Development of Innovative Material for LWR fuel

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Nessebar – September 16, 2025

Context and stakes on Fuel Technologies

- Fukushima accident highlighted the value of fuel margin in the case of a severe accident
- In some countries, the existing fleet of commercial nuclear power plants faces economic pressure from low natural gas prices and the emergence of utility scale renewable generation
- In some others, increased electricity demand to reduce carbon emission are incentives to have lifetime extension, build new reactors and/or to make power uprates
- The LWR fleet is evolving with closure of some reactors and erection of new ones

What innovations in the fuel technology can be useful for responding to the challenges?

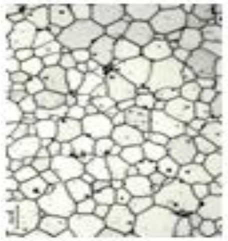
Fukushima Event

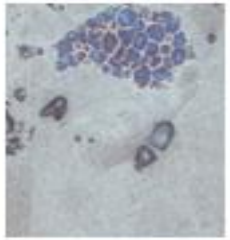
Following loss of cooling due to station black-out, fast temperature increase leading to:

- Rapid Oxidation of the cladding due to Zr-Steam reaction
- Hydrogen Release, followed by explosion
- Fission Products release in the atmosphere
- Core Melting

Fuel Technologies – four degrees of freedom

- Fuel type: UO_2, U_3Si_2, UN, UC, U-Mo, U-Zr
- Additives: Cr_2O_3, Mo, Cr, SiC, C, BeO …
- Structure:


monolithic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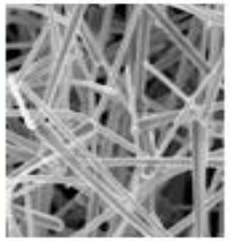
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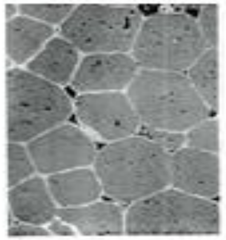
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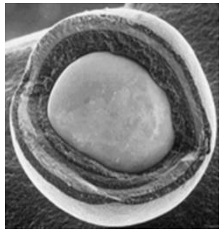
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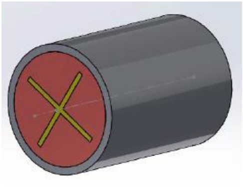
macro-structures

- Geometry: length / diameter ratio, chamfer, dish, annular pellet

Content

1. Assessment of various fuel type
2. Framatome E-ATF fuel
3. Take Away

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Assessment of various fuel type

Technical Aspects

Economic Aspects

Qualitative Synthesis

The Ideal Fuel is …

SAFE (S)

- DBA > 0 margins
- Delaying melting risk in severe BDBA accidents
- No strong water reaction
- Low Fission gas release
- Cold fuel in accident & operation

Quality (Q)

- No leaker due to fabrication
- Resistant to PCI
- Low wash out
- Full predictable performance
- Quality mastered throughout lifecycle

Economical (E)

- Highest Burnup
- High U235 content (incl. > 5%)
- High Fuel Utilization & Reactivity
- Capable of high Power
- Low batch size and long cycles
- Capable of Flexible operation
- Low front end and back-end costs

… and is available in the short term !

DBA: Design Basis Accident
BDBA: Beyond Design Basis Accident
PCI: Pellet Cladding Interaction

E-ATF Fuel Pellets
Desirable fuel properties for AOOs, DBA, BDBA

- For DBAs and BDBAs
  - Cold fuel (high thermal conductivity) for short duration postulated accidents only
  - High melting temperature to be kept
  - Decrease of internal pressure ie. internal pressure before the start of the accident and FGR during the transient is beneficial to avoid burst of claddings (LOCA and RIA)
  - Moderate swelling helps for X% strain criteria (also for AOOs)
- For AOOs
  - Cold fuel (high thermal conductivity) helps for DNB margins
  - Retention of fission products (Iodine) and reduction of stress on the cladding (improvement of pellet viscoplastic properties and/or modification of the pellet design) for PCI

DBA: Design Basis Accident
BDBA: Beyond Design Basis Accident
FGR: Fission Gas Release
LOCA: Loss Of Coolant Accident
RIA: Reactivity Inatiated Accident
AOO: Anticipated Operational Occurence
DNB: Departure from Nucleate Boiling
PCI: Pellet Cladding Interaction

Economic Aspects
Key Assumptions

- Investment costs / amortization not considered in the evaluation
- Natural Uranium Cost: 32 USD/lb U3O8
- Conversion Cost: 22 USD/kgU
- Enrichment Cost: 50 USD/SWU
- Fabrication Cost: 300 USD/kgU
- 10 USD/kgU could be considered per additional manufacturing step
- 25% of increase of manufacturing cost could be considered for the use of glovebox which leads to 75 USD/kgU

	U_3Si_2	UN	UO_2 w/ 5% Cr additive	UO_2 w/ 5% BeO additive
Additional mnfg step	use of glovebox	use of glovebox	No	One (to manage the use of Beryllium)
Neutronic penalty	/	/ (use of ^{15}N)	0,55% of ^{235}U	/
Fuel Water Reaction	reduced pellet diameter (reinforced cladding)	reduced pellet diameter (reinforced cladding)	N/A	N/A
Material over cost	0	3 USD/g of ^{15}N	10 USD/kg Cr	64 USD/kg BeO

Cases with $U_3Si_2Al_x$ not studied as their density of U are not enough favorable

No reduction of diameter considered to account for an increased swelling

Over cost minimized

R. Kliewer & Al - Advanced fuel technologies of the future - Topfuel 2019

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Economic Aspects

Application for a 18-month cycle Fuel Management

- Despite the increased density, U3Si2 and UN are not providing reduced batch costs
  - high manufacturing over costs coming from the use of gloveboxes and enriched 15N (for UN)
- Ceramic fuel with additive show some batch over costs
  - due to lower density which can even be aggravated depending on the additive chosen

17x17 Plant Segment - 18 month cycle	UO_2	U_3Si_2	UN	UO_2 w/ 5% Cr additive	UO_2 w/ 5% BeO additive
Pellet OD (mm)	8,192	7,701	7,701	8,192	8,192
Uranium Density (gU/cm^3)	9,34	10,7	13,5	8,796	8,796
Assembly Loading (kgU)	466	474	597	440	440
Reload Batch Size (#)	80	76	60	96	84
Reload Batch Average Enrichment (%)	4,519	4,773	4,522	4,885	4,79
Average Discharge Burnup (MWd/MTU)	50 532	50 661	50 949	43 205	49 378
Total Reload Batch Costs w/o mngfg over-cost ($M)	60,4	61,2	55,7	74,3	63,9
Additional manufacturing costs ($M)	0,00	2,70	9,47	0,02	0,41
Total Reload Batch Costs ($M)	**60,4**	**63,9**	**65,2**	**74,4**	**64,3**

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Fuel Pellets
Qualitative Synthesis

	UO_2	UO_2 > 5%	UO2 Cr doped	U_3Si_2	$U^{15}N$	UO_2 Cr microcells	UO_2 – BeO network
Melting T°	2860	2860	2860 - eps	1665	2650	2860/ 1900	2860/ 2530
Fuel Water reaction	Ref	Ref	+	- -	- - -	Ref	Ref
Thermal conductivity	Ref	Ref	Ref – eps	+ + +	+ + +	+	+
Fission Gas release	Ref	Ref	+ High BU & transient	+ +	+ +	+	+
Swelling	Ref	Ref	Ref + eps	- -	- -	Ref	Ref
Neutron absorption	Ref	Ref	Ref – epsilon	Ref – epsilon	Ref	- -	Ref + epsilon
U density (high BU capability)	Ref	+++	Ref + eps	+	++.	-	-
Manufacturing costs	Ref	-	Ref	- - -	- - - -	Ref + eps	- -

The Best Fuel choice improving safety margins at reasonable impact to the Fuel Cycle Costs are UO_2 and UO_2 enhanced materials

UO_2 with additives are worth exploring for new LWR type or new fuel management which would challenge safety margins

The high density fuel have a chemical behavior (breakaway oxidation) which is not acceptable in case of cladding failure in LWR

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Framatome E-ATF fuel

Framatome Cr_2O_3-doped UO_2 fuel

Framatome microcell fuel development

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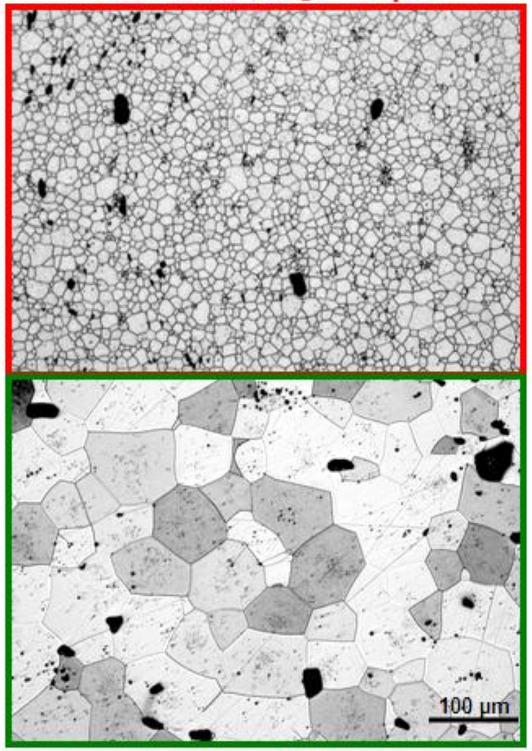
Framatome Cr_2O_3-doped UO_2 fuel Characteristics

- A nominal Cr_2O_3 addition of 0.16 wt.%
  - Additive content compatible with the solubility limit of Cr_2O_3 in UO_2
  - Large grain size of 50-60 µm
  - No large Cr_2O_3 free particles in UO_2 matrix
- Technical benefits
  - Enhanced viscoplasticity for improved PCI performance
  - Large grain microstructure for improved fission gas retention in accidental conditions
- Fully industrialized in Framatome fuel manufacturing plants in Europe and in the US
- Used in reload quantities in all US BWRs served by Framatome and in two European PWRs

Standard UO_2: ~12 µm

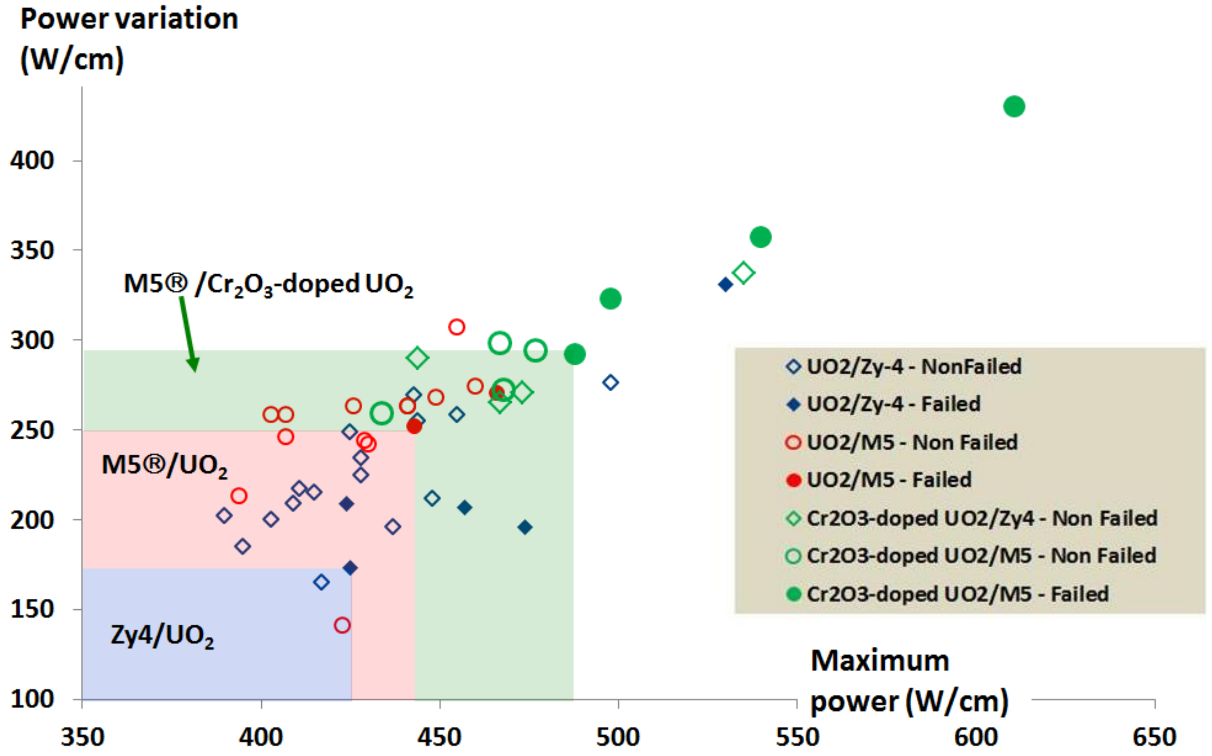


Cr_2O_3-doped UO_2 : 60 µm

More than 120 million Framatome Cr_2O_3-doped UO_2 fuel pellets manufactured

Framatome Cr_2O_3-doped UO_2 fuel Improved PCI performance

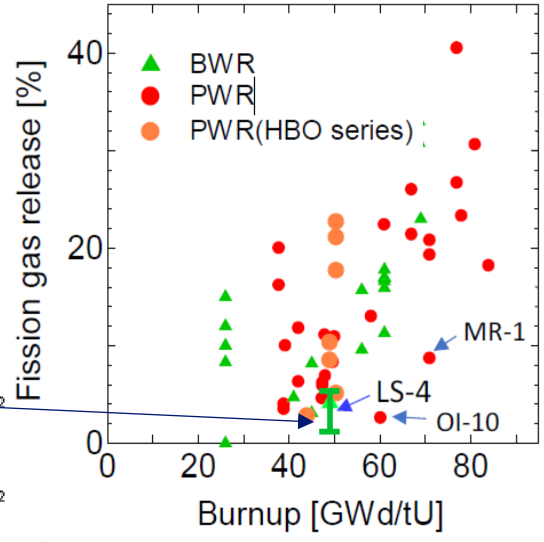
- Comprehensive power ramp test program for PWR products and BWR products
  - Tailored to maximize the potential of failure risk due to PCI and to derive a clear PCI failure threshold in normal operations and anticipated operational occurrence conditions
  - BU range of investigation [18-45] GWd/tU (additional test done at 62 GWd/tU on PWR product although classical PCI is not an issue at this BU)
  - 8 ramp tests with Cr_2O_3-doped UO_2 fuel and $M5_{Framatome}$ (PWR product)
  - 12 ramp tests with Cr_2O_3-doped UO_2 fuel and non-liner Zy2 (BWR product)
  - Initial Power [100-250] W/cm



PCI resistance increased with the Cr_2O_3-doped UO_2 fuel
Implementation in the US BWR reactors allows to reduce fuel cycle costs by replacing liner cladding by non-liner cladding

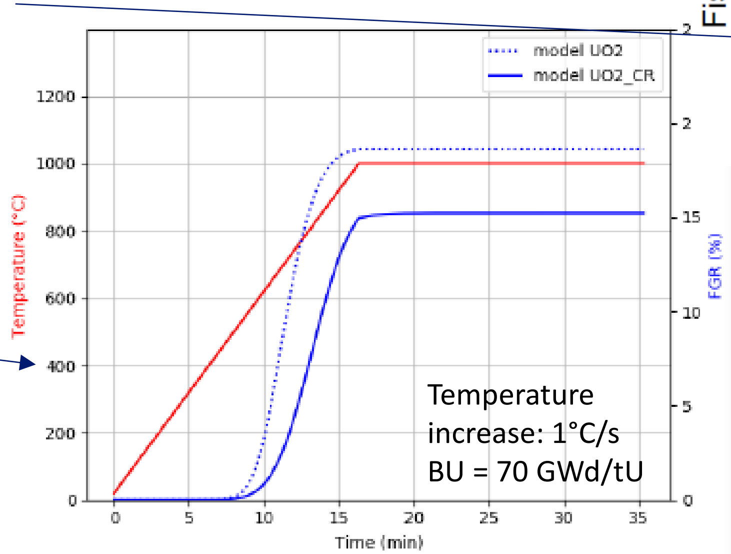
Framatome Cr_2O_3-doped UO_2 Fuel
Improved fission gas retention in accidental conditions

- RIA test done within ALPS2 program
  - BWR segment - BU of 49 GWd/t - pulse width ~5ms, peak enthalpy increase 549 J/g
  - During that test, DNB occurred (Tclad 600°C) - fuel rod has not failed
  - This Zy2 / Cr_2O_3-doped fuel shows a lot of margin to the Japanese safety limit (at this BU)
  - The rod puncture was made. JAEA indicates that the FGR is a lower value in the increasing trend compared with standard UO2 fuels



T. MIHARA & al., Behavior of high-burnup BWR UO2 fuel with additives under reactivity-initiated accident conditions, September 2022, Journal of Nuclear Science and Technology

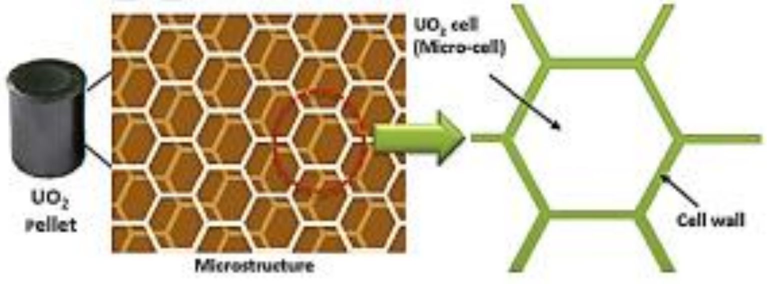
- LOCA at high BU
  - Heating test program to study transient FGR and fuel fragmentation on Cr_2O_3 doped UO_2 fuel
  - 18 tests performed on doped fuel allowed to derive a transient FGR model
  - Example of comparison between calculated transient FGR for UO_2 and Cr_2O_3 doped UO_2 fuel
  - Transient FGR reduced for Cr_2O_3 doped UO_2 fuel in comparison to UO_2 fuel

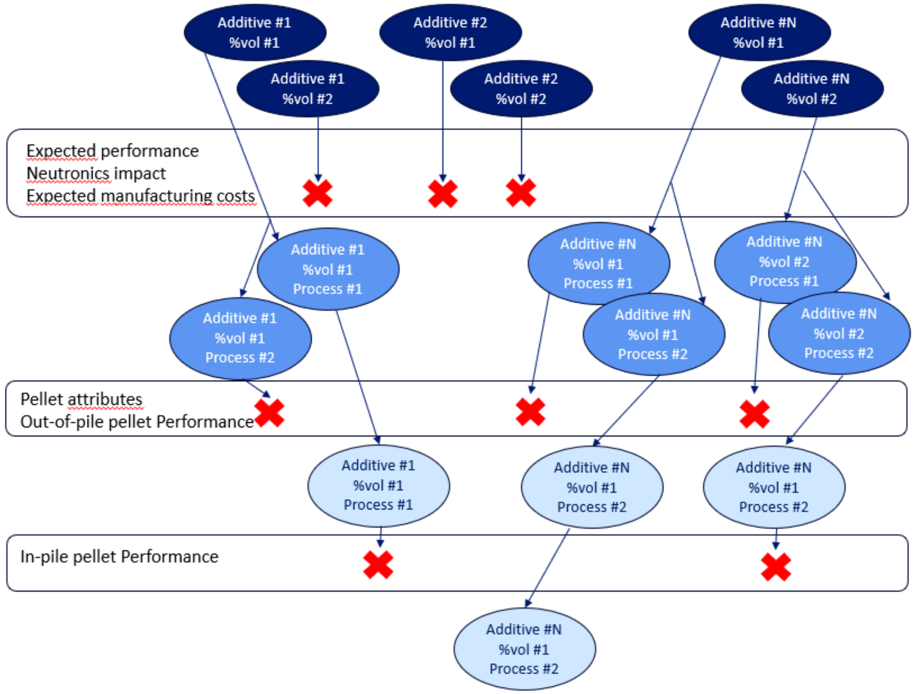


With reduced transient FGR, Framatome Cr_2O_3 doped UO_2 fuel reduces the risk of rupture in the unlikely event of an accident and thus the risk of fuel dispersal at high BU

Framatome microcell fuel development Characteristics

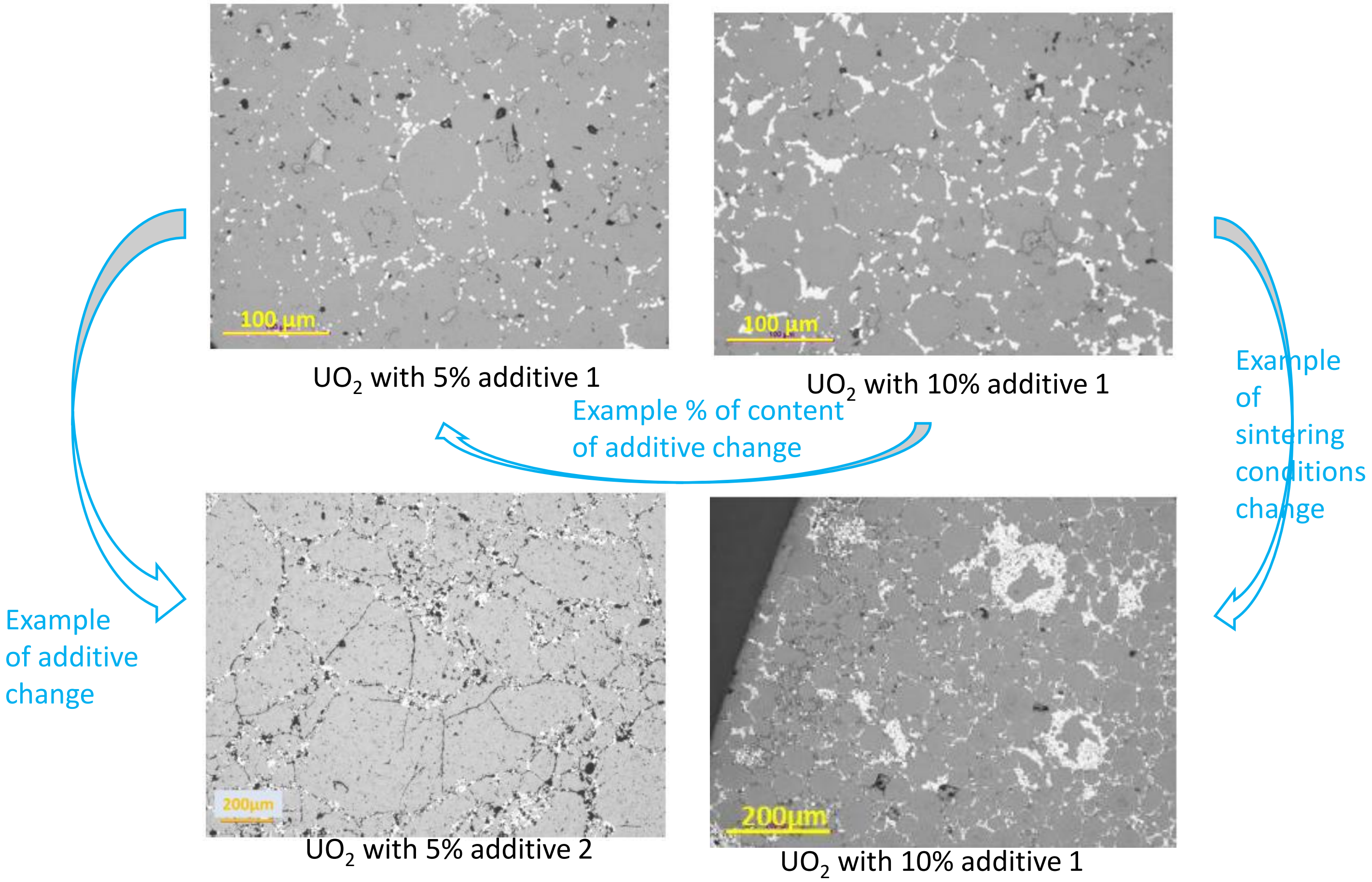
- Microcell fuel are expected to provide benefits in AOO and DBA accidents but are reducing the density of uranium (which can be compensated by an increase of enrichment) due to the presence of an additive. Some additive can in addition have a neutronic penalty.
- The choice of an additive and its percentage is ultimately the result of a trade off.
- Therefore, to explore the potential of microcell fuel, Framatome has launched a development project consisting in several phases
- The first phases addressed in this presentation are
  - Identification of candidates
  - Manufacturability assessment and characterizations
  - Irradiation in a test reactor





Framatome microcell fuel development
Manufacturing

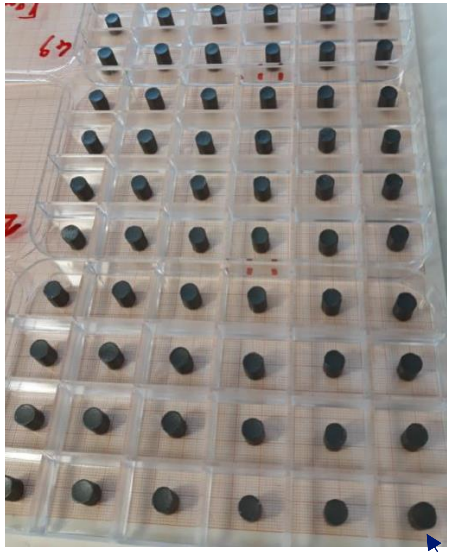
- Fuel pellets were prepared by mixing UO_2 powder with several additive as precursor (in metal or oxide form)
- Sintering conditions were particularly evaluated (temperature, heating rate, holding time, gas mixture) for each variants of additive / content



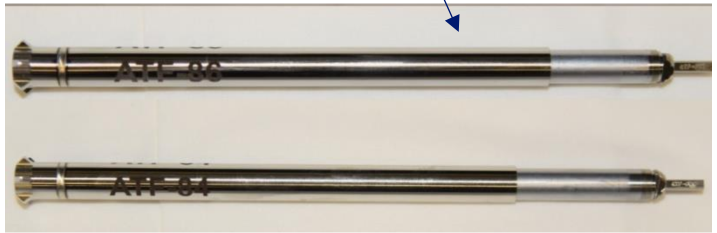
Framatome achieved adequate microstructure, density, O/U for several additives through fine tuning of the manufacturing parameters

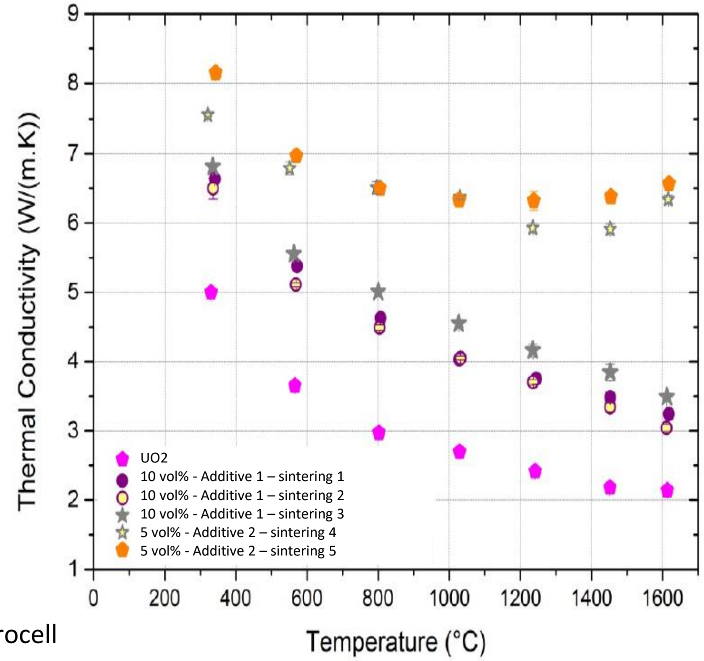
Framatome microcell fuel development Characterization

- Thermal conductivity of microcell pellet variants having adequate microstructure were evaluated
- Thermal-conductivity increase (vs UO_2) depends on the additive, content, manufacturing technique – multiple factor in the range [1,5 – 3]
- Some rodlets were manufactured and irradiated several cycles in the ATR test reactor at INL
- Some of the rodlets are equipped with UO_2 as reference material and some with microcell variants
- Some PIE are planned from this year on irradiated material which include density, microstructural analyses, thermal diffusivity, FGR, pressure



Finished Framatome microcell pellets (top)
Finished rodlets containing Framatome microcell pellets before insertion in ATR (bottom)





Thermal-conductivity measured on several as-fabricated fuel variants

Framatome has launched irradiation of several variants of microcell fuel with increased thermal-conductivity and will acquire results after PIE which will allow to downselect the most promising concepts for continuation of developments

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Take Aways

Conclusions

- With the current LWR reactor fleet / current fuel managements, the best fuel choice improving safety margins at reasonable impact to the fuel cycle costs are UO_2 and UO_2 enhanced materials
- UO_2 with additives are worth exploring for new LWR type or new fuel management which would change of paradigm by challenging safety margins
- The high density fuel have a chemical behavior (breakaway oxidation) which is not acceptable in case of cladding failure in LWR

- Framatome has developed, qualified, licensed in several countries and industrialized Cr_2O_3-doped UO_2 fuel
  - Technical benefits: enhanced viscoplasticity for improved PCI performance and large grain microstructure for improved fission gas retention in accidental conditions
  - Used in reload quantities in all US BWRs served by Framatome and in two European PWRs

- Framatome has launched development of microcell fuel with increased thermal-conductivity. Several variants are under irradiation in the ATR test reactor and PIE which will done will allow to downselect the most promising concepts for continuation of developments

Acknowledgment

- This work is supported by:
  - The U.S. Department of Energy under Award Number DE-NE0009034 (and previously DE-NE0008818 and DE-NE000822)
  - The BPI France under the contract DOS0151318

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Thank you