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FUEL QUALIFICATION FOR GEN-IV SYSTEMS
–
case of MOX fuels

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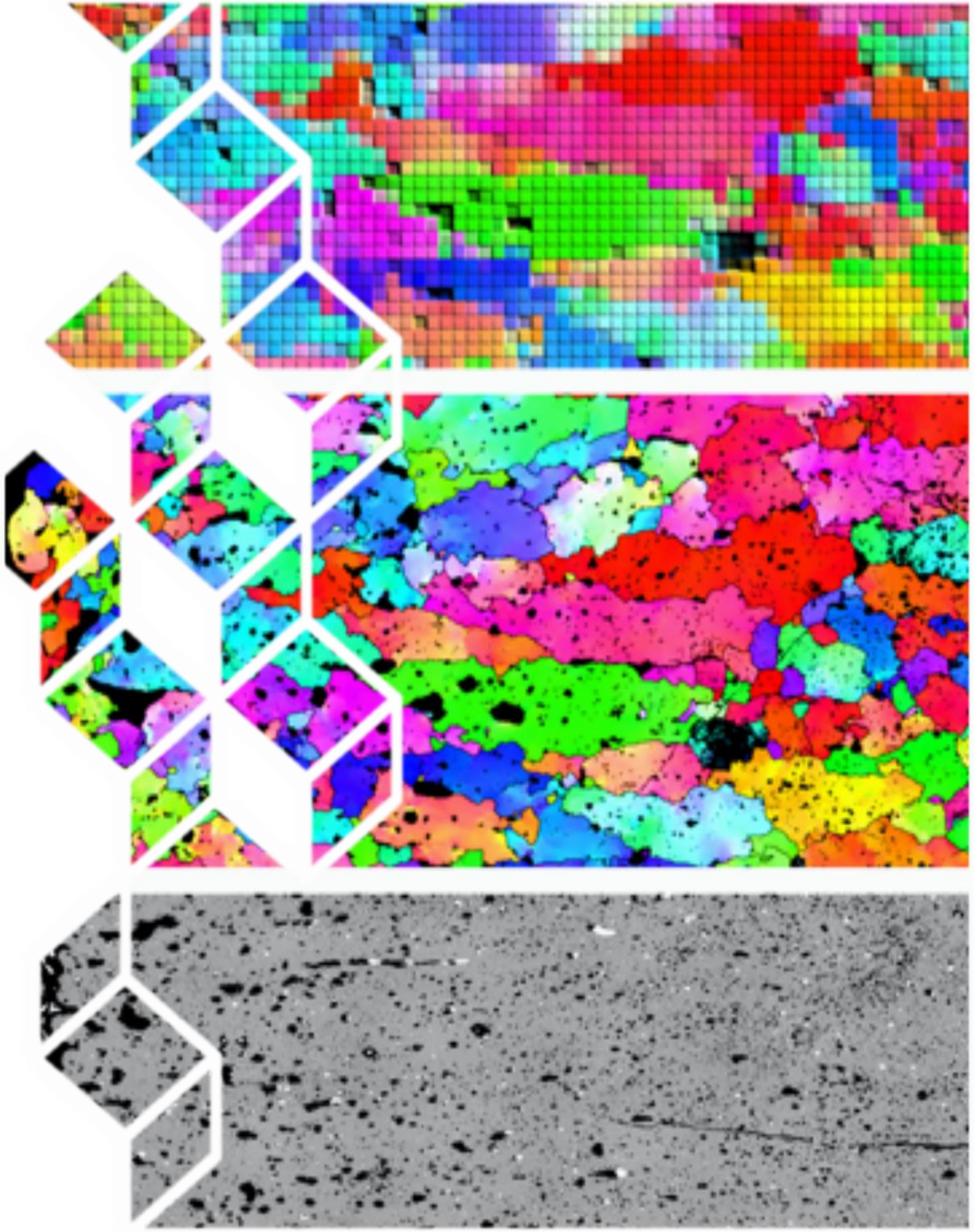


Fuel element licensing : definitions

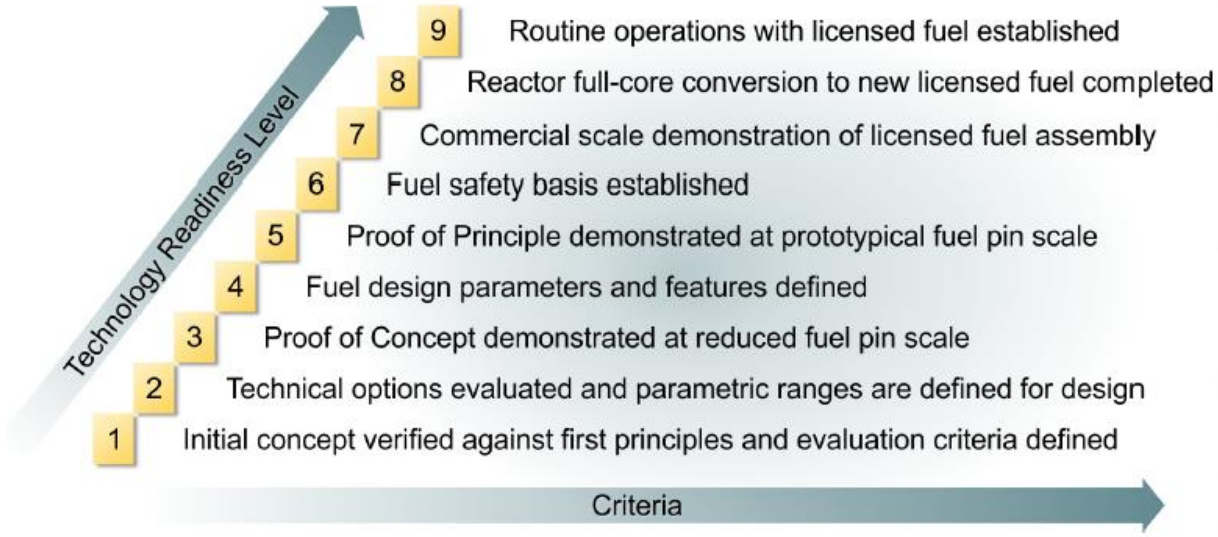
- "The objective of nuclear fuel qualification is the demonstration that a fuel product fabricated in accordance with a specification behaves as assumed or described in the applicable fuel licensing safety case, and with the reliability necessary for economic operation of the reactor plant"
  OECD/NEA/CNRA Guidance on Fuel Qualification

- "Demonstration of fuel compliance to the various requirements is done with the help of fuel performance codes, which take into account all the known phenomena and which have been developed and validated against experimental results."
  Comprehensive Nuclear Materials (Second Edition), Volume 2, 2020,

- "Fuel elements and assemblies for the nuclear power plant shall be designed to maintain their structural integrity, and to withstand satisfactorily the anticipated radiation levels and other conditions in the reactor core, in combination with all the processes of deterioration that could occur in operational states."(IAEA- safety of nuclear power plants : design, req 43). "The fuel elements and fuel assemblies and their supporting structures for the nuclear power plant shall be designed so that, in operational states and in accident conditions other than severe accidents, a geometry that allows for adequate cooling is maintained and the insertion of control rods is not impeded."(IAEA- req 44)

- **References :**
  - D. Crawford, D. Porter, S. Hayes, M. Meyer, D. Petti, and K. Pasamehmetoglu, (2007), «An approach to fuel development and qualification, » *Journal of Nuclear Materials*, 371 (2007) 232-242.
  - NEA (2012), NEA-7072, « Nuclear Fuel Safety Criteria Technical Review, » Second Edition.
  - December 2020, NEA/CNRA approved "Regulatory Perspectives on Nuclear Fuel Qualification for Advanced Reactors"
  - USNRC (2007), NUREG-0800, « Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants : LWR Edition, » Section 4.2, « Fuel System Design, » Rev. 3.
  - "Nuclear fuel qualification: History, current state, and future": https://www.sciencedirect.com/science/article/pii/S0149197024004104
  - Fuel Qualification for Advanced Reactors NUREG 2246
  - "Accelerating nuclear fuel development and qualification: Modeling and simulation integrated with separate-effects testing": https://www.sciencedirect.com/science/article/pii/S0022311519316733
  - IAEA safety report series n°123, Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and Small Modular Reactors
  - NEA/CNRA Guidance on Fuel Qualification

Fuel element licensing : process for qualification



High Level TRL Completion Criteria for Nuclear Fuels and Materials

TRL	Function	Definition
1	Proof-of-Concept	A new concept is proposed. Technical options for the concept are identified and relevant literature data reviewed. Criteria developed.
2	Proof-of-Concept	Technical options are ranked. Performance range and fabrication process parametric ranges defined based on analyses.
3	Proof-of-Concept	Concepts are verified through laboratory-scale experiments and characterization. Fabrication process verified using surrogates.
4	Proof-of-Principle	Fabrication of samples using stockpile materials at bench-scale. Irradiation testing of small-samples (rodlets) in relevant environment. Design parameters and features established. Basic properties compiled.
5	Proof-of-Principle	Fabrication of pins using prototypic feedstock materials at laboratory-scale. Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative compositions under normal operating conditions quantified. Fuel behavior models developed for use in fuel performance code(s).
6	Proof-of-Principle	Fabrication of pins using prototypic feedstock materials at laboratory-scale and using prototypic fabrication processes. Pin-scale irradiation testing at relevant and prototypic environment (steady-state and transient testing). Predictive fuel performance code(s) and safety basis established.
7	Proof-of-Performance	Fabrication of test assemblies using prototypic feedstock materials at engineering-scale and using prototypic fabrication processes. Assembly-scale irradiation testing in prototypic environment. Predictive fuel performance code(s) validated. Safety basis established for full-core operations.
8	Proof-of-Performance	Fabrication of a few core-loads of fuel and operation of a prototype reactor with such fuel.
9	Proof-of-Performance	Routine commercial-scale operations. Multiple reactors operating.

LWR Accident Tolerant Fuels (TRL 1–3)

Transmutation Fuel (TRL 4)
TRU-metal, TRU-oxide
(roughly same TRL)
Metal experience: mostly U.S.
Oxide experience: mostly International (France and Japan)

Fast Reactor Metallic U-Pu-Zr (TRL 7)
- Not formally licensed for a full core load
- Not used in industrial scale

Fast Reactor Metallic (U-Zr), Oxide (U, Pu) (TRL 7–8)
- Licensed for reactor operations
- Successful mission operations
- Operational database wider for MOX, especially considering International experience

LWR UO_2-Zr Fuels (TRL 9)

Summary of TRL Definitions for Advanced Nuclear Fuels Development.

Technology Readiness Levels For Advanced Nuclear Fuels and Materials Development
Jon Carmack, January 2014 FCRD-FUEL-2014-000577

Fuel element licensing for advanced reactors

- Depends on the regulator (country) requirements
- Based on :
  - A range of Fuel composition
  - A fabrication process for liability and requirement compliance towards fuel element composition + microstructure + geometry
  - A clad material
  - A fuel element design : fuel element types, composition and geometry
- Conditions : a range for each following parameter
  - Linear heat rate
  - Burn-up at%
  - Clad dose
  - Clad temp
- Results :
  - Limiting factors vs performances

EXISTING QUALIFICATION FOR OXIDE FUEL ELEMENTS OF FAST REACTORS

Fast Reactors in the world

- Long experience since end of 50's:
  - On MOX fuel :
    - Started in BR-5 in 1957 in Russia, Rapsodie in 1967 in France, SEFOR in USA,
    - Then EBR-II and FFTF in the USA, BR-10, BOR-60, BN-350, BN-600 and BN-800 in Russia, the prototype fast reactor (PFR) in the UK, Phenix and Superphenix in France, KNK and SNR-300 in Germany, JOYO and Monju in Japan, FBTR in India and Experimental Fast Reactor (CEFR) in China.
  - On metal (U,Pu)Zr fuel
    - Started in EBR-I in 1951 in USA
    - Then UK Dounreay Fast Reactor (1963), Enrico Fermi FBR (1963), EBR-II (1964), FFTF (1982)

- Fast reactors in operation :
  - BOR60, BN600, BN800 : UOx and MOX, pellet or vi-pack
  - *JOYO : MOX, pellet*
  - FBTR : carbide, pellet as driver fuel, MOX and (U,Pu)Zr experimental pins
  - CEFR, CFR600 : UOX, pellet

TECDOC 1531, 1691

70 years of experience of oxide fuels for Fast Reactors

	Type	Reactor power	FUEL	CLADDING	Type of fuel element	Pellet diameter	Central hole diameter	Fuel density	%Pu	Linear heat rate - max	Burn-Up – max (at%)	Dose - max
Rapsodie	SFR	12	MOX	316	Very small Φ	5.7	0	high	26	430	27at%	40
PHENIX	SFR	250	MOX	316, 15-15Ti, AIM1	small Φ + solid pellet	5.42	0	high	24 – 28%Pu	450	17,5at%	155
SUPERPHENIX	SFR	1200	MOX	15-15Ti, AIM1	large Φ + annular pellet	7,14	1.0	high	15-20%	480	6at%	60
BOR60	SFR	12	UOX (45%) - MOX	316	large Φ	5,95	1.0 at 1.7	high	5 to 40%Pu	490 - 540	15,3at%	50
BN 350	*SFR*	*52*	*UOX driver - MOX exp*	*316*	small Φ + annular pellet	*5,95*	*1,7*	*high*	*26%Pu*	*450*	*10 at%*	*40*
BN 600	SFR	560	UOX driver - MOX exp	CH-S68 or ODS	small Φ + annular pellet	5.95	1.6	high	18-20-23%Pu	470 460	15at% 20,6at%	110 182
BN 800	SFR	820	MOX	EK164-CH-S68	small Φ + annular pellet	5.95	1.6	high	18-20-23%Pu	480	>10at%	>80
DFR	SFR	15	MOX	316	small Φ + solid pellet	5.0	0	high	22 -28%Pu	400-600	7at% MOX	40
PFR	SFR	250	MOX	PE16	small Φ + annular pellet	5.04	1.5	high	21 -28%Pu	450	>10at%	200
KNK 2	SFR	17	MOX	316	small Φ + annular pellet	6.0	1.0	high		450		60
JOYO	SFR	30	MOX	PNC316	small Φ + solid pellet	4.63	0	high	16-30%Pu	420	15at%	100
MONJU	SFR	280	MOX	PNC316	small Φ + solid pellet	5.4	0	low	32%Pu	360	9.4at%	100
SEFOR	SFR	0	MOX	316	Very large Φ + solid pellet	22,22	0	high	20-27%Pu	60-600	5 at%	30
FFTF	SFR		MOX	316	small Φ + annular pellet	5.55	1.47	high	22, 27%Pu	430	14at%	70
EBR2	SFR	20	Metal driver + MOX exp	316	small Φ + annular pellet	5.5364	1.397	high	29%Pu	348	23.6 MOX	155
FBTR	SFR	12	(U,Pu)C driver + MOX exp	D9	small Φ + annular pellet	5.52	1.8	high	21 -28%Pu	450 MOX	12at% MOX	62
PBFR	SFR	500	MOX	316, D9	small Φ + annular pellet	5.52	1.8	high	21 -28%Pu	450	>10at%	85
CEFR	SFR	20	UOX driver – MOX exp	316, CN15-15	small Φ + annular pellet	5.2	1.6	high	25%Pu	430	8	40
CFR600	SFR	650	UOX then MOX	CN15-15, FMS, ODS	small Φ + annular pellet	5.0	1.5	high	25%Pu		>10 at%	60

- *To be published : Nuclear Energy Series No. NF-T-2.6, "Nuclear Fuel Technologies for Liquid Metal Cooled Fast Reactors (LMFRs)"*
- *IAEA-TECDOC-1531, Fast Reactor Database*
- *https://world-nuclear.org/nuclear-reactor-database#*

Synthesis on MOX fuel qualification for FRs

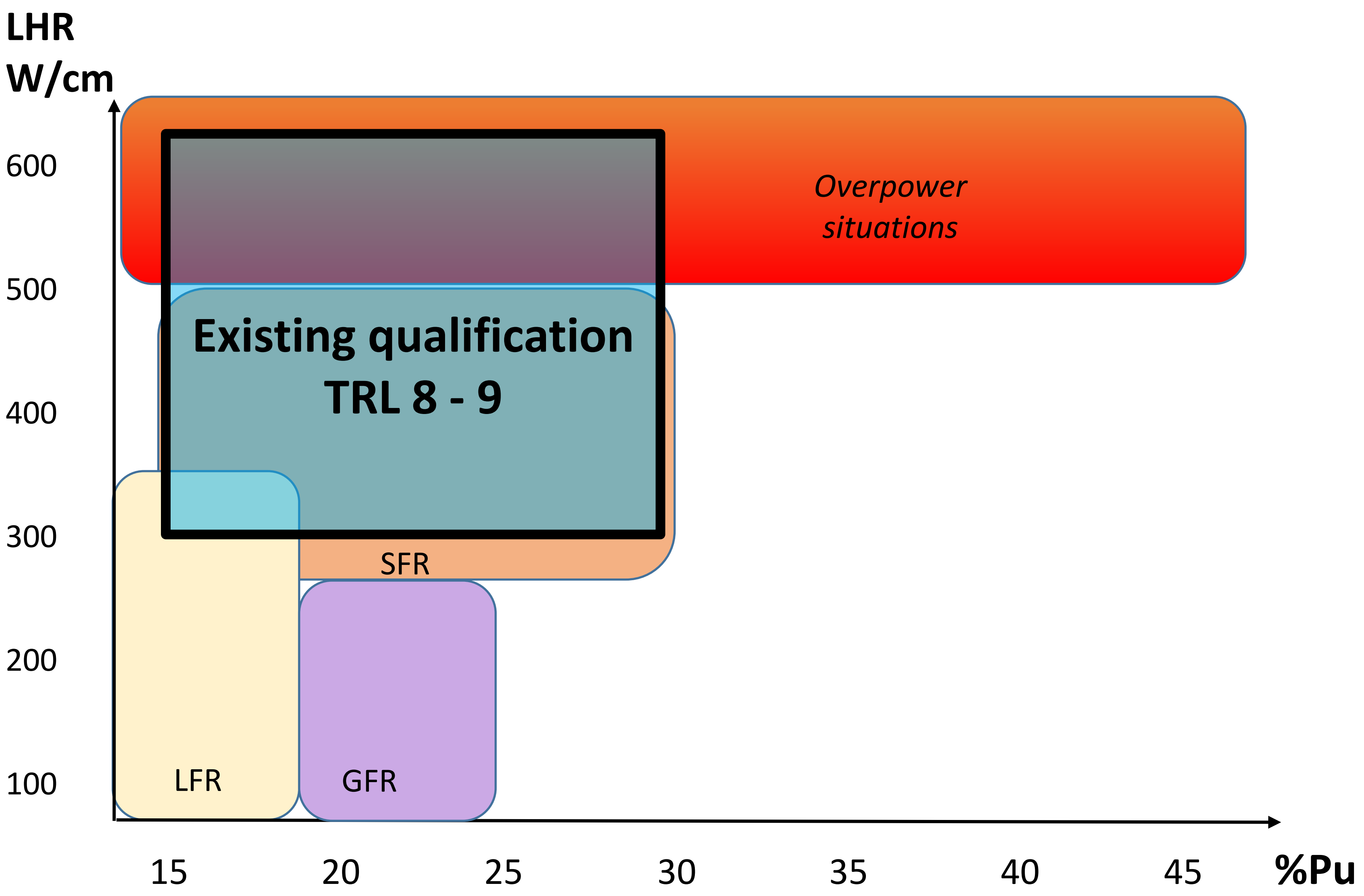
- Licensing (existing or passed in several countries):
  - →Small pin - full or annular pellets & Large pin - annular pellets
  - →sodium
  - →MOX at 15-28%Pu
  - →several (<5) claddings
  - →several fuel fabrication processes
  - →LHR >300 W/cm
  - →burn-up < 10at%

MOX case :

limiting factors : margin to fuel melt, margin to clad failure (FCCI, FCMI), low clad strain (coolability)

performances : high burn-up, high flexibility (reactor, fuel cycle)

QUALIFICATION OF MOX FUEL FOR GENIV SYSTEMS



NEW FUEL ELEMENTS FOR FAST REACTOR WITH LARGE AND SMALLER CORES (AMR)

Reactor under design, construction, regulatory review - oxide fuels for fast reactors

	Type	Reactor power MWe	FUEL	CLADDING	Type of fuel element	Pellet diameter	Central hole diameter	Fuel density	%Pu	Linear heat rate - max	Burn-Up - max	Dose - max
NEWCLEO	LFR	30 - 200	MOX	15-15Ti : AIM1	large Φ + annular pellet	7,14	1,0	high	23 – 30 W/Wo Am	50 - 320	10	100
OTRERA	SFR	150	MOX	AIM1	large Φ + annular pellet HAX	>10	1.0 – 2.0	high	17	250 - 400	10	
HEXANA	SFR	150	MOX	AIM1	large Φ + annular pellet	7,14	1,0	high	30	400-450	10	
ALFRED	LFR	125	MOX	AIM1		9.0	2.0	high	20-26	350	10	
ELFR/EAGLESCK ANSALDO ENEA	LFR	630	MOX	AIM1				high	23-30		10	
ALLEGRO	GFR	25	MOX/UPuC	AIM1	small Φ + solid pellet	6,5	0	high	20	80		
MYRRHA	ADS	30	MOX driver	AIM1	small Φ + solid pellet	5.42	0	high	30	80-230	7	
MBIR	SFR	50	MOX driver	CH-S68	small Φ + annular pellet	5.7	1.0	high	36,5	500-700	12	
BN1200	LFR	2800	UPuN or MOX	EK 164 - ID				high	20-30	465		
BREST-OD-300	LFR	300	UPuN driver MOX exp	EP823-Sh	large Φ + annular pellet	5.95	1.6	high	Pu+ Am	420	6	
SVBR-100	LFR	100	UOx or (U,Th)O2					high			6	
DEMO-SFR	SFR	650	MOX	ODS	small Φ + annular pellet	7.32	2.0	high	20-30	430	25	250
Westinghouse	LFR	450	MOX					high				
CFR1200	SFR	1200	MOX					high				
CLEAR - M	LFR	3	UOX - MOX	316				high				
BLESS-D	LFR	300	UOX	15-16Ti				high				

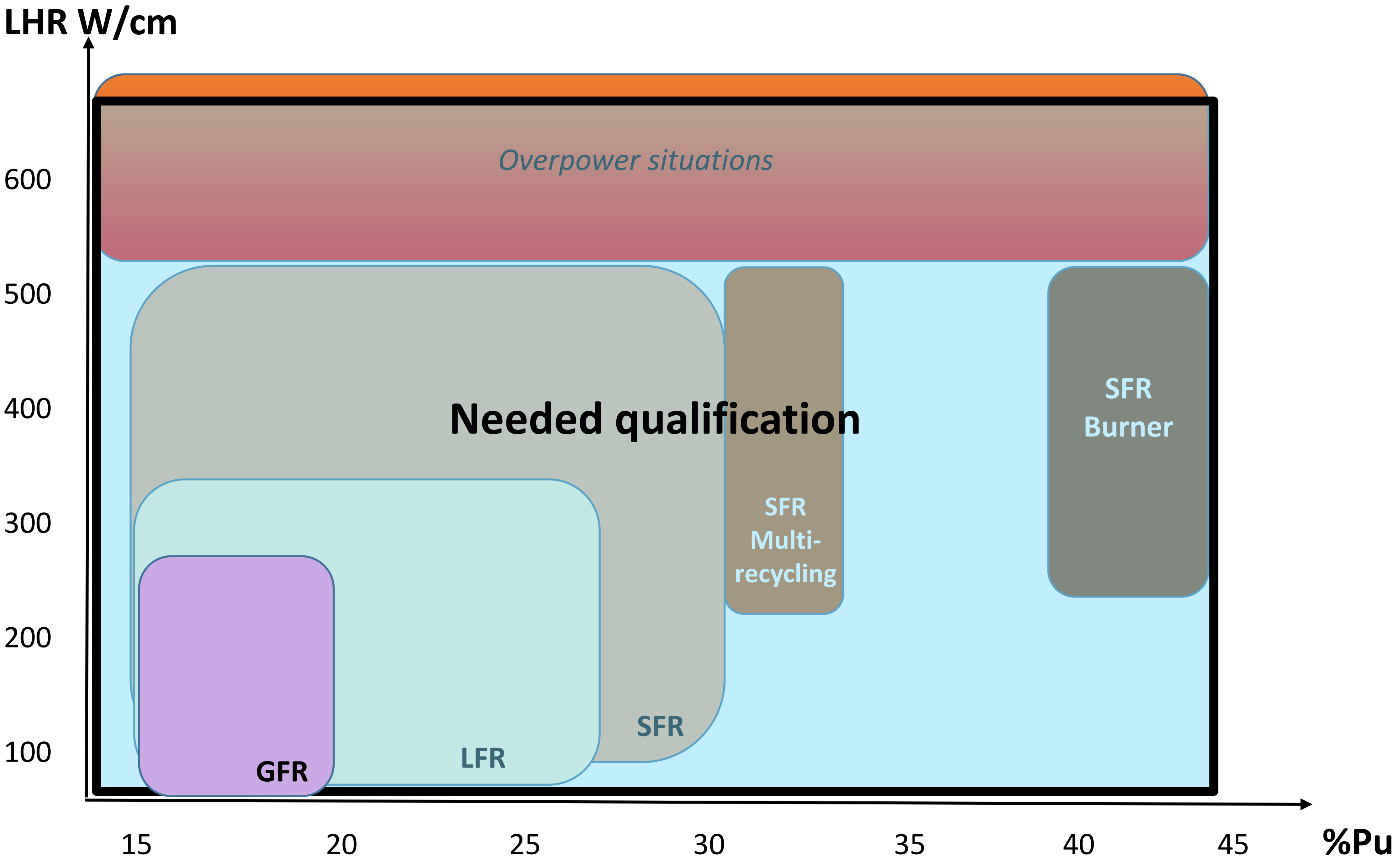
https://aris.iaea.org/Characteristics/

https://aris.iaea.org/Publications/booklet-fr-2013.pdf

Fast reactors : needs for MOX fuel qualification

	SFR	LFR	GFR	ADS
Countries	Japan, Russia, China, USA, France, E.U., Korea,	China, Russia, E.U.,USA	E.U.	Belgium, China
		REACTOR		
power	3 to 3000 MWe			
		FUEL CYCLE		
Options	Open cycle – close cycle – mixed park (PWR → FRs)– increasing nuclear power part (COP28) – introducing renewables – symbiotic park			
Objectives	Pu : burner – isogenerator – breeder multirecycling or not , MA : burner or not			Pu and MA: burner
Pu management	Pu from PWR UOX spent fuel, Pu from PWR MOX spent fuel, Pu from FR UOX spent fuel			Pu from PWR UOX spent fuel
U management	U : Urep - Udep – Unat - HALEU			
Minor actinides	0-1-2-3%Am			>20% in targets
Industrial processes	Fabrication : conventionals, otimised, 3D printing, …, reprocessing: several processes			
		FUEL ELEMENT		
Fuel material	MOX or UOX			U free fuel - MOX
Fuel composition	15-30-45% Pu			Pu% > 30%
Fuel element	Small/large pin, solid/annular pellets			
Clad	Austenistic, ODS, HEA, refractory metals….			
Clad temperature	400-700°C			
LHR	50 – 500 W/cm			
Burn-up	6 to 20at%			

QUALIFICATION OF MOX FUEL FOR GENIV SYSTEMS

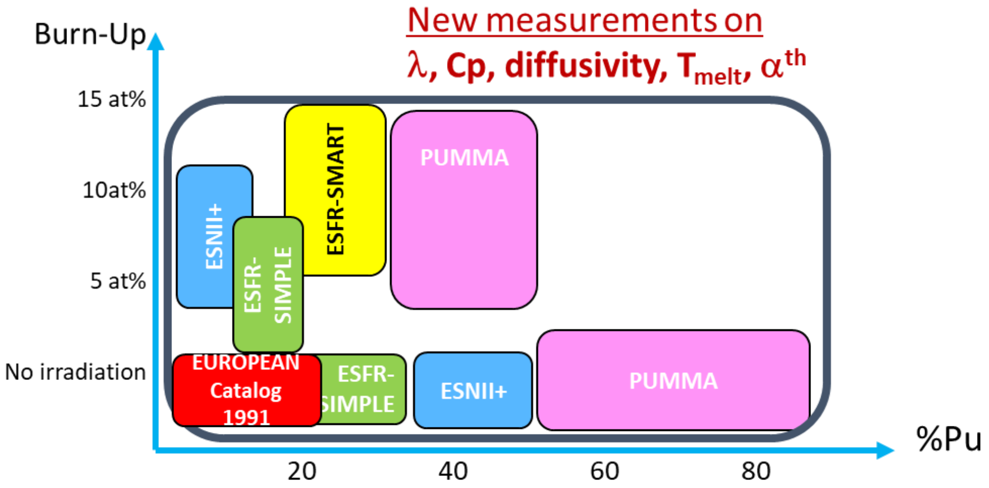


Fuel element qualification : needs

- Licensing needs:
  - →extension to different fuel compositions (Pu: 15–32–45%)
  - →extension to low LHR
  - →extension to different coolants (chemistry, temperature)
  - →impact of fuel cycle options (reprocessing and multirecycling)

MOX properties : needs for extension

- Extend the validation range of each property towards temperature, fuel composition (%Pu, density, microstructure, O/M)
    - Experimental programme in Europe (JRC-K, CEA)
    - Experimental programme in Japan (JAEA)



- Recommendations on laws for fuel performance codes for each property with uncertainties and domain of validation
(OECD-NEA-NSC-Expert Group on Innovative Fuel Element)
    - First international reference of fuel properties for fuel performance codes for fast reactors – and possibly beyong
    - Focus on mixed oxide (UPuO2) and metal fuels (UPuZr)
    - Identify missing data to extend the validation domain

https://www.oecd-nea.org/jcms/pl_107583/recommendations-on-fuel-properties-for-fuel-performance-codes

$(U,Pu)O_2$	UPuZr
• Lattice parameter • Solidus temperature • Thermal expansion • Thermal conductivity • Specific heat • Elastic constant • Oxygen potential	• Phase transition temperature • Melting temperature • Specific heat • Thermal conductivity • Thermal expansion • Thermal creep

Conclusion

- Oxide fuel for fast reactors has proved to be a mature, reliable, performant and very robust fuel concept

- Now, Fast Reactors must be flexible towards fuel cycle options (U: U_{REP} - HALEU, Pu : burner-iso-breeder, multirecycling) and reactor designs (size, power, grid adjustment, coolant)

- Qualification of MOX fuel is well demonstrated with many options but must be :
  - →extended to different fuel compositions, different fabrication processes and different irradiation conditions
  - →accelerated (new approach required, task force at OECD launched in 2025)
  - →applicable in different countries
  - →single design and different fuel composition to cover all the needs

- Associated activities
  - → fuel performance code validated with integral and analytical irradiations and out-of-pile tests
  - → experimental programme on fuel properties

MOX fuel elements for Fast Reactors

- The low conductivity of mixed oxide may appear as a weakness of this fuel as it induces a limitation of linear heat generation. However, thanks to its high operating temperature and related high creep rate, fuel mechanical loadings to the cladding remain low, and oxide fuel pins have demonstrated an ability to reach extremely high burnup. Experience achieved in the past decades on oxide fuel behavior in fast reactors paves the way to face the new challenges of the next generation of reactors for Generation IV systems. The first prototypes of this new generation which are currently built in China, India and Russian federation and under design in Europe and Japan will use oxide as it is the most mature fuel among the various candidates. All phenomena occurring in fast oxide fuel during its irradiation are relatively well understood, modeled and managed in the fuel element design.

Comprehensive Nuclear Materials (Second Edition), Volume 2, 2020,

Thank you

For any comment on the data, please contact me at nathalie.chauvin@cea.fr