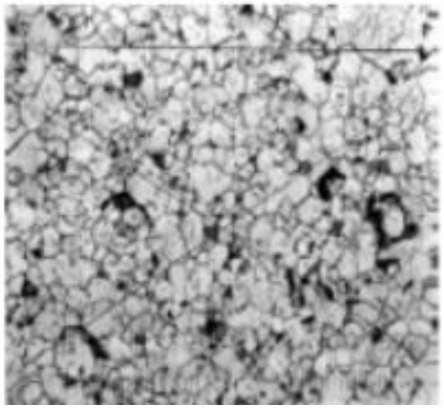
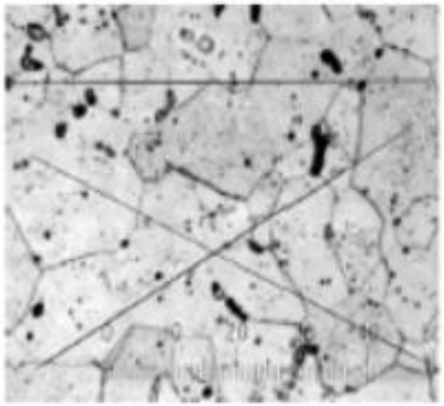
Benefits of ADOPT Fuel Pellets

- Extensive commercial experience in Europe
- Higher density
  - Approximately 10 kg additional U per assembly
- Lower transient FGR at high burnups
- Improved oxidation resistance
- Increased PCI margins at high temperature transients
  - Dopants trap fission products
  - Higher fuel creep rate mitigates PCMI (softer pellet)
  - Unique pellet cracking patterns may relieve cladding stress

Standard pellet
Grain size 9 μm



ADOPT pellet
Grain size 31 μm



FGR: fission gas release
PCI: pellet cladding interaction
PCMI: pellet cladding mechanical interaction

Long Term Solutions

SiC Cladding

U_3Si_2 Fuel Pellets

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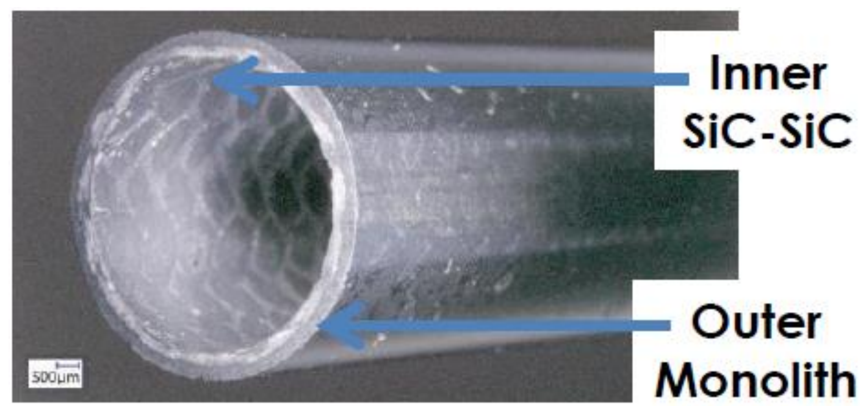
SiGA™ SiC Cladding

- Oxidation kinetics are orders of magnitude lower than Zr
  - Eliminate oxidation driven temperature spikes
- Extremely high melting point enables cladding to contain fission products and maintain coolable geometry
- Minimal and predictable swelling under irradiation
- Eliminates fretting wear to cladding
- Potential fuel cycle cost savings



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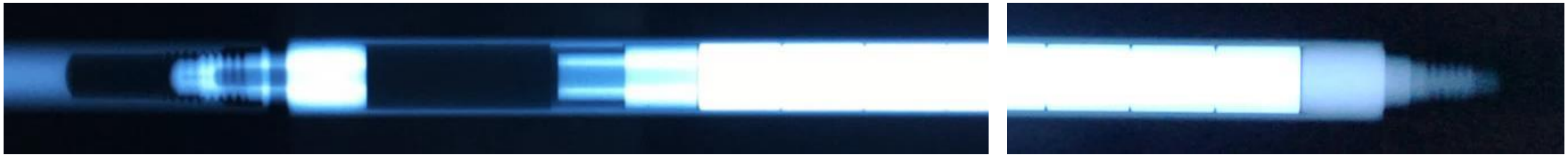
GENERAL ATOMICS

Physical Benefits of U_3Si_2 Pellets

- 17% more uranium with <5% enrichment
  - Driver of fuel economics → reduced batch size, longer cycles, or lower enrichments to support current cycle lengths
- Higher thermal conductivity
  - Resistant to fuel centerline melting during transients
- Good irradiation behavior
  - Reduced swelling and FGR
  - Minimal stress on cladding to increase PCI margin



X-ray image of U_3Si_2 fuel segment built for Byron LTR

FGR: fission gas release
PCI: pellet cladding interaction

Summary

- Customer interest for:
  - Safety benefits
  - Longer cycles enabling higher burnup
    - Potential link with industry initiative for high enrichment UO_2 pellets
  - Debris and wear resistance benefits
- Development and optimization of advanced cladding and fuel ATF technologies on track to support industry demand for deployment
- Licensing underway

EnCore® Fuel

We're changing nuclear energy … again

Westinghouse

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Enhanced Accident Tolerant Fuel Program

Jeffrey Reed
Program Director, Advanced Fuel Development

NAYGN Conference
July 25, 2019
Charlotte, NC

www.nextevolutionfuel.com

Acknowledgement

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ATF Phase-2 Success Criteria

- **Develop Fuel products that deliver positive safety impact for the current fleet of operating reactors**
  - **Can tolerate loss of active cooling in the reactor core for a considerably longer period of time than conventional fuel**
  - **Maintains or improves fuel performance during normal operations, operational transients, design basis events and beyond design basis events**
- **Implement licensing and regulatory changes to improve operating limits or margins**
- **Acceptance by the utilities**

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Framatome Solutions

- Near Term Solution:
  - Chromium-coated cladding
  - Chromia-doped fuel
- Long Term Solution:
  - Silicon carbide cladding

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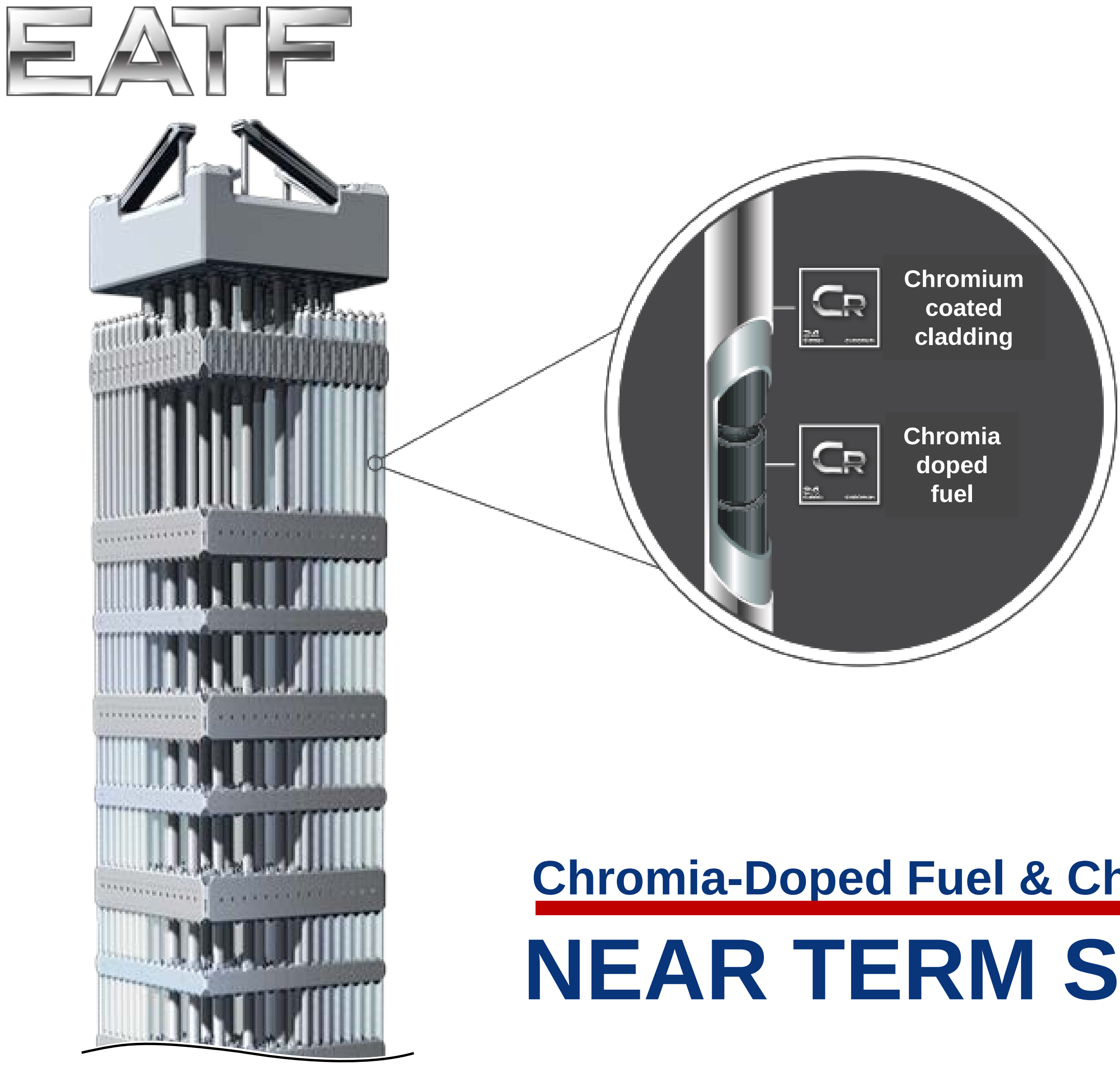

Chromia-Doped Fuel & Chromium-Coated Clad

NEAR TERM SOLUTION

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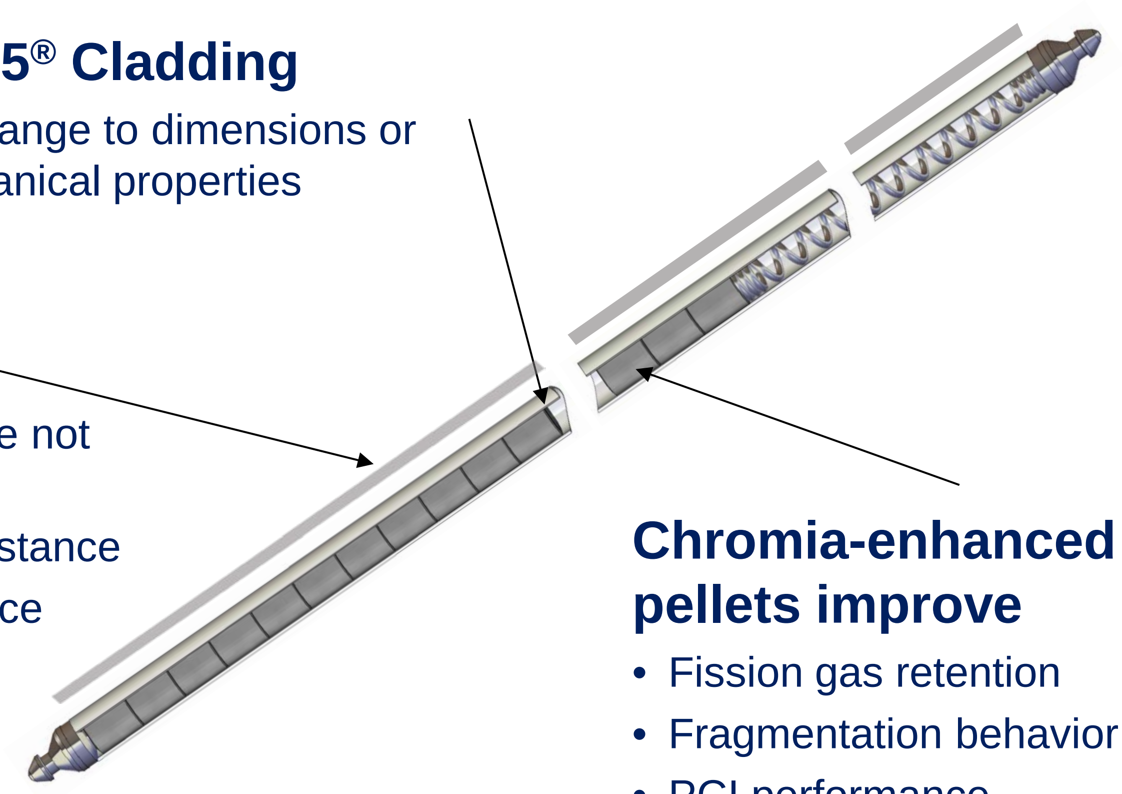
$Cr\text{-}Cr_2O_3$ EATF Concept Global View



Base M5® Cladding

- No change to dimensions or mechanical properties

Cr-coating

- 10-20 µm
- Base M5® properties are not altered
- Improved oxidation resistance
- Improved wear resistance

Chromia-enhanced UO_2 pellets improve

- Fission gas retention
- Fragmentation behavior
- PCI performance
- Wash-out behavior

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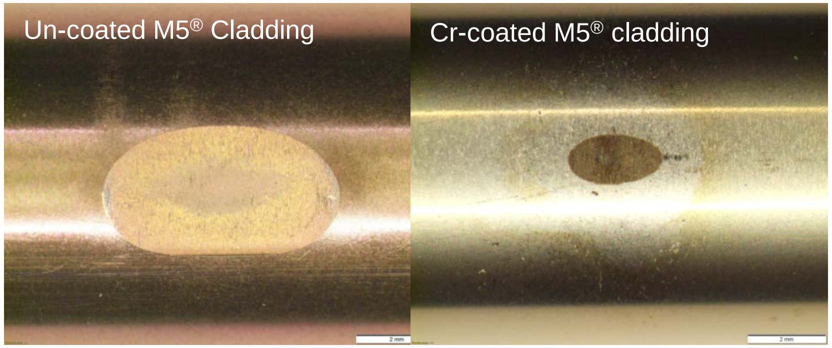
EATF

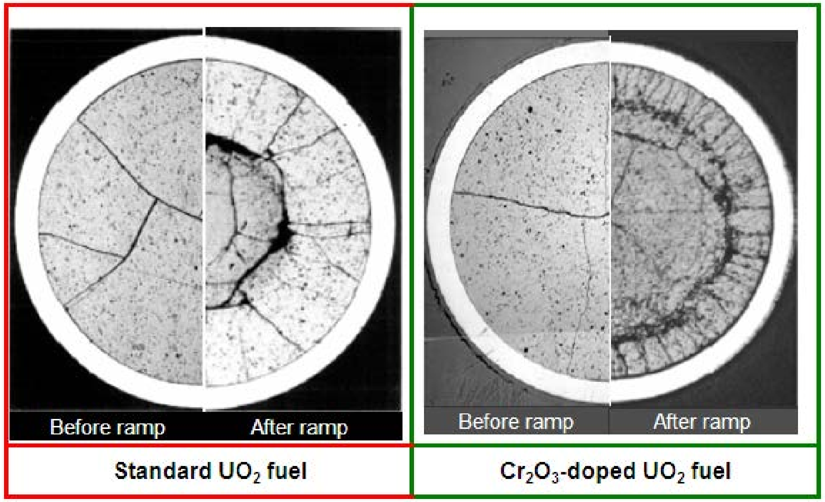
Normal Operations & AOO

Cr-Coatings (optimized PVD) and Cr_2O_3-Enhanced Pellets Potential Benefits

- Compatible with current FA designs
- Improved wear resistance – Reduced fuel failures due to debris
- Increased Ramp Rates – Reduced PCI
- Improved corrosion & oxidation resistance
- Extended partial power operations
- Reduced Fission Gas Release



Improved wear resistance



Reduced stress concentrations on the cladding

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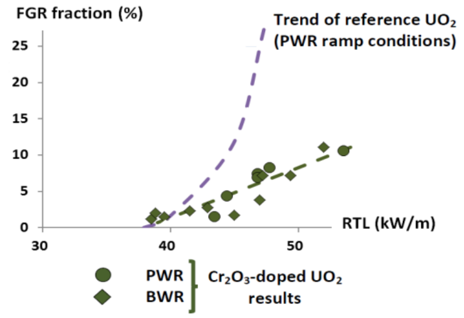
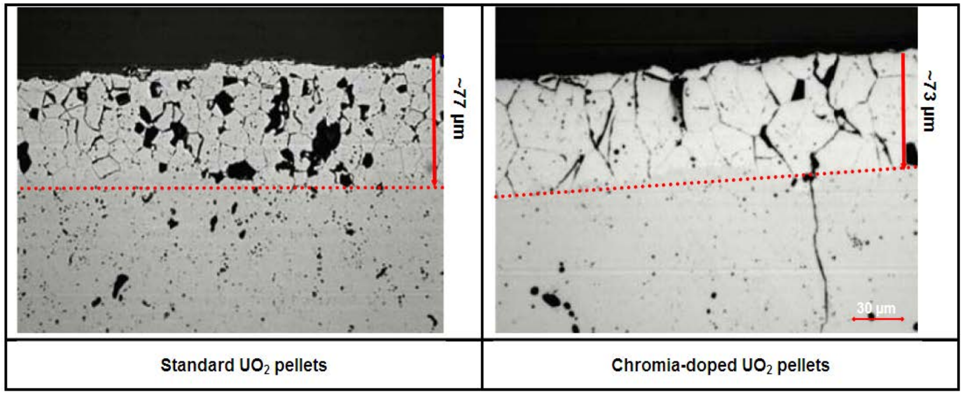
Behavior During Accidents

- **Postulated Accidents (Design Basis Accidents)**
  - Improved corrosion & oxidation resistance
  - Delayed onset and reduced Hydrogen production
  - Reduced Fission Gas Release
  - Reduced ballooning
- **Severe Accidents (Beyond DBA)**
  - Reduced fuel dispersal during accident
  - Improved Wash-Out behavior – lowers activity release in defective rods



Improved FGR kinetics

Improved clad swelling and rupture performance



Improved Wash-Out behavior lowers activity release in defective Rods

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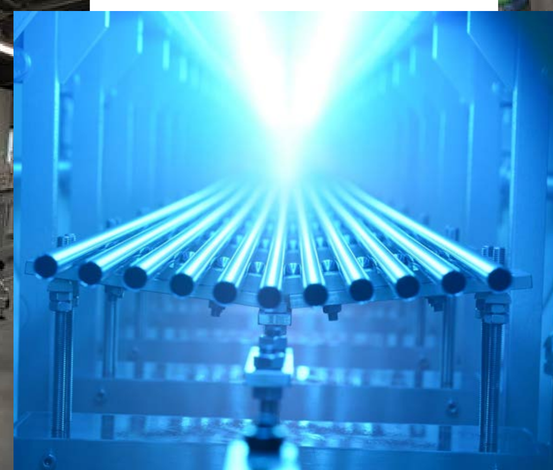
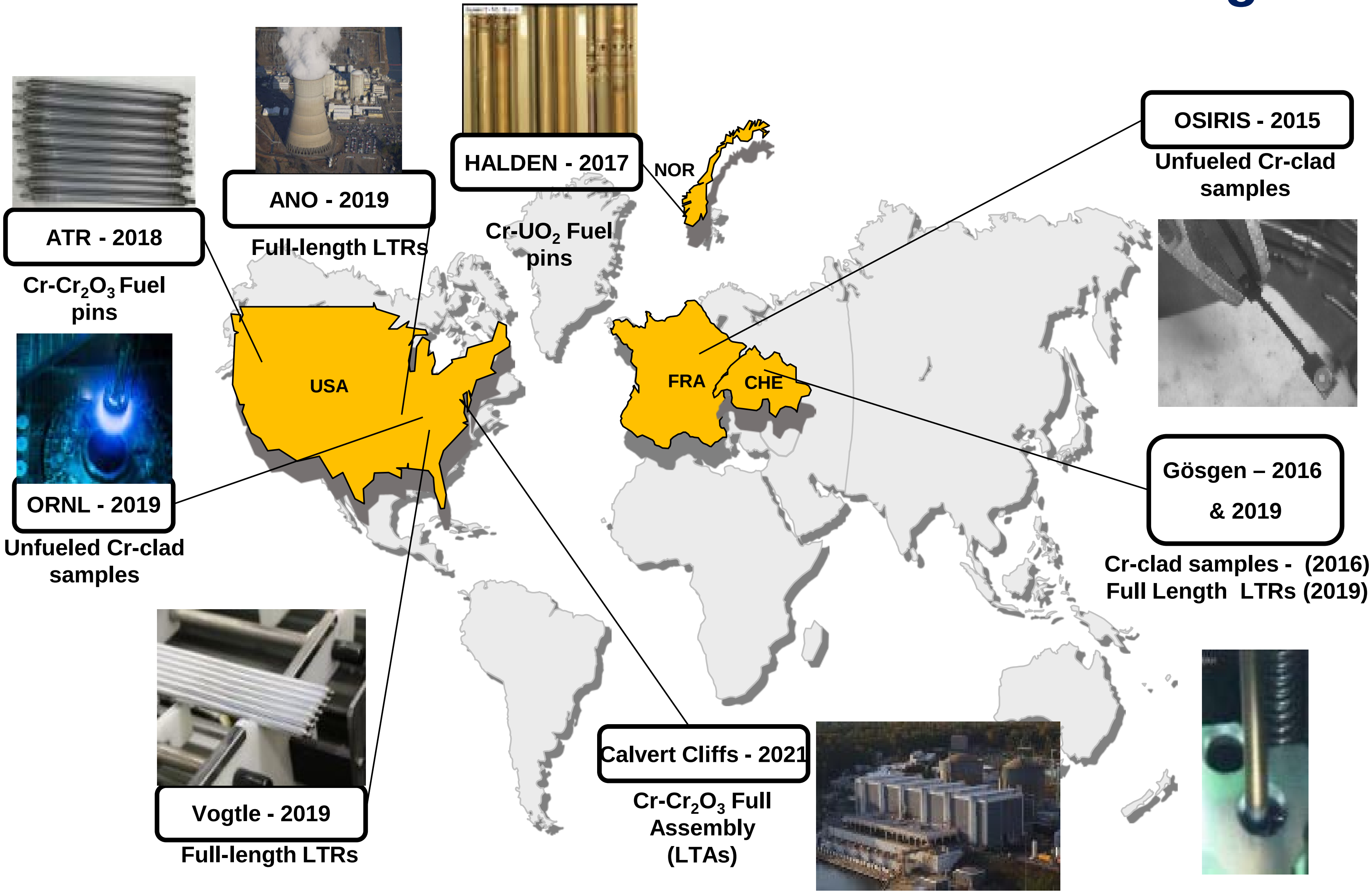
Status Update
Chromium-Coated Cladding

Manufacturing

- Prototype equipment built, coats 10 tubes per batch
- Process optimized and qualified Spring 2018
- Vogtle Lead Rods completed Fall 2018
- ANO Lead Rods completed Spring 2019
- CCL production to begin summer 2019 for 2021 delivery



Cr-Clad Irradiation Program



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Long Term Solution

Silicon Carbide based Cladding

Different Cladding Options / SiC/SiC

Silicon Carbide is an example of a different fuel rod material that can be developed with different techniques and properties

Introduces a Much Different Rod Material

- New Behaviors
- New Challenges

SiC Cladding
Why Silicon Carbide?

Benefits over zirconium based cladding

- Smaller neutron absorption cross-section
- Resistance to high temperature steam oxidation
- Exceptional irradiation resistance
- Withstands high burnups and high operation temperatures
- Minimal activation
- Stable in nuclear waste

SiC Cladding Technical Challenges

Hydrothermal Corrosion
- Unacceptable rate of mass loss in LWR coolant
- Protective layer on the surface
- Modifications to LWR coolant chemistry

Hermeticity
- Issues with containment of gaseous fission products
- Monolithic layer (inside or outside)
- Metallic Liner

Joining Methods
- Should withstand the irradiation and corrosive environments
- Screw type end-plug
- Brazing / Diffusion bonding
- Metallic Liner

Design & Fabrication
- Optimized structure & Scalable fabrication method
- Requires a larger production facility – uniformity in temperature distribution and reactant flow condition along the full length tube
- Thin and uniform layer (<600 microns for mono-layer, <300 for multi-layer) on full length tube
- Compatibility of densification chemistry with metallic liner material

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$Cr\text{-}Cr_2O_3$ EATF Concept Delivering Value

- **All research conducted thus far supports continued study and development of these concepts so that a complete and robust solution providing the benefits identified by industry can be delivered in the needed timeframe.**

- **Recent Congressional budget approval supports an increase in DOE program funding level required to stay on target for 2025 Batch Reload readiness.**

- **Coordinated approach by NEI, EPRI, Vendors, NRC, DOE and the Utilities is required to be successful in streamlining the licensing process.**

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ATF
The Next Generation of Nuclear Fuel

Presented to: Duke Energy NAYGN Conference

July 25, 2019






Robert St.Clair
Manager, Oconee Nuclear Design

DUKE ENERGY®

ATF – The next advancement in nuclear fuel

- Who is developing ATF?

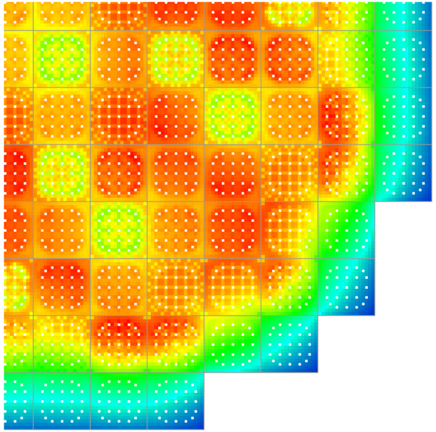
- U.S. Efforts lead development and testing (Gov't. and industry)
- International Efforts coordinated by Organization for Economic Cooperation and Development, Nuclear Energy Agency in Paris

- What are the goals of ATF?
  - Increased "coping time", time without cooling prior to clad melt
  - Minimize/Eliminate Hydrogen production
  - Retain fission products in the fuel

ATF – The next advancement in nuclear fuel

- Implementation of “lessons-learned” improve plants that are already very safe. Why introduce the uncertainty of a new fuel design and/or material to make them even safer?

- Additional benefits of ATF?



- Potential to eliminate backup/redundant power and cooling capability
  - » Less Equipment to purchase, maintain, and test periodically
- Lower fuel costs
  - » Increased Uranium “loading” or density improves core design efficiency
  - » Higher thermal limits improve core design efficiency and ability to load follow with nuclear plants
  - » Higher fuel enrichment and burnup limits provide additional fuel cycle efficiency and reduce waste

ATF – The next advancement in nuclear fuel

- What are the next steps?

- Complete preliminary cost benefit analyses
- Continue irradiation and transient testing
- Refine designs
- Complete irradiation and examination of Lead Test Rods/Assemblies in commercial reactors
- Finalize manufacturing capabilities
- License with the NRC

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