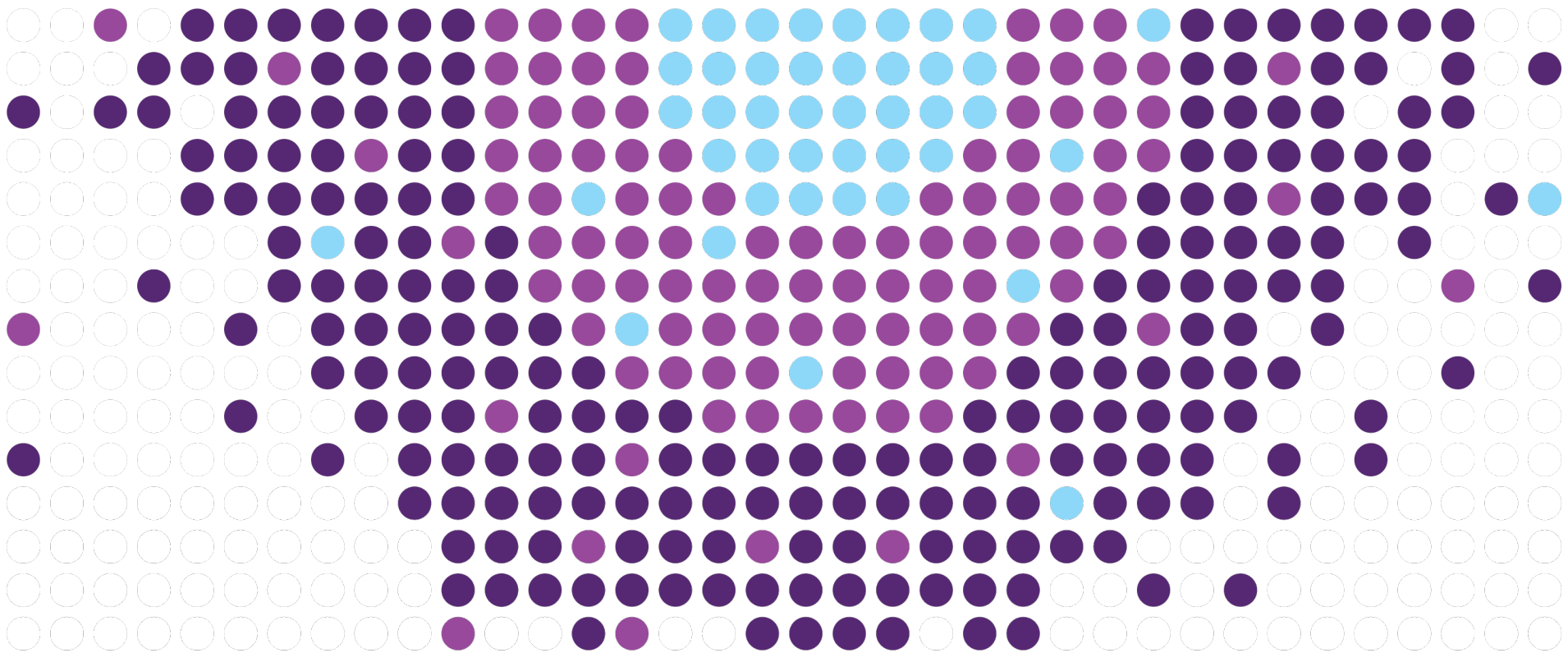


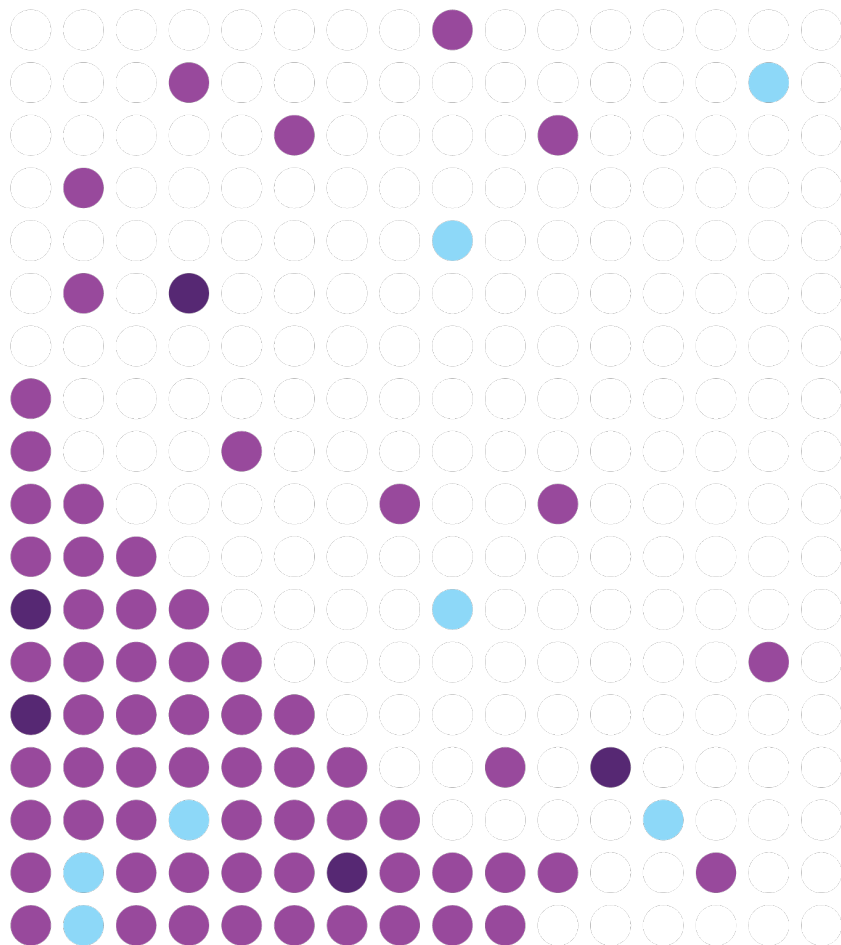


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Belgian Nuclear Research Centre

Dr. Ir. Joris Van den Bosch, MBA - 27/02/2025

From Accident Tolerant Fuel to Advanced Technology Fuel

Contributions by K. Pasamemetoglu INL, A. Nelson, ORNL, S. Gavrilov, M. Verwerft, SCK CEN



Introduction & Definitions
ATF Concepts
Material Candidates
Qualification & Licensing
Economics & Future outlook
Conclusions
Q&A

ATF Common Knowledge

The screenshot shows a Windows desktop with a taskbar at the bottom containing icons for various applications like File Explorer, PowerPoint, and Google Chrome. The main window is the Wikipedia page for "ATF (disambiguation)". The browser's address bar shows the URL "en.wikipedia.org/wiki/ATF_(disambiguation)". The Wikipedia page has a standard layout with a search bar at the top, a table of contents on the left, and the main article content on the right. The article title is "ATF (disambiguation)" with a language dropdown set to "19 languages". Below the title, there are tabs for "Article" and "Talk", and links for "Read", "Edit", "View history", and "Tools". The main text explains that ATF is the Bureau of Alcohol, Tobacco, Firearms and Explosives, a federal law enforcement organization within the US Department of Justice. It also lists other uses of the acronym ATF, categorized into Organizations, Places, and Science and technology. The Organizations section lists: American Type Founders, Anti-Terrorism Squad, As Trustee For, Asia Task Force, Asian Tennis Federation, and Atlantic Theatre Festival. The Places section lists: French Southern and Antarctic Lands and Chachoan Airport. The Science and technology section lists: Anatomical transfer function.

en.wikipedia.org/wiki/ATF_(disambiguation)

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ATF (disambiguation)

19 languages

Article Talk

Read Edit View history Tools

From Wikipedia, the free encyclopedia

The **Bureau of Alcohol, Tobacco, Firearms and Explosives** is a federal law enforcement organization within the US Department of Justice.

ATF may also refer to:

Organizations

- American Type Founders**, former dominant American manufacturer of metal type
- Anti-Terrorism Squad**, counterterrorism units of police departments in India
- As Trustee For*, a legal term for an entity acting as a trustee; see **Trust law**
- Asia Task Force**, a committee of UK businesses, informing the UK response to globalisation
- Asian Tennis Federation**, a continental body of national tennis associations of Asian countries
- Atlantic Theatre Festival**, a professional theatre company located in Wolfville, Nova Scotia, Canada

Places

- French Southern and Antarctic Lands** (ISO 3166 country code)
- Chachoan Airport** (IATA code), Ambato, Ecuador

Science and technology

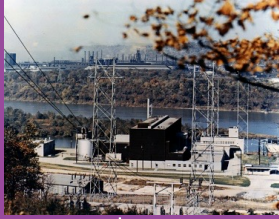
- Anatomical transfer function**, the mathematical description of sound wave propagation through the human body



U.S. Navy

Decision to use
Zr cladding in
nuclear
submarines

1946



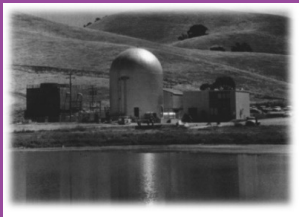
Shippingport PWR

Fuel rod:
UO₂ / Zircaloy-2

1957

Vallecitos Boiling Water Reactor

Fuel plate:
UO₂ / 304 SS



TMI2

1979

2011

Fukushima



2020

**EnCore™ ATF Fuel
ADOPT™
(Al₂O₃+Cr₂O₃ doped
fuel) +
Cr coated Zr
Installed in Doel 4**



2025

**Commercial
offer ATF**

...

Evolution of Zirconium Alloys for Nuclear Cladding

SS for cladding (50s-80s)

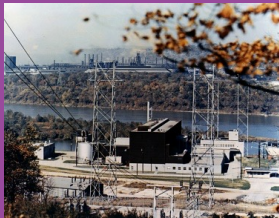
Development of alternative cladding

Development of coating for Zr cladding-coolant interface



U.S. Navy

Decision to use Zr cladding in nuclear submarines



Shippingport PWR
Fuel rod:
UO₂ / Zircaloy-2

TMI2

1946

1957

1962

1979

2011

2020

2025

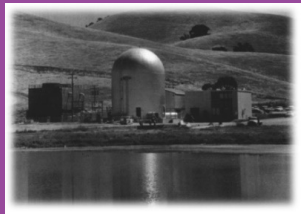
...

Vallecitos Boiling Water Reactor
Fuel plate:
UO₂ / 304 SS

BR3 PWR (SCK CEN)
Fuel rod:
UO₂ /
Stainless Steel

Fukushima

EnCore™ ATF Fuel ADOPT™
(Al₂O₃+Cr₂O₃ doped fuel) +
Cr coated Zr
Installed in Doel 4



sck cen

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altenative reference

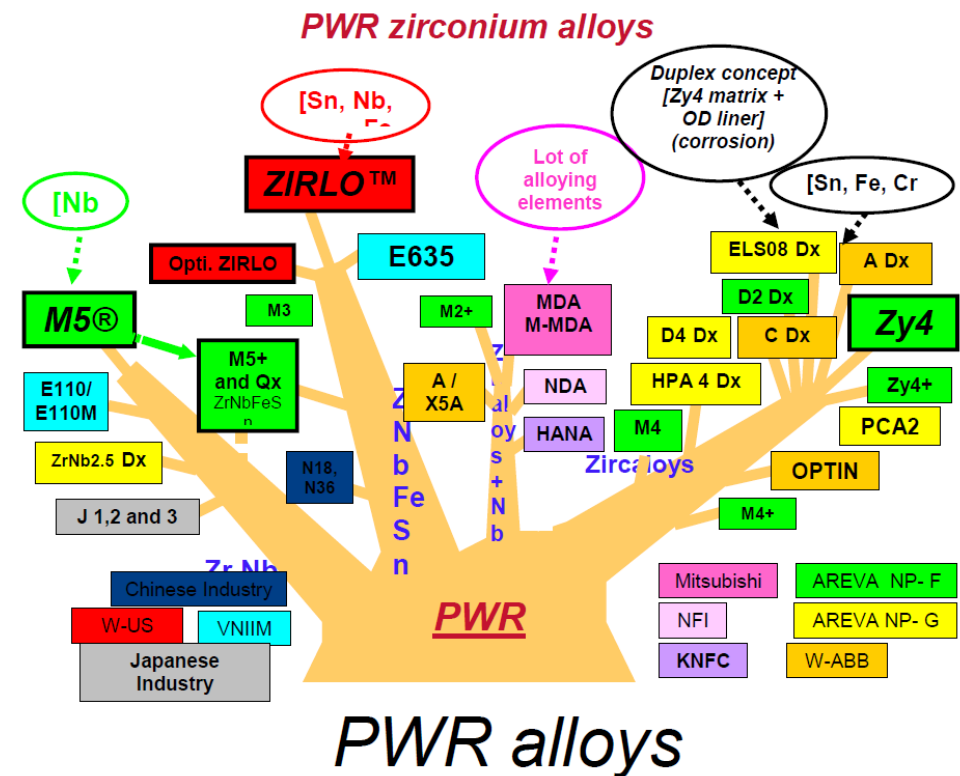
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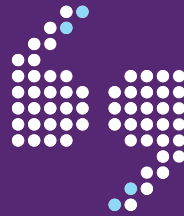
ISC: Restricted

Evolution of Zirconium Alloys for Nuclear Cladding

From Early Challenges to Modern Success

- Early Challenges: Aluminum Limitations and Pure Zirconium Corrosion
- Breakthroughs: Zircaloy-2 and Beyond
- 90's – 2010:
 - higher capacity factors, burnup, power;
 - improved QA;
 - zero leakage programs -> optimization & qualification of new Zr-based alloys;
- Modern Achievements: Enhanced Performance and Safety





Traditional fuel systems UO_2 / Zr alloy cladding are

- highly effective with superb performance and
- accident tolerant for postulated accidents (DBA)

But...

Severe accidents beyond DBA



TMI2
1979

- Core overheating
- Zirconium-steam reaction:
 - Hydrogen gas
 - Additional heat
- Core meltdown
- Radioactive release



Fukushima
2011

- Core overheating
- Zirconium-steam reaction:
 - Hydrogen gas
 - Additional heat
- Cladding failure / Fuel degradation
- Hydrogen explosions
- Radioactive release

ATF initiating event?

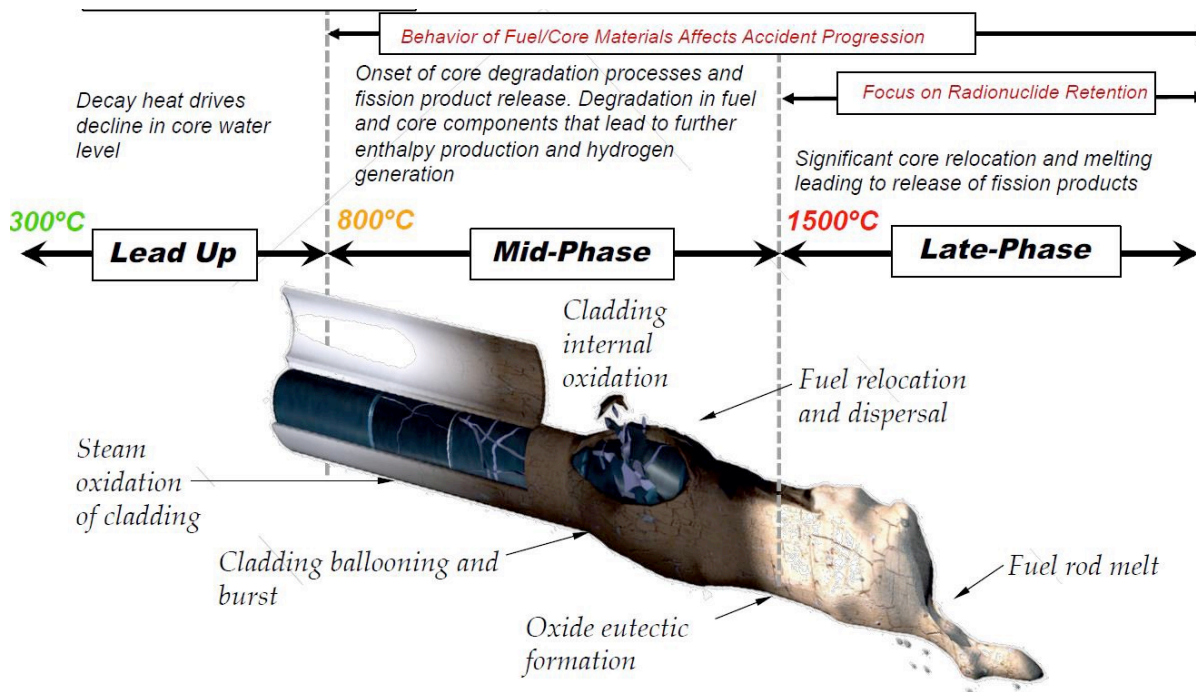
Fukushima Daiichi

- ▶ ~3/4 of the core exposed
 - ◆ Cladding exceeds ~1200°C
 - ◆ Zirconium in the cladding starts to burn under Steam atmosphere
 - ◆ $\text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2$
 - ◆ Exothermal reaction further heats the core
 - ◆ Generation of hydrogen
 - Unit 1: 300-600kg
 - Unit 2/3: 300-1000kg
 - ◆ Hydrogen gets pushed via the wet-well, the wet-well vacuum breakers into the dry-well





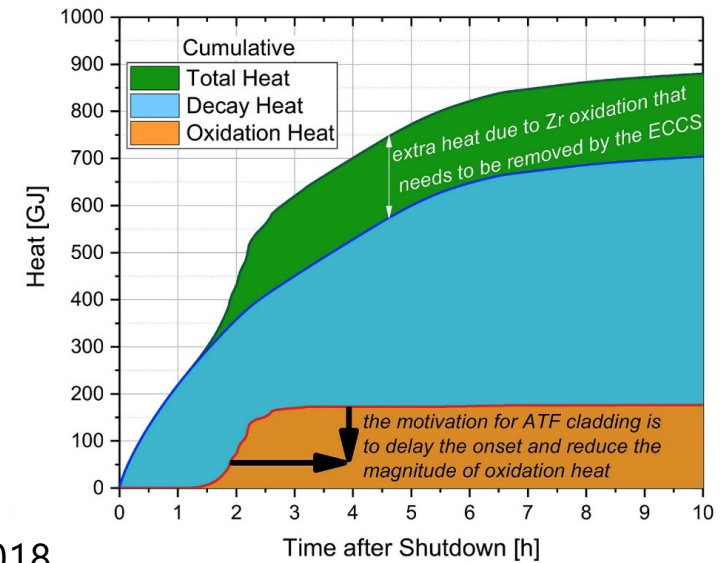
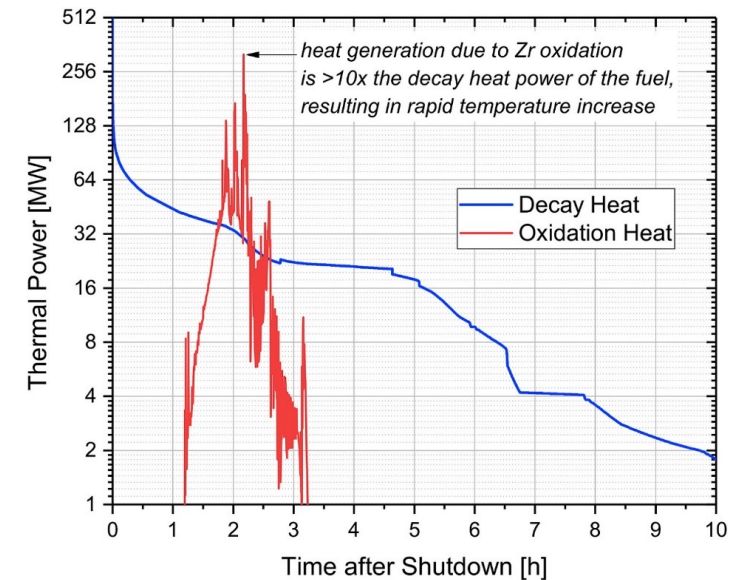
Highly exothermic reaction



1 FA = 125kg Zr = 820MJ heat + 2700 mols of hydrogen

LWR cores: 20-50 tones of Zr

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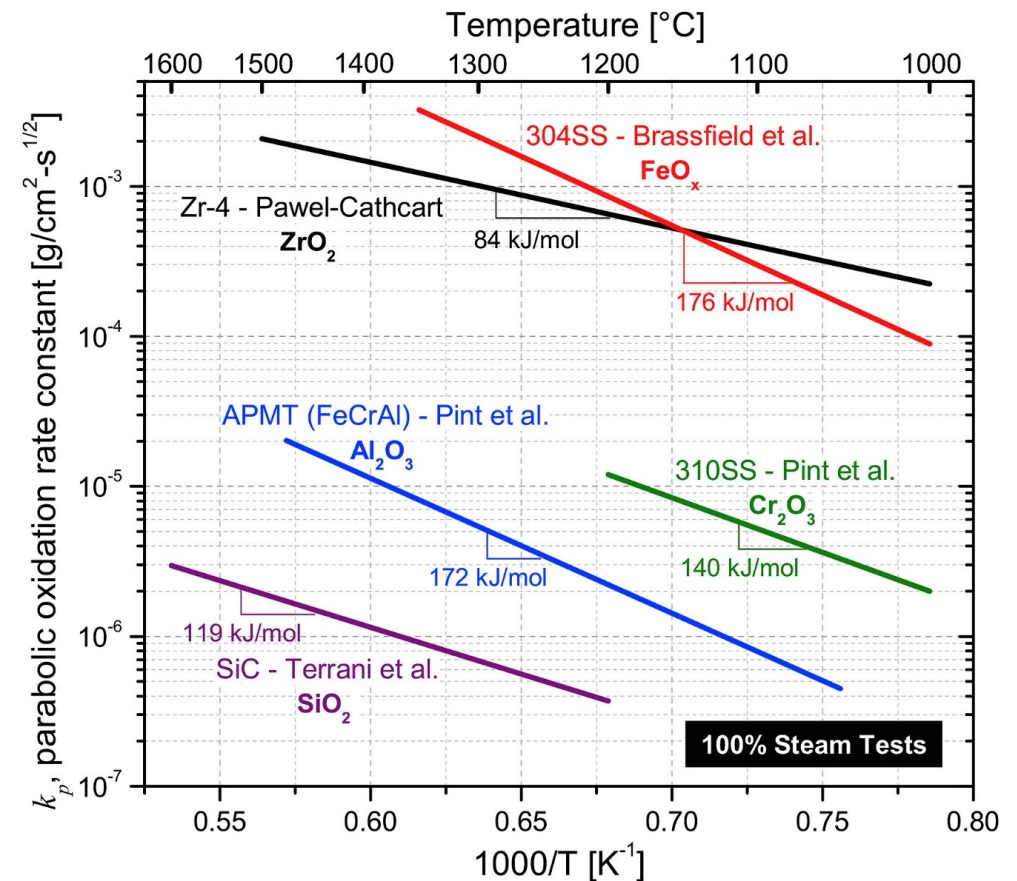


Terrani, JNM, 2018

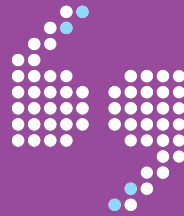
Enhancing the accident tolerance

Goal to reduce exothermic HT oxidation reaction with corresponding H release -> additional time to handle the event

- SiO_2 , Al_2O_3 , Cr_2O_3
- Materials:
 - Cr-based coating
 - FeCrAl alloy
 - SiC/SiC
 - Mo alloys
 - MAX phases



The parabolic oxidation rate of various cladding materials and their resulting oxides in high temperature steam.



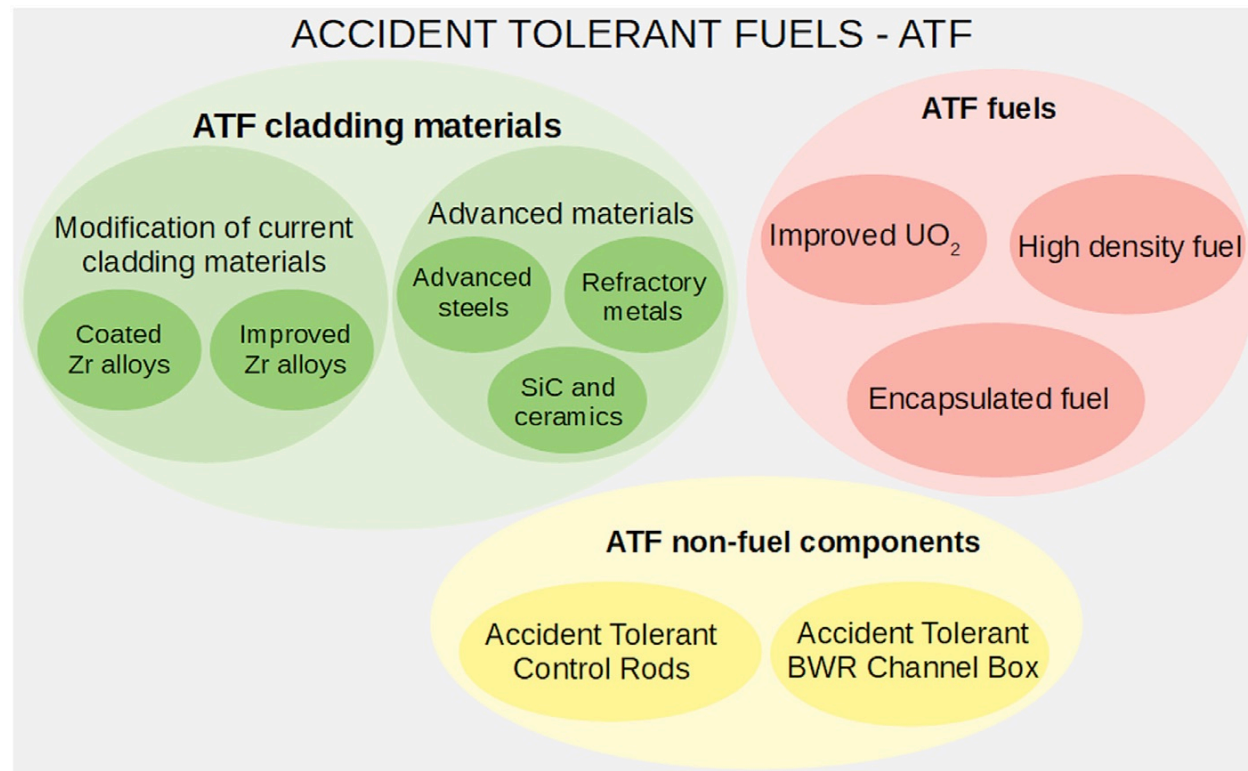
Nuclear fuels that can tolerate a severe accident in the reactor core for a longer time period than the current $\text{UO}_2\text{--Zr}$ alloy fuel system, while maintaining or improving the fuel performance during normal operations and operational transients

ATF according to OECD/NEA

Accident Tolerant Fuels key features

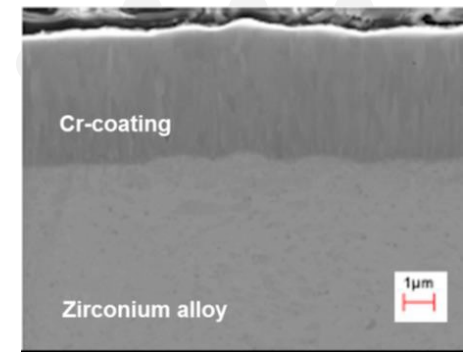
- **Enhanced Safety Margins:** ATFs are engineered to maintain structural integrity and prevent significant hydrogen production during severe accidents, thereby extending the coping time for operators to restore cooling systems
- **Improved Materials:** ATFs often feature advanced cladding materials such as chromium-coated zirconium alloys, FeCrAl alloys, and SiC composites, which offer superior oxidation resistance and reduced hydrogen generation compared to traditional zirconium alloys
- **Advanced Fuel Pellets:** Some ATFs incorporate doped uranium dioxide or other high-density fuel materials to enhance thermal conductivity and neutron economy, potentially allowing for longer fuel cycles
- **Compatibility with Existing Infrastructure:** ATFs are designed to be compatible with current reactor designs and fuel cycles, making them a viable upgrade for existing fleets
- **Economic Benefits:** By potentially reducing the need for redundant safety systems and extending fuel cycles, ATFs can offer economic advantages alongside improved safety

Classification of ATF concepts under development



Chromium-coated zirconium alloy cladding

- Chromium-coated zirconium alloy cladding
 - Vendors:
 - Westinghouse (EnCore™), Framatome (PROtect), GNF (ARMOR)
 - TRL: High (7-8)
 - Status: Lead test rods have been irradiated in commercial reactors and are undergoing post-irradiation examination
- Minor modification of existing fuel
- Improved corrosion and oxidation behaviour,
- Harder surface providing better resistance to fretting wear,
- Near term, e.g. loaded in Doel 4 in 2020
- Eutectic interaction between Cr and Zr at around 1330°C
- Economic benefits are to be confirmed



PVD coating by Framatome (Bischoff, et al., 2018)

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world nuclear news

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First European reactor loads EnCore accident tolerant fuel

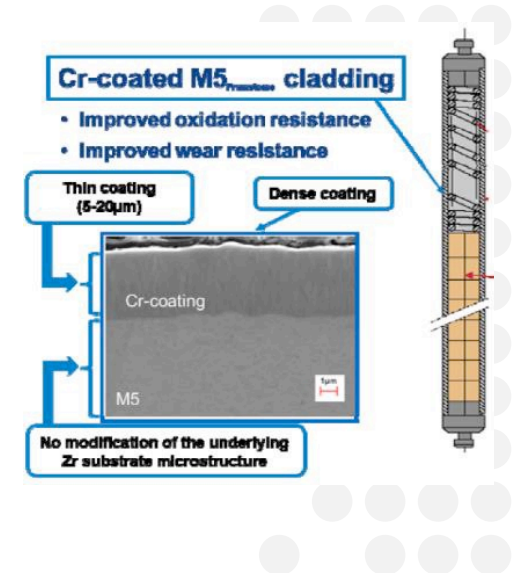
Wednesday, 9 September 2020

Lead test assemblies of EnCore accident tolerant fuel have been installed in Engie Electrabel's Doel unit 4 in Belgium, Westinghouse Electric Company and ENUSA Industrias Avanzadas have announced. Doel 4 is the second commercial nuclear power plant in the world, and the first in Europe, into which EnCore assemblies have been installed.



ATF solutions for cladding

- Chromium-coated zirconium alloy cladding
 - Vendors: Westinghouse (EnCore™), Framatome(PROtect)
 - TRL: High (7-8)
 - Status: Lead test rods have been irradiated in commercial reactors and are undergoing post-irradiation examination
 - EnCore™ Installed in 2020 in Doel 4, first deployment in a European reactor
- Ceramic coated zirconium cladding
 - Vendor: Global Nuclear Fuel (ARMOR)
 - TRL: Medium-High (6-7)
 - Status: Lead test assemblies have been loaded into commercial reactors
- Iron-chromium-aluminium (FeCrAl) cladding
 - Vendor: Global Nuclear Fuel (GNF)
 - TRL: Medium-High (6-7)
 - Status: Lead test assemblies have been loaded into commercial reactors
- Silicon carbide (SiC) composite cladding
 - Vendors: Westinghouse, General Atomics
 - TRL: Medium (5-6)
 - Status: Under development as a longer-term solution, with testing ongoing



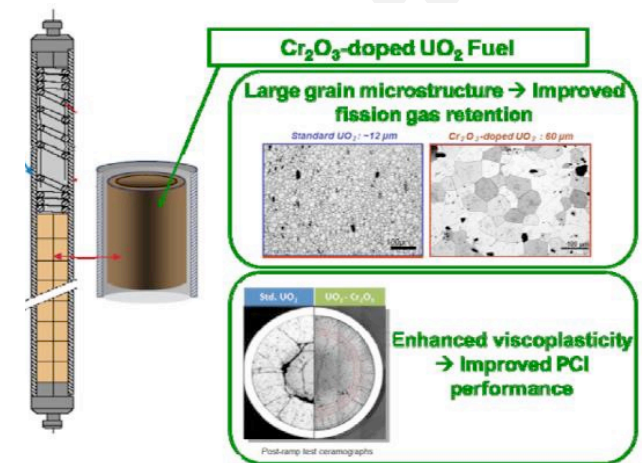
Advanced Fuel Pellets

- ADOPT Fuel Pellets by Westinghouse
 - Part of EnCore Accident Tolerant Fuel program
 - doped with small amounts of chromia (Cr_2O_3) and alumina (Al_2O_3) to improve neutron efficiency and reduce parasitic neutron absorption
 - Features
 - Increased uranium efficiency through a 2% increase in fissile material.
 - Improved thermal stability and reduced fission gas release.
 - Enhanced safety benefits, such as reduced fuel fragmentation and relocation during accidents.
 - Compatible with all zirconium-based cladding materials and fuel enrichments, suitable for PWR and BWR designs



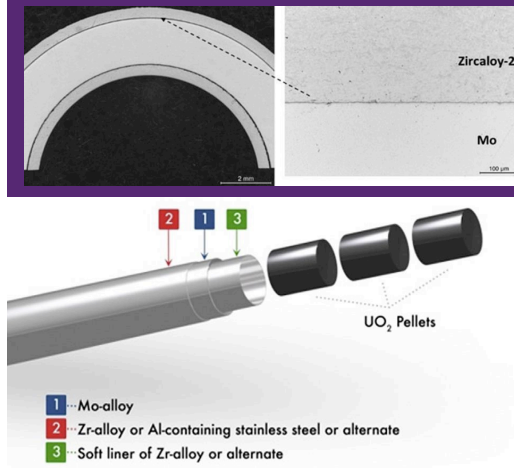
ATF Fuel Concepts Beyond Cladding

- ADOPT™ (Advanced Doped Pellet Technology) fuel pellets
 - Vendor: Westinghouse (EnCore™)
 - TRL: High (7-8)
 - Status: Approved by the U.S. Nuclear Regulatory Commission for use in U.S. Pressurized Water Reactors
- Chromia-doped fuel pellets (PROtect)
 - Vendor: Framatome
 - TRL: Medium-High (6-7)
 - Status: Testing has been conducted at Idaho National Laboratory
- Uranium nitride (UN) fuel pellets
 - Vendor: Westinghouse
 - TRL: Medium (5-6)
 - Status: In development as part of Westinghouse's long-term EnCore fuel program

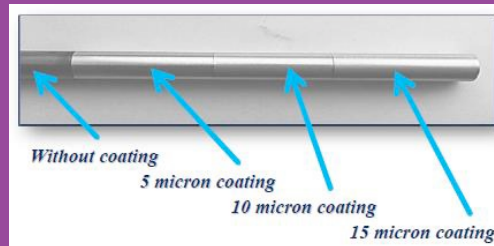


Other ATF concepts

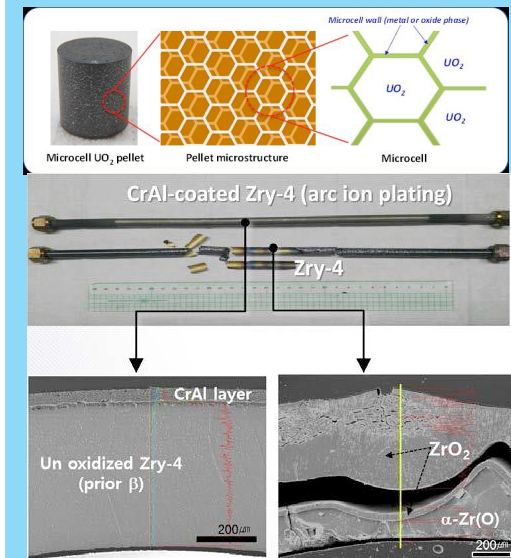
EPRI



TVEL

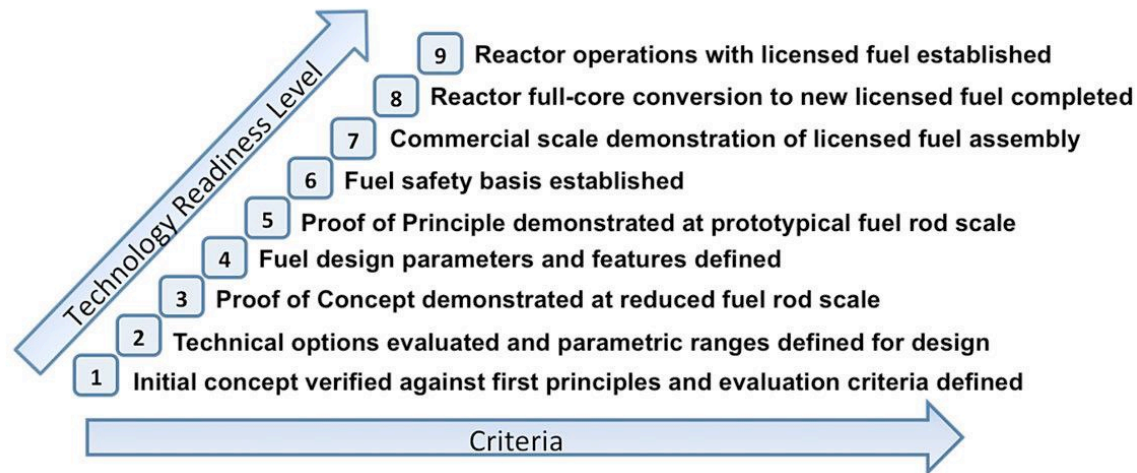


KAERI/KNF



Qualification & Licensing

- Outline the current licensing framework for new fuel designs
- Lead Test Rods and Lead Test Assemblies
- Fuel Licensing Practices in Various Countries
- Discussion on testing methods: out-of-pile tests, in-pile irradiation experiments (e.g., use of ATR, HFIR, BR2 in Belgium)



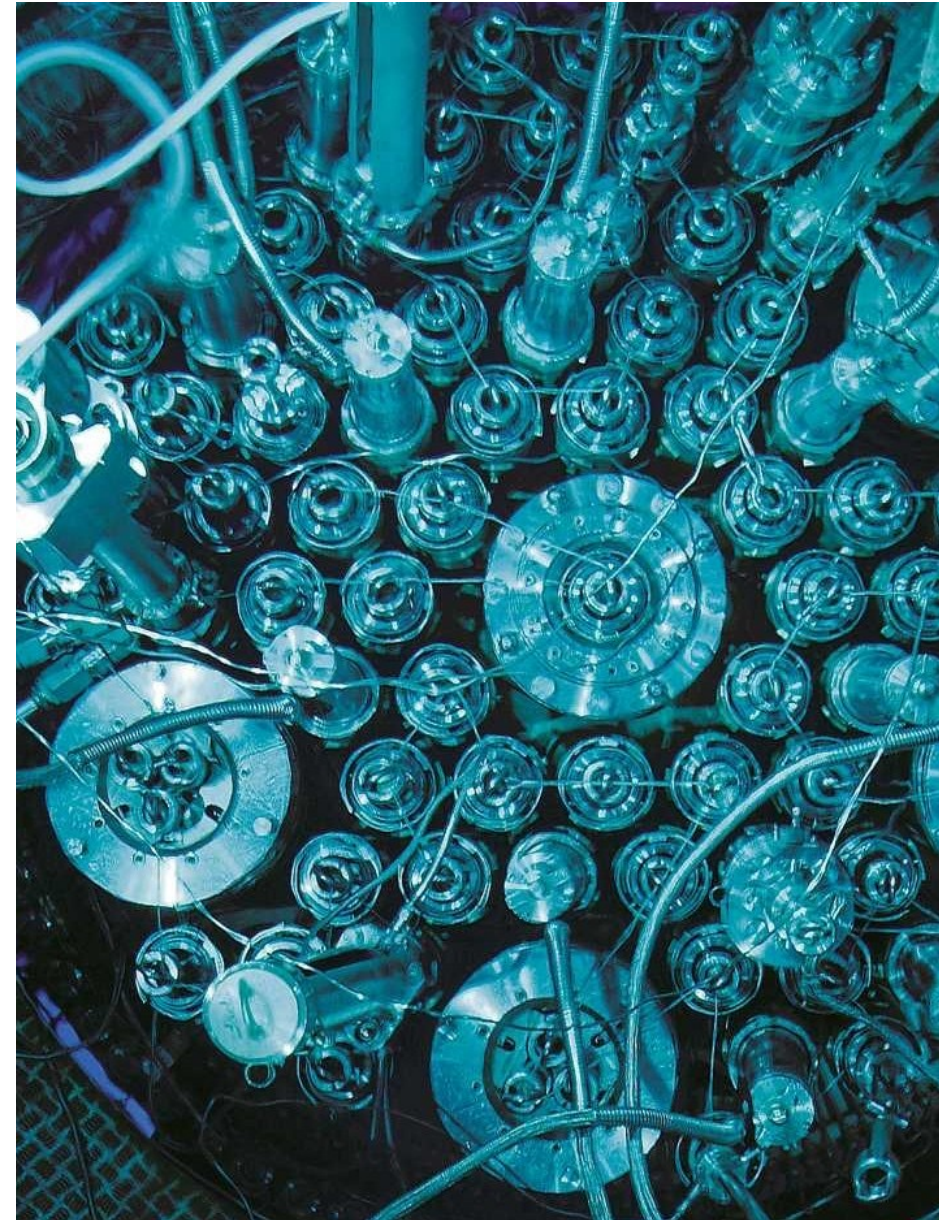
Irradiation facilities

Irradiation testing and PIE

NPP's used for normal operation of coated Zr alloy fuels (ref. ADOPT in Doel 4)

But MTR (such as BR2) and hotlabs for

- Accident conditions
- Power transients
- Different material concepts (SiC, Mo,...)



ATF Licensing Approach in the EU

- In July 2022, the EU ratified a delegated act including nuclear energy as an environmentally sustainable economic activity.
- This act requires the use of accident tolerant fuel (ATF) as a technical criterion for nuclear-related activities to access the green taxonomy.
- The requirement to use ATF applies after 2025, and the technology must be certified and approved by the national safety regulator
- Belgian Licensing Approach:
 - Belgium's licensing process for nuclear installations involves multiple stages, including application submission to the Federal Agency for Nuclear Control (FANC), safety and environmental assessments, and public consultations.
 - For new fuel types, including ATF, the licensing process in Belgium would likely follow this established framework.
 - The process involves close collaboration between Bel V and FANC in reviewing safety cases for new technologies.
- Timeframes and Considerations:
 - The regulatory approval process itself can take between 4 weeks and 1.5 years, depending on the extent of changes from existing fuel designs.
 - For new fuel types like ATF, a timeframe of 7 to 15 years can be expected, including development and testing.
 - Compatibility with waste management and storage requirements for spent fuel is an important consideration in the licensing process.

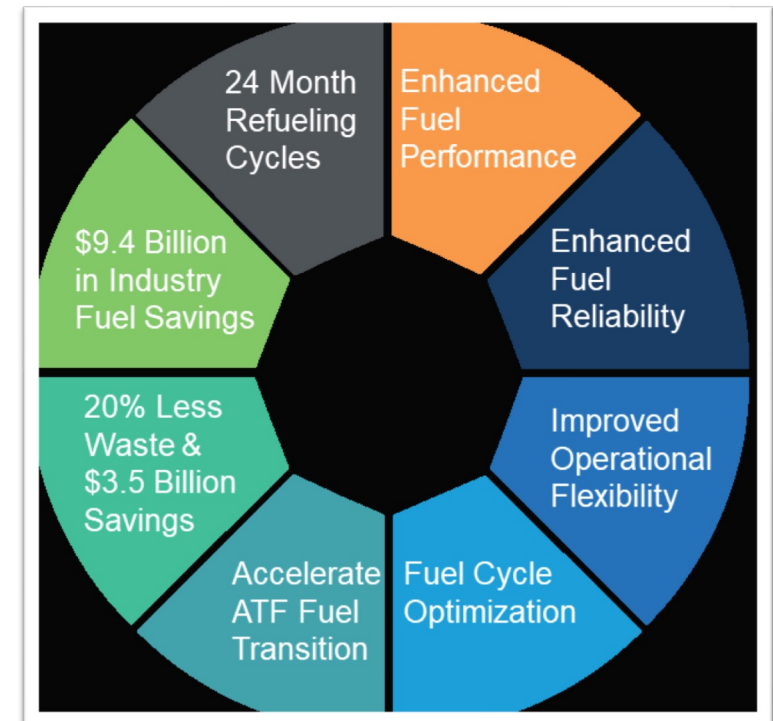
Challenges ATF qualification

- Naming: ATF as Advanced Technology Fuels with improving safety margins and improved thermo-mechanical performance
- Copping time as the fundamental metric that all stakeholders want to know is system- and scenario-dependent (it's not always welcomed because it requires complex analysis and does not give simple answers)
 - The original goal of 72 hours without any operator action is impossible to achieve for some scenarios but there are scenarios (e.g. SB-LOCA) where it's achievable
- All concepts have benefits and negatives and the best choice of material is system-, utility-, and market-dependent
 - Utility A with ABWR –might have problems with fretting, CRUD deposition or hydrogen uptake => concept A
 - Utility B with PWR-900 –might be under market economical pressure + needs to operate load-follow mode => concept B

Economic Considerations

Balancing Costs and Benefits

- Initial Investment vs. Long-term Benefits
- Potential Cost Reductions
- Operational Flexibility
- Market Competitiveness
- Economic assessment carried on by EPRI (2019)
- Reference: ANT International Report, ATF economics considerations



Lessons learned from ATF

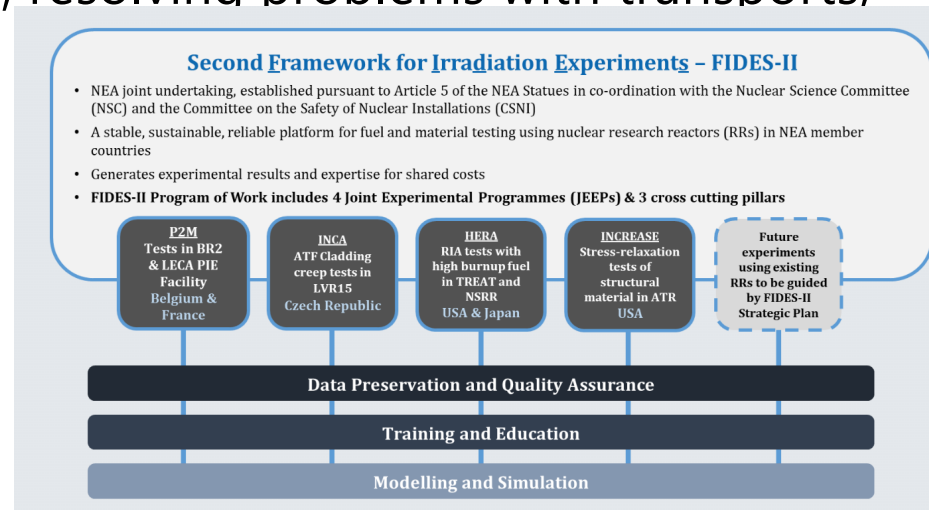
- Qualification of new materials for nuclear is long and resource consuming collective effort with no guarantee to succeed
 - Even boost as DOE and EU support after Fukushima are not sufficient to bring materials to maturity, max 1-2 steps on TRL scale
 - Utilize as many “old” and qualified materials as possible
 - Use new materials only when there’s a potentially significant benefit
- Design the systems hand-in-hand with the core design not separately

Lesson learned from ATF (2)

- Lesson learned from ATF: Move early to in-pile testing and representative reactor conditions
 - Out-of-pile tests are needed first but the critical point is the irradiation damage and irradiation-assisted effects
 - Simple corrosion, HT oxidation tests and mechanical tests should be done within months to qualify for research reactor testing –most attention and resources should go towards in-pile tests
- High-quality in-pile testing capabilities needed
 - To establish safety criteria for LWRs
 - To develop modelling and simulation tools –V&V
 - Qualify new materials and fuel designs for in-reactor operation
 - Ensure safety and support regulatory decision-making
 - Support license amendments
- Availability of research reactor limited; Decline of interest in many countries, very expensive facilities, radioactive waste, complicated transports

FIDES II- OECD/NEA Initiative

- Need to address the post-Halden situation –provide continuity, sustainability in experimental support in nuclear fuel and materials testing
- Performing experiments in member countries
- Support diversity –not to place eggs into one basket
- Support of bilateral agreements, resolving problems with transports, identifying gaps...



Current Status of ATF Development & Commercialization Progress

- Framatome
 - Stage: Near commercialization.
 - Milestone: GAIA fuel assemblies with Protect EATF technology completed a full 4.5-year lifecycle at Vogtle-2 (USA) in 2024, validating performance under normal and accident conditions.
 - Technology: Chromium-coated zirconium cladding and advanced fuel pellets.
- Westinghouse
 - Stage: Advanced testing.
 - Milestone: Uranium silicide fuel pellets (higher uranium density, 4x faster heat transfer) tested in lead test rods at Byron-2 reactor (USA) since 2019.
 - Next Step: Transition to silicon carbide cladding for enhanced accident resilience
- General Electric (GE)
 - Stage: R&D collaboration with DOE.
 - Focus: Developing proprietary ATF designs, though public milestones remain limited compared to peers

Future Outlook

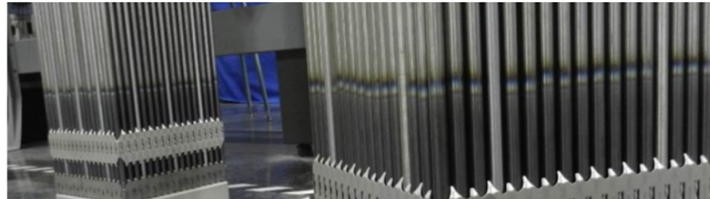


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Westinghouse, EDF to study use of accident-tolerant fuel

Wednesday, 27 July 2022

Westinghouse Electric Company and France's EDF are to jointly explore the functionalities of Westinghouse's EnCore accident-tolerant fuel technology. Westinghouse will study the use of the fuel in an EDF reactor for potential deployment across the EDF nuclear fleet after 2030.



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Framatome's ATF reaches new operational milestone

Friday, 15 November 2024

Framatome's PROtect Enhanced Accident Tolerant Fuel chromium-coated M5Framatome cladding has become the world's first ATF technology to operate with full length fuel rods at a burnup rate above 60 GWd/tU.



- Commercial deployment ongoing but significant R&D efforts required

Conclusions

- ATF developments after the Fukushima-Daiichi events have been very successful. It did not bring the ultimate super-safe cladding but significantly advanced the field and provided funding for research institutes, universities, and fuel vendors to accelerate innovations in the nuclear fuel area.
- Some ATF concepts are already in commercial reactors as lead test rods or assemblies and partial core reloads are expected in 2-3 years. There is no universal solution and the preferred concept is case-dependent.
- Despite being more expensive, ATFs allow improving the economics of operating reactors by opening a way to enrichment above 5% and extending BU limits above the current peak BU~63 MWd/kgU.
- Advanced Technology Fuels continue to develop and improve safety, operability and fuel cycle economics

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