



An Assessment of the Management of Advanced Fuels after Discharge

David Hambley, Dave Goddard and Joel Lucas

*IAEA Webinar on Accident Tolerant Fuels and
Their Impact on Spent Fuel Management
2nd December 2020*

Introduction

- Context and concepts
- Potential impacts
- Case of short term ATF deployment

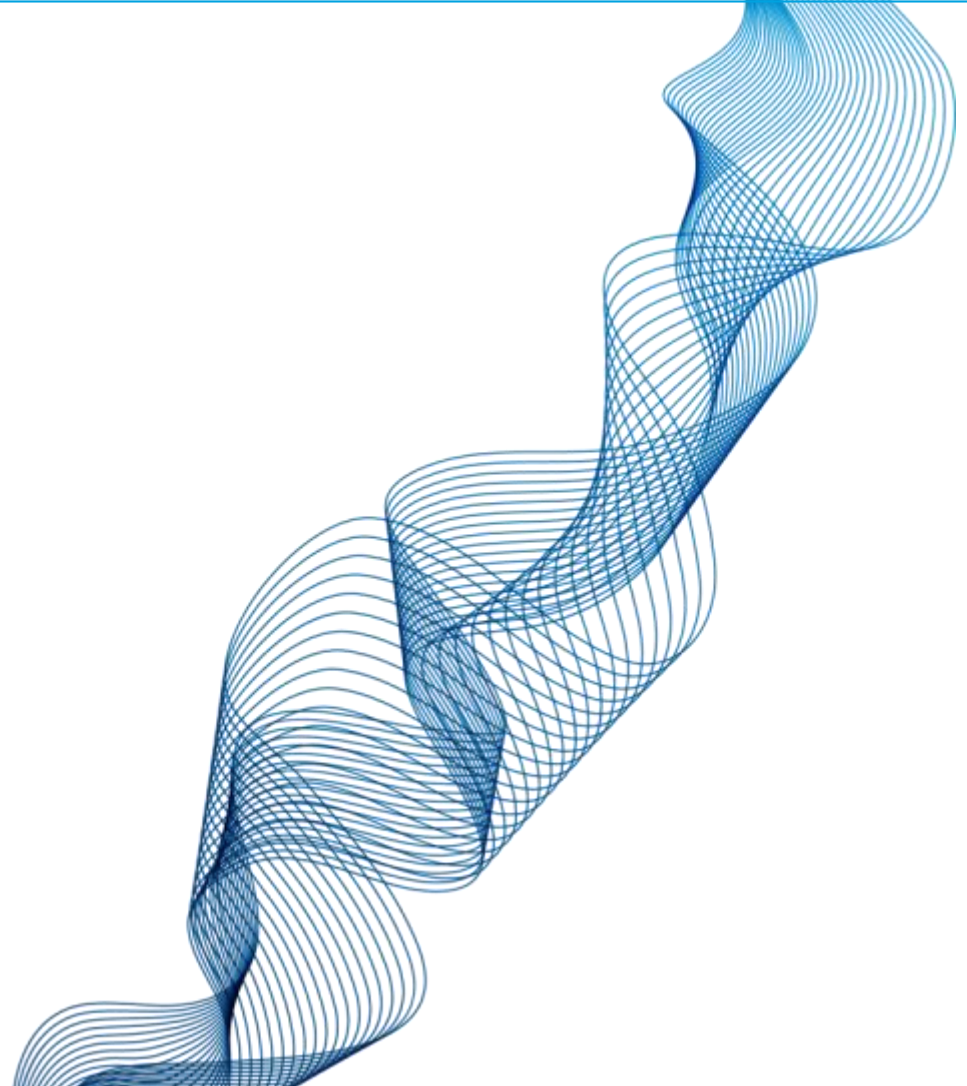
Cladding:

- Cr coatings
- Iron-based alloys
- SiC

Fuel:

- Higher density fuels
- Higher enrichment fuel

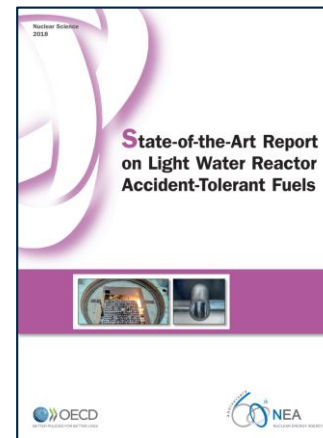
Status and Summary



- Fukushima provided a focus for the industry to develop fuels with enhanced resilience to severe accident scenarios.
- Particular target to extend coping time during a Loss of Coolant Accident.
- Fuel and cladding concepts have been developed that range from *evolutionary* to *revolutionary* in their ambition.
- Deployment potential in existing LWR fleets, new build LWRs and some SMR designs.
- *Revolutionary* concepts might also be applicable to some Gen-IV reactor concepts.



Accident at Fukushima-Daiichi in 2011

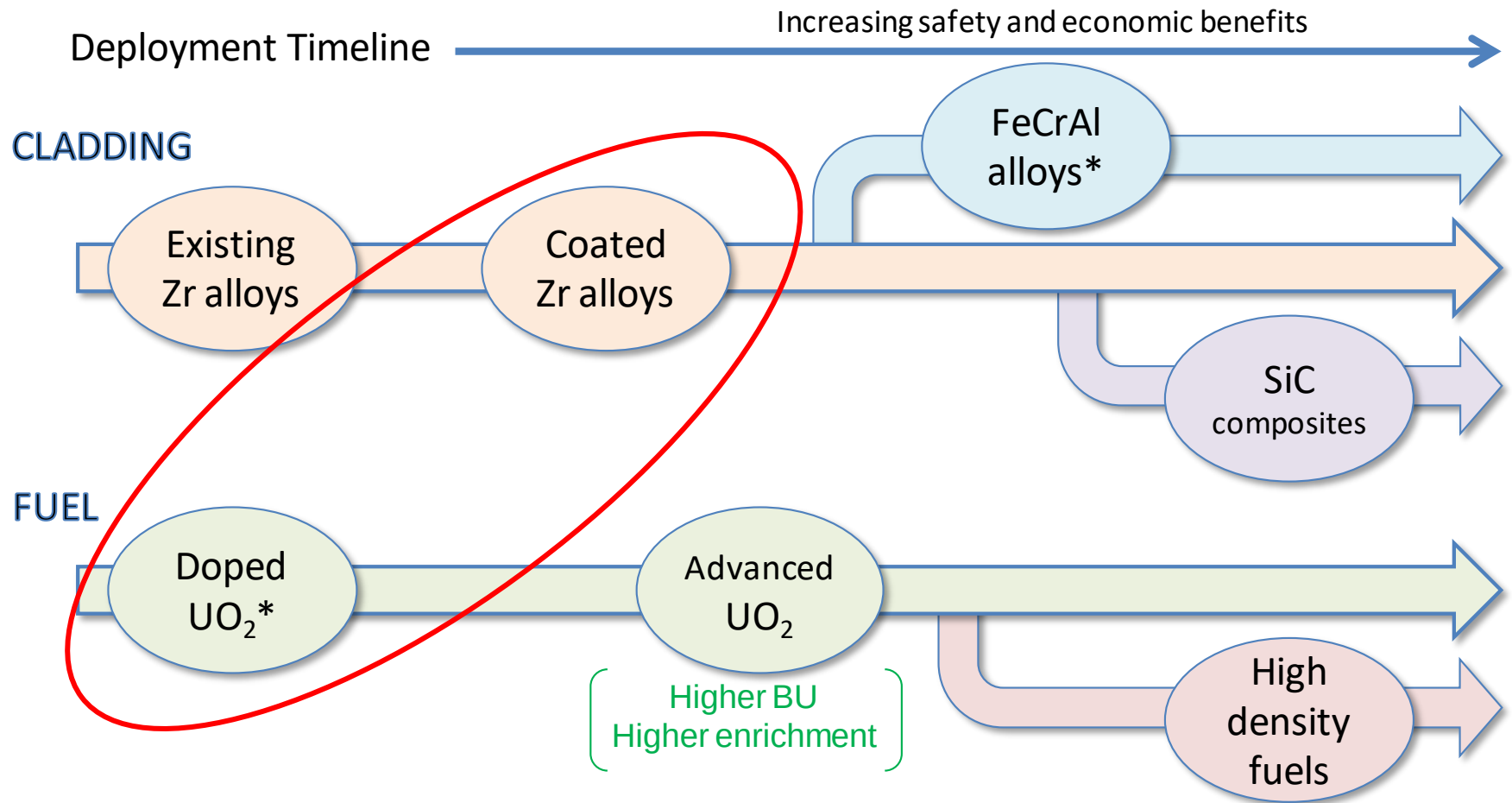


OECD-NEA Report
published in October 2018

372 pages of
detailed analysis of
concepts but
only ~ 5 pages
devoted to spent fuel
management!

Leading ATF Concepts

Managing ATF after Discharge



* Cr doped fuel exists

Impact of ATF on SPENT Fuel Management

Managing ATF after Discharge

Main issues

- Fuel/cladding properties
- Corrosion behaviour
- Criticality
- Heat load

Reactor Fuel Pond



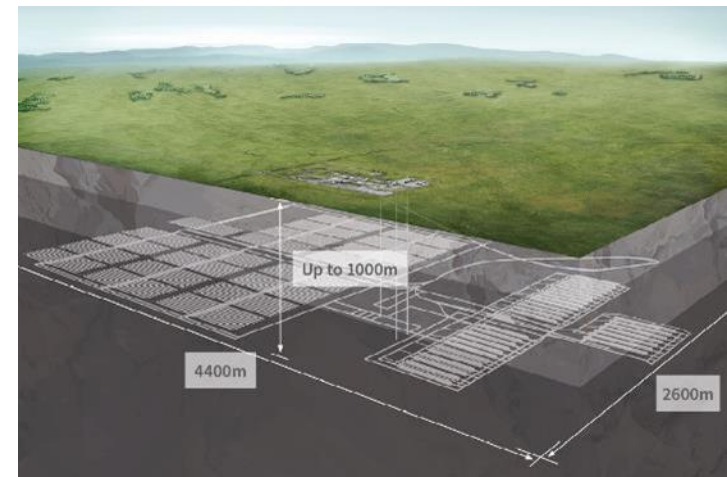
Storage



Transport



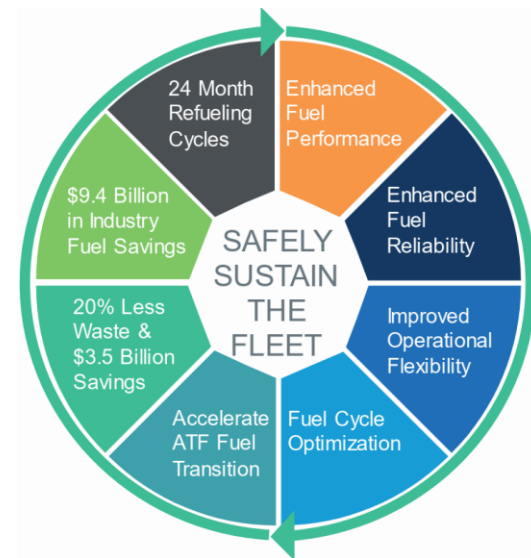
Disposal



Recent accident analysis work indicates some gains in coping times for near term advanced fuels, but not sufficient to off-set higher manufacturing costs.

ATF development initially focussed on higher density fuels to improve economics.

More recently, work by EPRI showed that short term deployment case can be made by increasing burn-up and enrichments:



EPRI Report 3002015091

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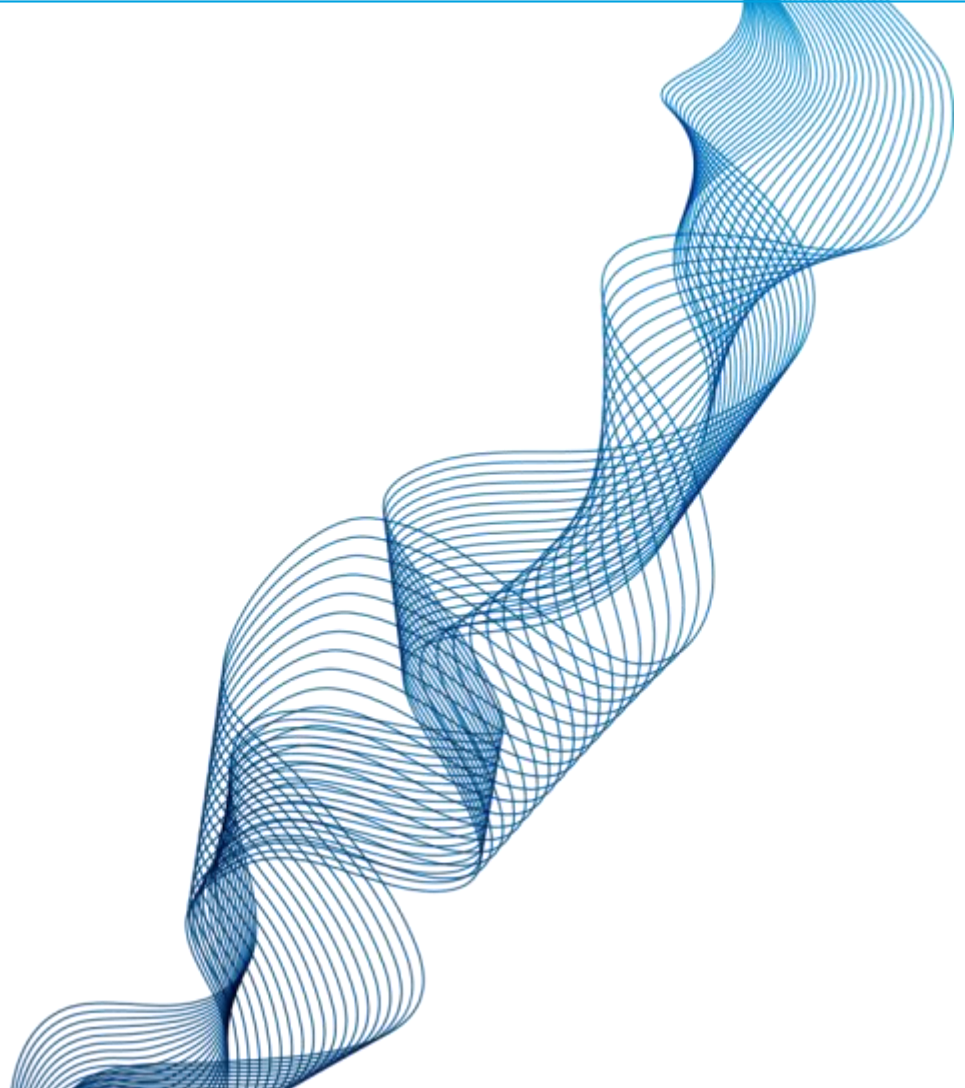
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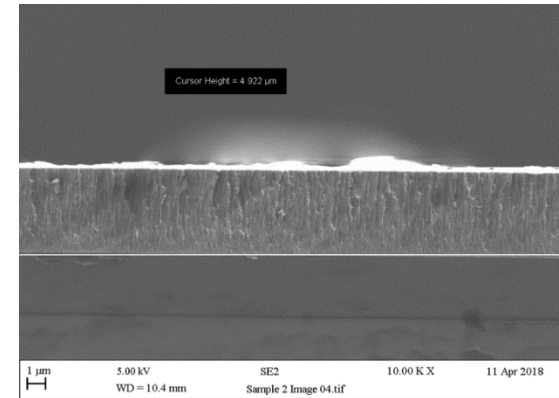


Coated Zr Alloy

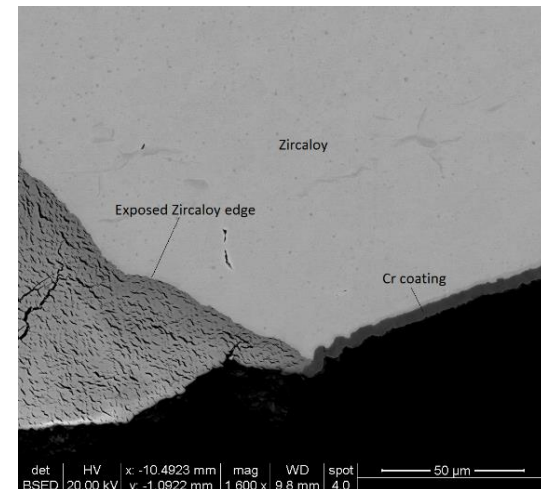
- Focus on Cr based coatings.
- Reaction with steam forms a protective Cr_2O_3 surface layer.
- Limited by Cr-Zr eutectic formation between 1300-1400°C.



Cr coated ZIRLO cladding tubes



Cross-section through Cr coating

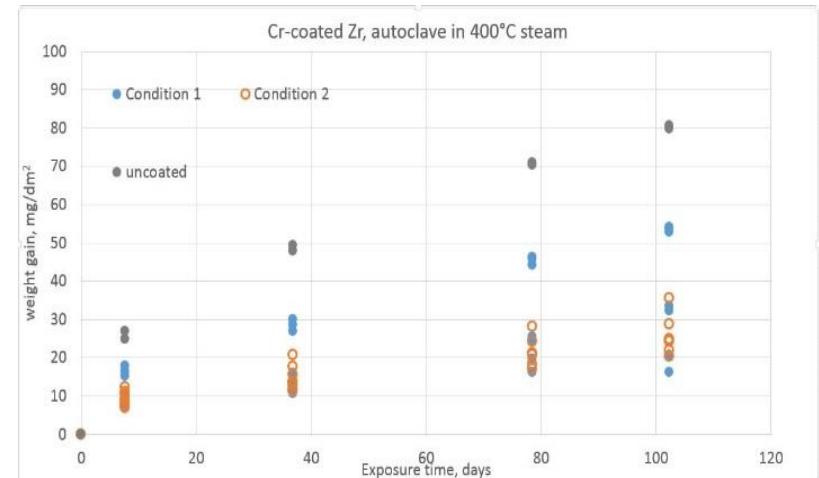


700°C oxidation test for 72 hours shows protective ability of Cr coating

SFM Considerations for Cr coated cladding

Managing ATF after Discharge

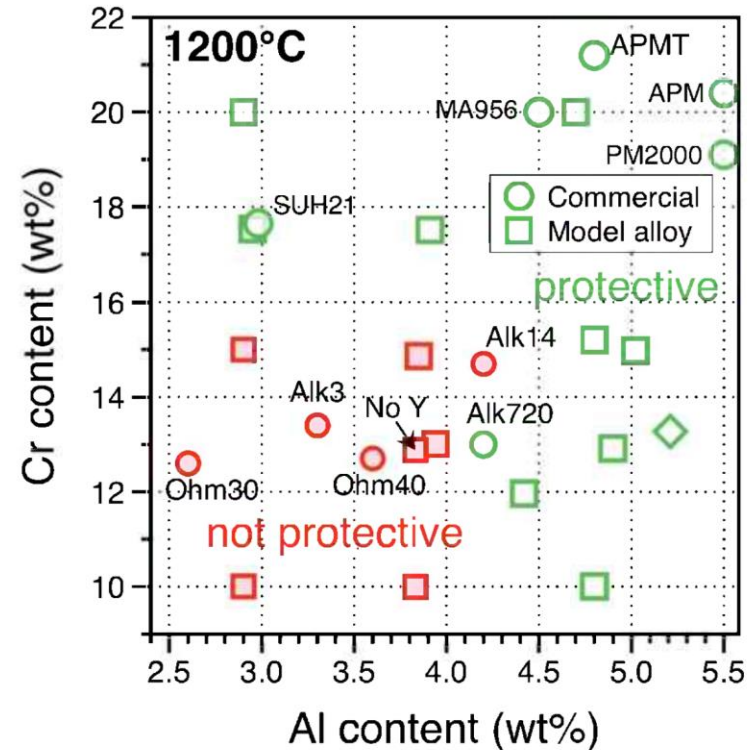
- Significantly reduced weight gain in accelerated 400°C steam testing of Cr clad fuel
- Reduced H₂ generation has potential to reduce hydride formation in cladding and delayed hydride cracking/hydride reorientation
- General performance will not adversely affect storage, transport, reprocessing or disposal
- Failure site characteristics and fuel matrix corrosion not adversely affected
- Dissolution of Cr is expected to be low, but could form CrO_4^{2-} altering water chemistry near fuel and hence long term fuel corrosion rate
- Validation of storage, disposal and transport performance likely to be required



Advanced Fe Alloys

Managing ATF after Discharge

- Austenitic stainless steels (e.g. 304, 304L, 348, 348H) used in some early in LWRs
- Zr adopted because of lower neutron penalty and better corrosion performance
- ATF focus is on ferritic Al containing FeCrAl alloys (e.g. APMT, Fe-21Cr-5Al-3Mo and other model alloys)
 - **Fe,Cr spinel protective layer forms under normal operating conditions**
 - **Al₂O₃ layer provides protection in severe accident scenarios (up to ~1400°C)**
- Neutronic penalty can be partially offset by reducing cladding thickness

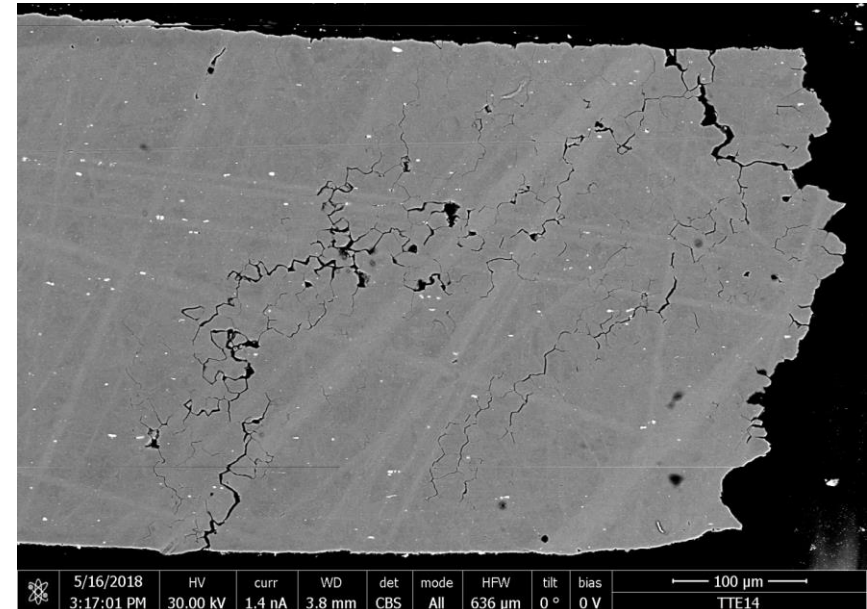


Pint et al, Metallurgical and Materials Transactions E, vol 2, p190-196 (2015)

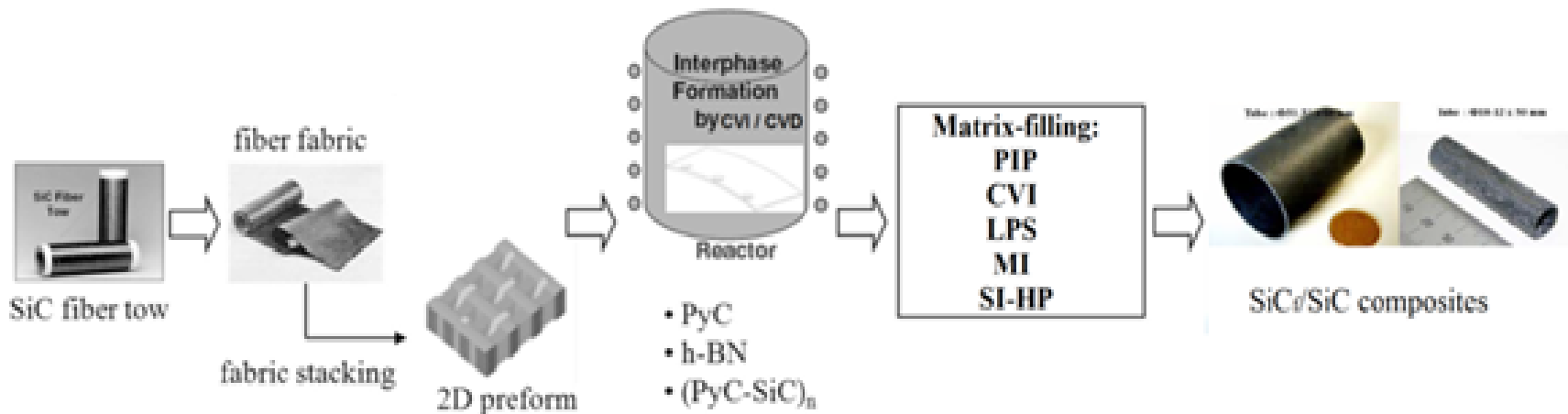
SFM Considerations for Advanced Fe Alloys

Managing ATF after Discharge

- EPRI has reported on wet storage of stainless steel clad LWR fuels for up to 25 years (EPRI TR-106440).
 - **Uniform corrosion estimated to be <15µm at 15-50°C over 50 years.**
- Steels are susceptible to depletion of Cr at grain boundaries (thermal and radiation induced) leading to sensitisation to corrosion. Extent depends on the grade of steel, irradiation and temperature.
- SFR and AGR fuel cladding and BWR shroud experience is relevant:
 - **Long term pond storage possible with inhibitor**
 - **Low humidity air storage conditions must be avoided, although safe threshold not firmly established.**
- Steels are not effective hydrogen getters so tritium release will need to be considered.
- No significant issues identified for transport, reprocessing or disposal.

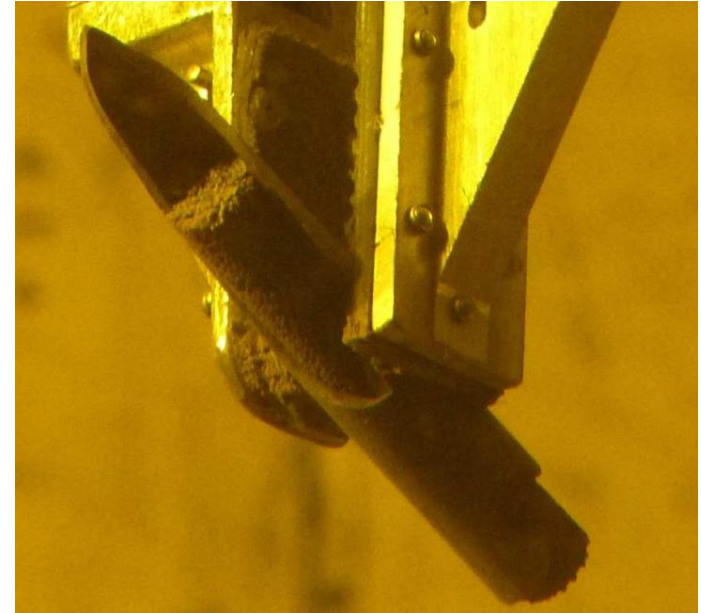


SCC in aged AGR fuel cladding (20/25 Nb stabilised austenitic steel). AGRs operate at higher temperatures than LWRs – more prone to sensitisation.



- SiC composites are attractive due to their high temperature oxidation resistance and lower neutron absorption than Zr alloys.
- Low TRL compared to coated Zr or iron-based alloys
- Key challenges are:
 - **cost of manufacture (especially high purity fibres),**
 - **joining technologies for end plugs,**
 - **hydrothermal corrosion during normal operation not well understood**
 - **licensing of a material with very different mechanical properties to current metallic cladding.**

- Limited data on post irradiation properties and behaviour of SiC composites.
- SiC clad fuel tested in the Windscale Advanced Gas Cooled Reactor (WAGR) in the 1960's has been examined recently.
 - **No evidence of deterioration during pond storage.**
- Evaluation:
 - **Low risk of significant issues in storage**
 - **Behaviour under cyclic loading and accidents conditions in post irradiation/post storage transport uncertain**
 - **Significant impact on reprocessing not expected**
 - **Long term corrosion behaviour is repository uncertain**



A broken SiC cladding tube containing UC_2 coated particle fuel embedded in SiC that was irradiated to low burn up in WAGR in the 1960's and had been wet stored until examination in 2015.

Testing of modern composite materials, at relevant burn-ups is required.

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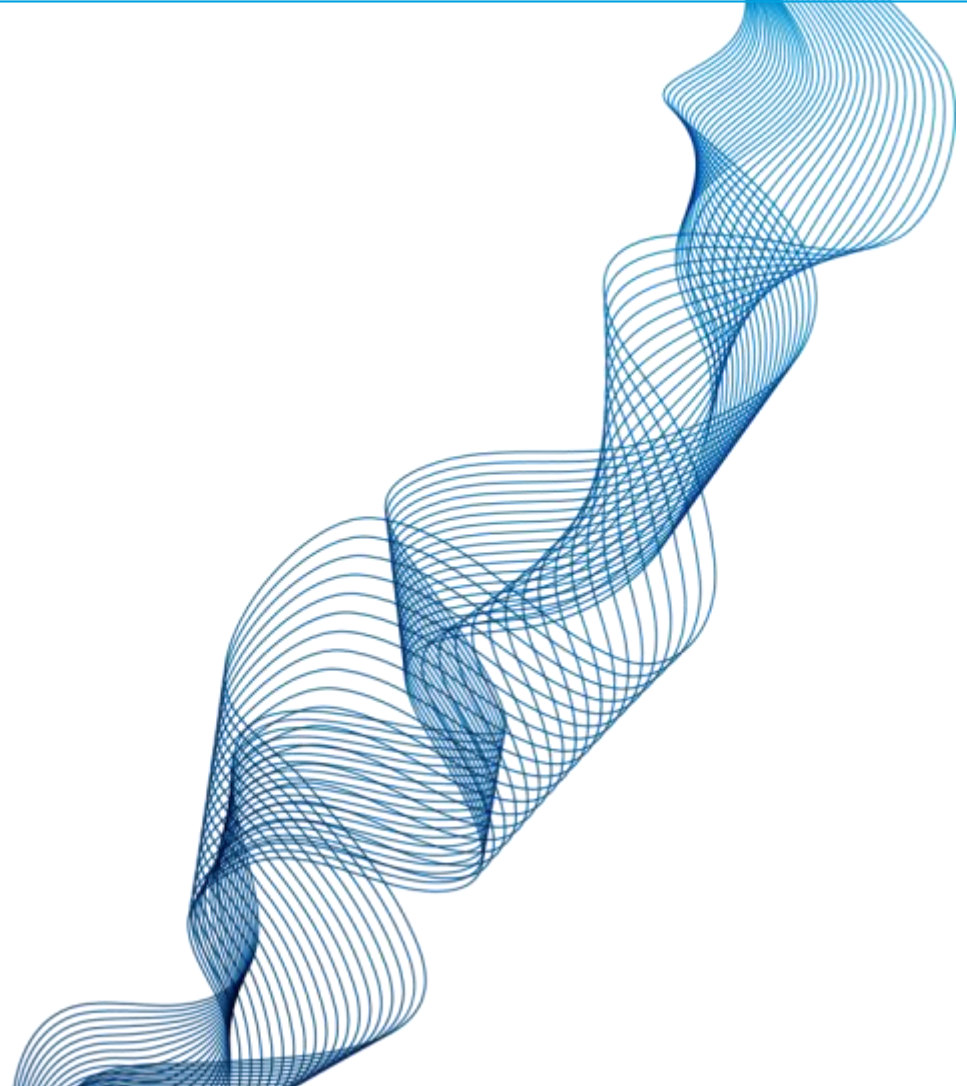
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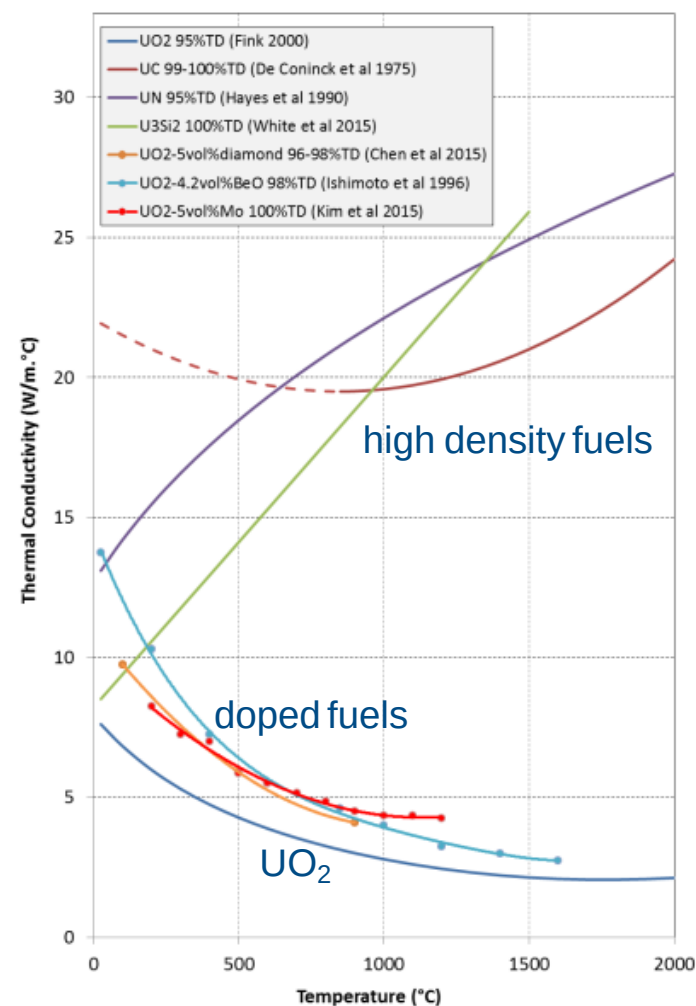
Status and Summary



Doped UO_2 Fuels

Managing ATF after Discharge

- Incorporating materials with a higher thermal conductivity (e.g. Mo, BeO) into UO_2 can reduce peak centreline pellet temperatures and reduce fission gas release.
- Significant additions reduce uranium density of the fuel so may need higher enrichments.
- Reduced fission gas release in larger grain Cr doped fuel – impact of disposal being assessed experimentally.
- Irradiation performance of these fuels will require testing.
- Storage, transport, reprocessing and disposal behaviour is expected to be similar to UO_2 , although different additives will exhibit differing oxidation behaviour which could alter fuel fragmentation and some may have some limited impact on reprocessing chemistry.



High Density Fuels

Managing ATF after Discharge

Material	U density increase (%)	Irradiation Performance	Water Reactivity	Ease of Manufacture	Isotopics
UO₂	-	Excellent	Excellent	Very good	No issues
U ₃ Si ₂	17	Uncertain. Lack of data in relevant LWR conditions. Swelling expected to be higher.	Borderline	Difficult	No issues
UN	40		Poor	Fair but additional processing steps required beyond UO₂ manufacture	¹⁵N enrichment required to avoid ¹⁴C
UC	34		Very poor		No issues
UB ₂	21		Not well understood	Difficult	Depletion in ¹⁰ B required*

**unless considered as a burnable absorber*

U₃Si₂ largely dropped due to poor water tolerance and difficulties in manufacturing.

UN is currently most favoured but required dopants or coatings to control reactivity.

SFM Considerations for High Density Fuels

Managing ATF after Discharge

- Reactivity with water and air is problematic for storage, transport and disposal. Long term isothermal testing needed to understand scale of challenge.
- Differences in microstructure and the presence of impurity phases may influence behaviour under cyclic and impact loading and long term bulk swelling.
- Mechanism of air and water reaction may be different (e.g. U_3Si_2 can form a hydride).
- In reactor performance requirements will drive improvements in water stability, longer duration exposure during storage and oxidation rate in repositories may still be challenging.
- Reprocessing requires some adjustment but is feasible:
 - **Recovery of 15-N would probably require a voloxidation type pre-treatment to separate & capture**
 - **Carbides have pyrophoric concerns & generate organics that could affect downstream processes**
 - **Silicides difficult to dissolve on nitric acid and lead to more precipitation**



U_3Si_2 pelleting
via arc melting
and
conventional
sintering
at NNL

Summary of issues for increased enrichment

Managing ATF after Discharge

Criticality:

- Adequacy of benchmarks for $>5\%$ ^{235}U fuels
- Validation of inventory codes for burn-up credit above ^{235}U
- Potential impact on rack spacing / B doping of reactor ponds
- Impact of cask (storage) and canister (disposal) designs

Heat Load:

- Individual assembly heat loads are increased
- Heat load per MW however remains relatively static
- Potential impact of storage system designs

Operator Perspective:

- concerns over operational doses for higher burnup fuel

Reprocessing

- MOX experience indicates higher enrichments can be managed

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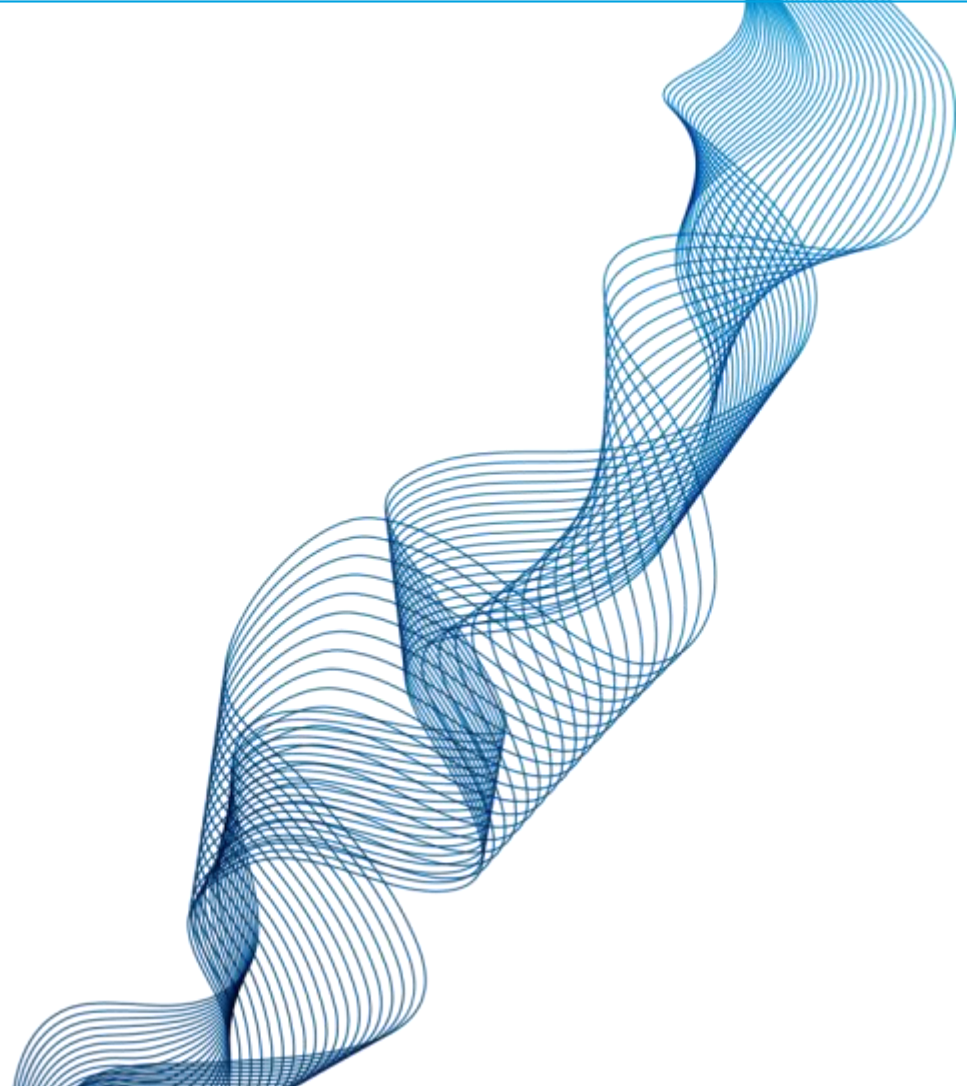
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Status and Summary



There is a need for more detailed understanding of the potential impact of changes to fuel and cladding on fuel performance in storage, transport, reprocessing and disposal.

Relevant international activities focussed are:

- US-DOE funding US national labs to complete a gap analysis for storage of Cr-clad, Cr-doped fuels
- EPRI ESCP task group on ATF established within fuels sub-committee
- EPRI ESCP International sub committee to seek wider understanding of back end impact assessments
- IAEA proposal for a new CRP on “Testing and Simulation for Advanced Technology Fuels” (ATF-TS) (2020-2023)



- Management of spent advanced fuel is beginning to be given the level of consideration required to avoid repeating mistakes of the past.
- For ATF concepts nearest deployment,
 - **fuel should behave at least as well as current Zr alloy clad UO₂ fuel in wet/dry storage, transport, reprocessing and long term geological disposal.**
 - **confirmatory testing will, however, be required to underpin the expected behaviour.**
- The greatest focus for high density fuel materials due to their reactivity to water and oxygen at moderate temperatures.
 - **Modifications to these fuel forms are likely to be required for acceptable use in reactor conditions, which would be expected to improve their behaviour in long term storage.**
 - **Manufacturing and reprocessing will be more complex, especially for isotopically enriched fuels**
- Testing of irradiated SiC cladding will be required to understand behaviour during storage, transport, reprocessing and disposal as there is little evidence of similar materials to rely on.