Accident Tolerant Fuel Cladding for Light Water Reactors

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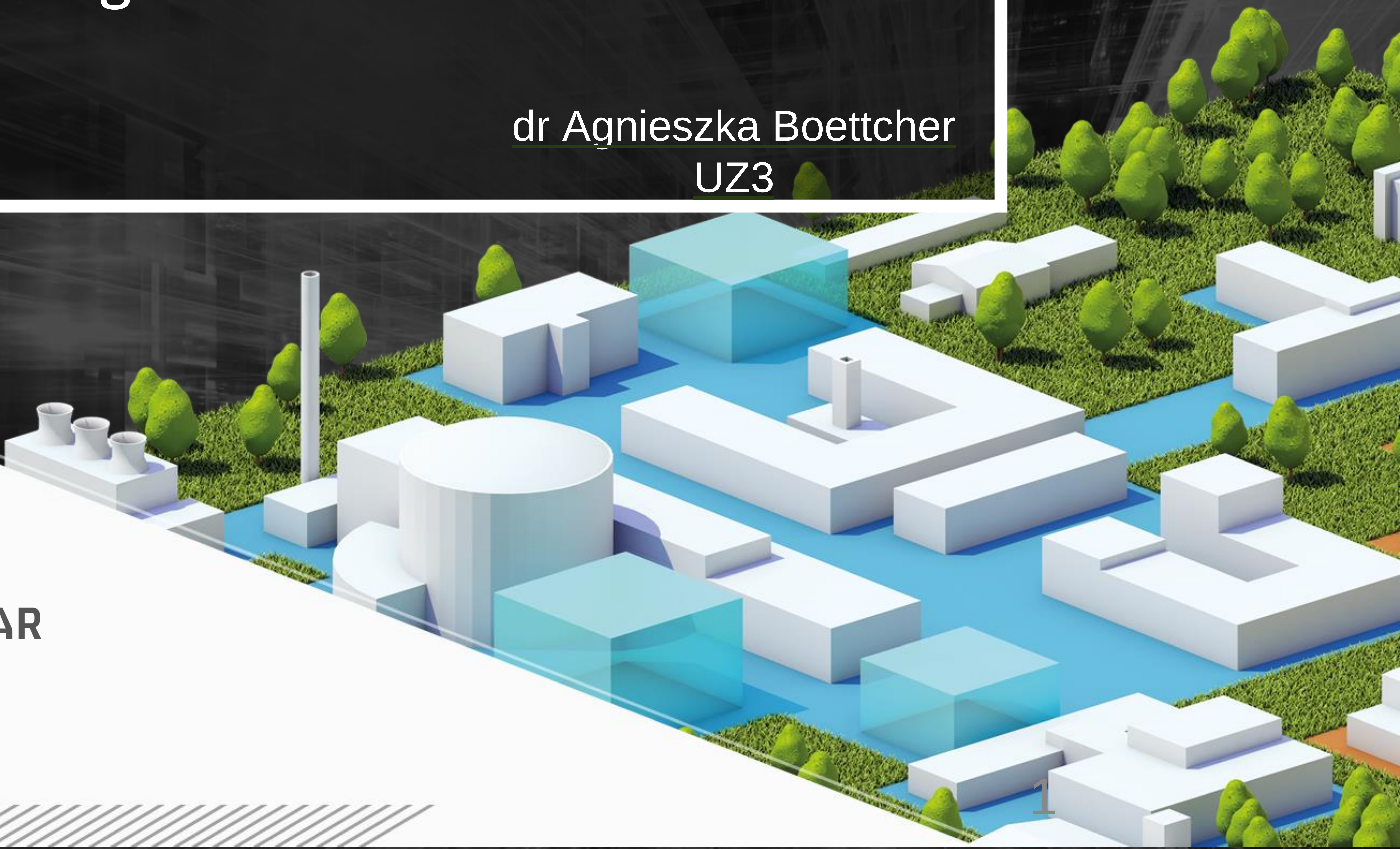
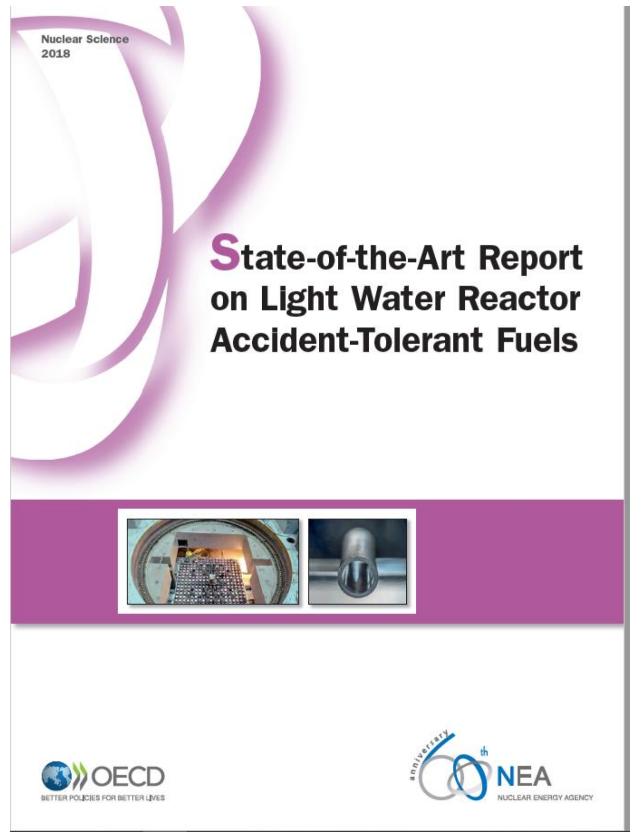


OUTLINE

1. What ATF mean?
2. What criteria should ATF meet?
3. Examples of ATF cladding candidates.
4. Summary.
5. Proposed reference

What ATF mean?

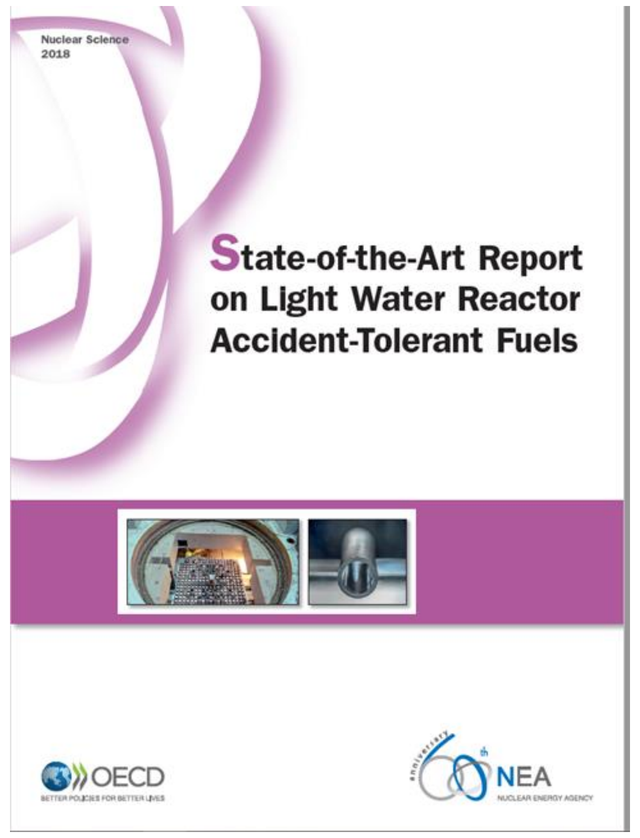


fuel + fuel cladding

Accident Tolerant Fuels may offer opportunities to enhance the safety and competitiveness of commercial nuclear power plants.

Enhanced accident-tolerant fuels (ATFs) are defined as fuels that can tolerate a severe accident in the reactor core for a longer time period than the current UO_2 zirconium alloy fuel system, while maintaining or improving the fuel performance during normal operations and operational transients.

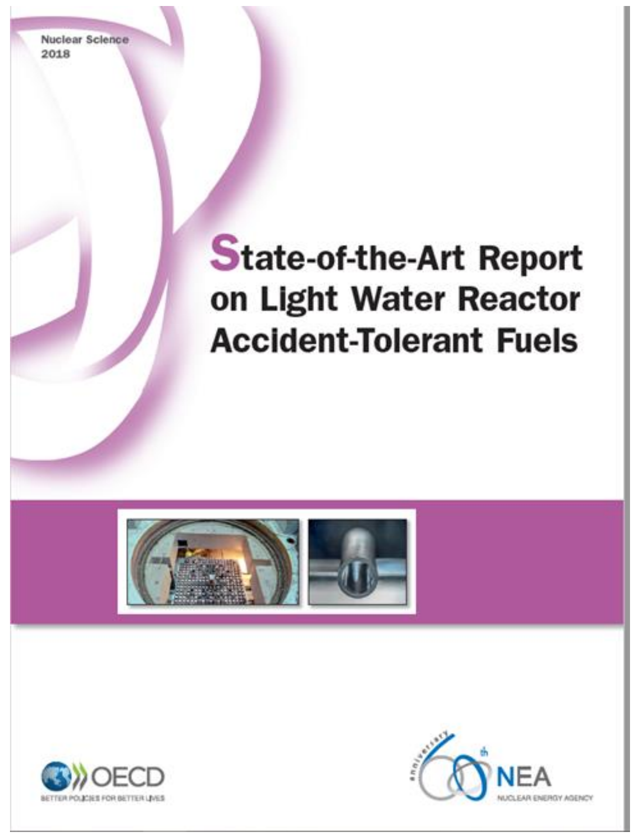
What criteria should ATF meet?



Fuel cladding is a second barrier in a nuclear reactor and first of all, should prevent the penetration of fuel fission products into the cooling circuit.

The goal of accident-tolerant fuel (ATF) development is to identify alternative fuel system technologies to further enhance the safety, competitiveness and economics of commercial nuclear power. Any new fuel concept should be evaluated against current design, operational, economic and safety requirements to assess the regulatory safety compliance with operational and economic constraints. Holistic considerations of the potential impact of ATF concepts on the entire fuel cycle should be addressed.

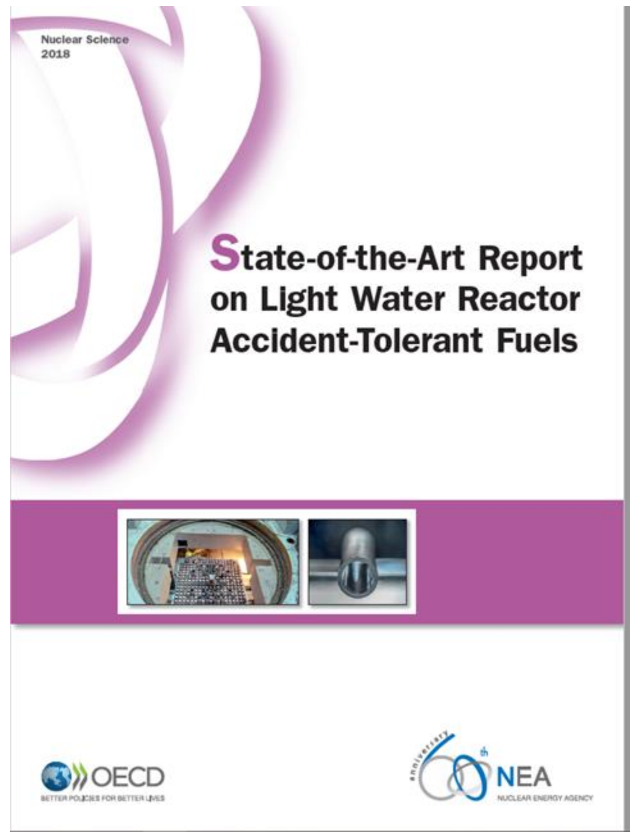
What criteria should ATF meet?

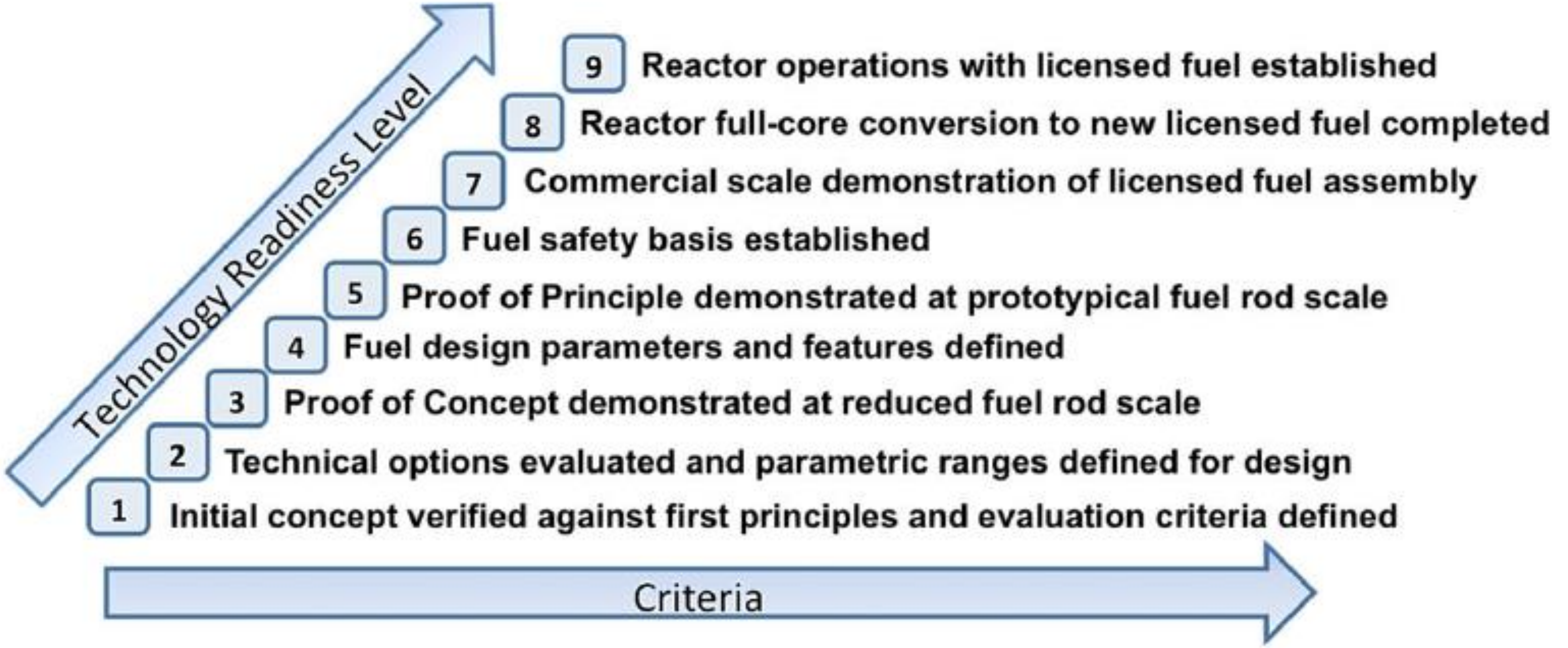


The constraints associated with commercial nuclear fuel development and deployment that are applied to ATF designs include:

- backward compatibility: compatible with existing fuel handling equipment, fuel rod or assembly geometry and co-resident fuel in existing and future LWRs; concept designs should maintain or increase access to non-intrusive and intrusive examinations and inspections;
- operations: maintains or extends plant operating cycles, reactor power output and reactor control; fuel system concepts seeking regulatory approval will need to demonstrate reliability under normal operations and transients (i.e. anticipated operational occurrences);
- safety: meets or exceeds current fuel system performance under normal, operational transient, design-basis accident (DBA) conditions and design extension conditions (DECs; previously referred to as beyond-design-basis accidents [BDBAs]);
- front end of the nuclear fuel cycle: adheres to regulations and policies, for both the fuel fabrication facility and the operating plant, with respect to technical, regulatory, equipment and fuel performance considerations;
- back end of the nuclear fuel cycle: cannot degrade the transport, storage (wet and dry) or repository performance of the fuel (assuming a once-through fuel cycle); should consider possible use within a closed fuel cycle.

What criteria should ATF meet?- TRL

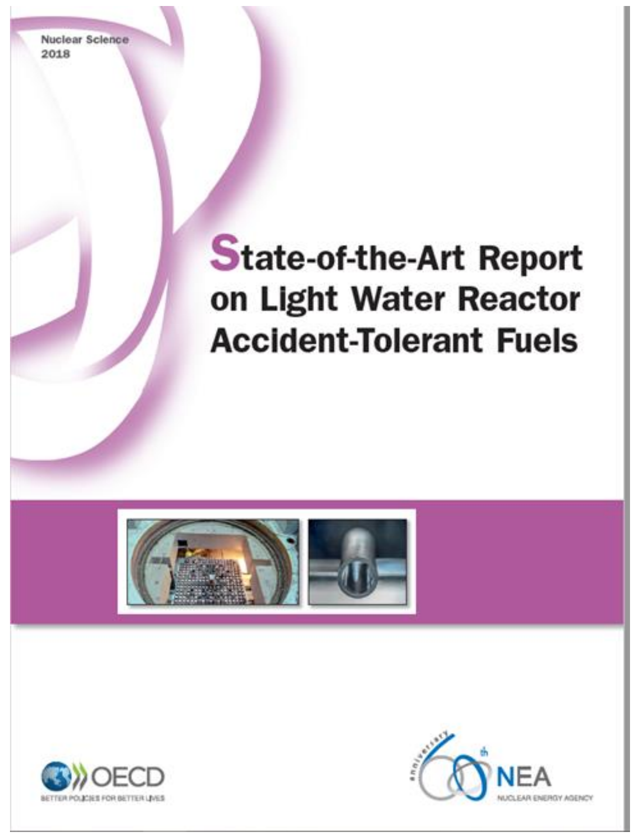




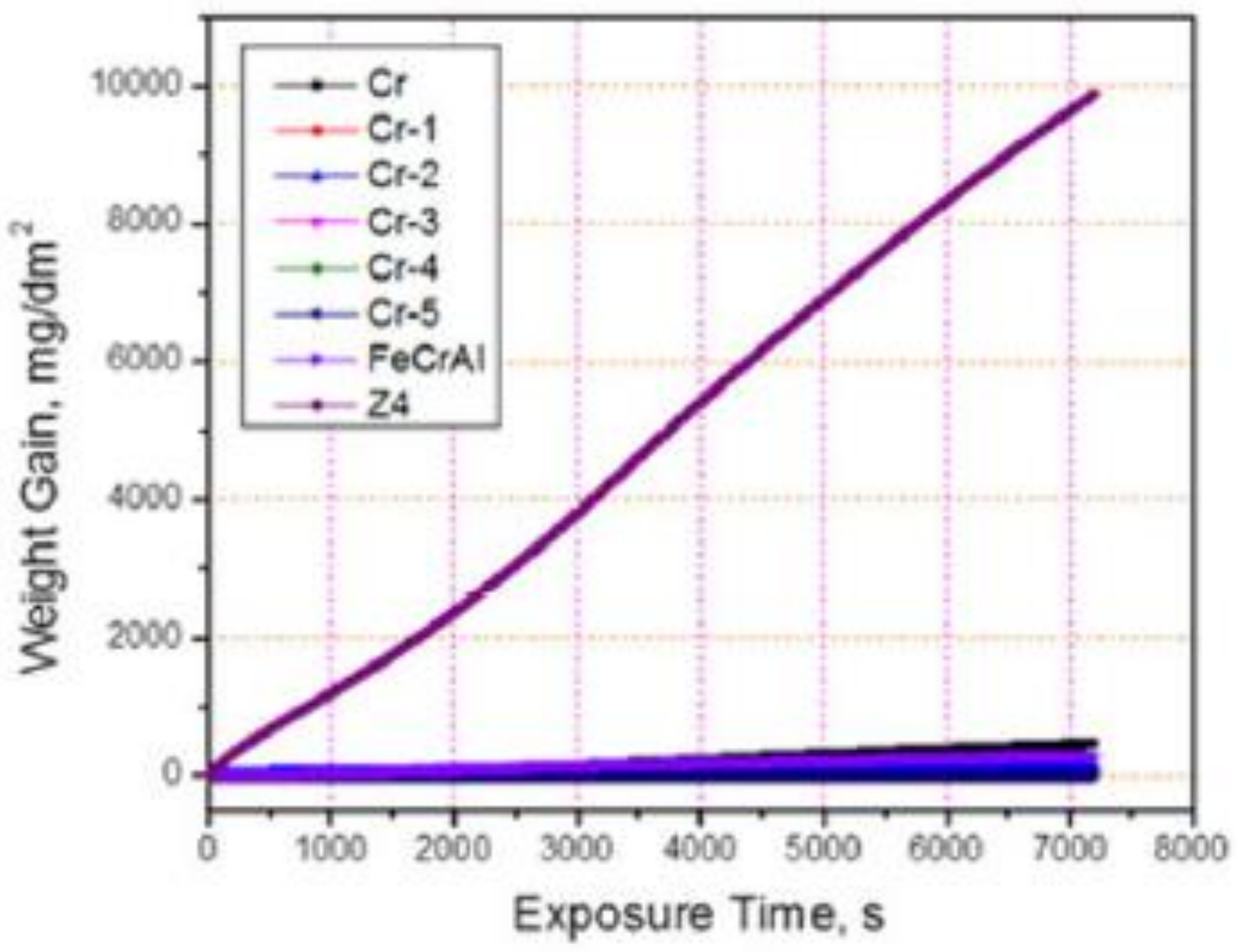
Source: Modified from OECD (2014) and Carmack et al. (2017).

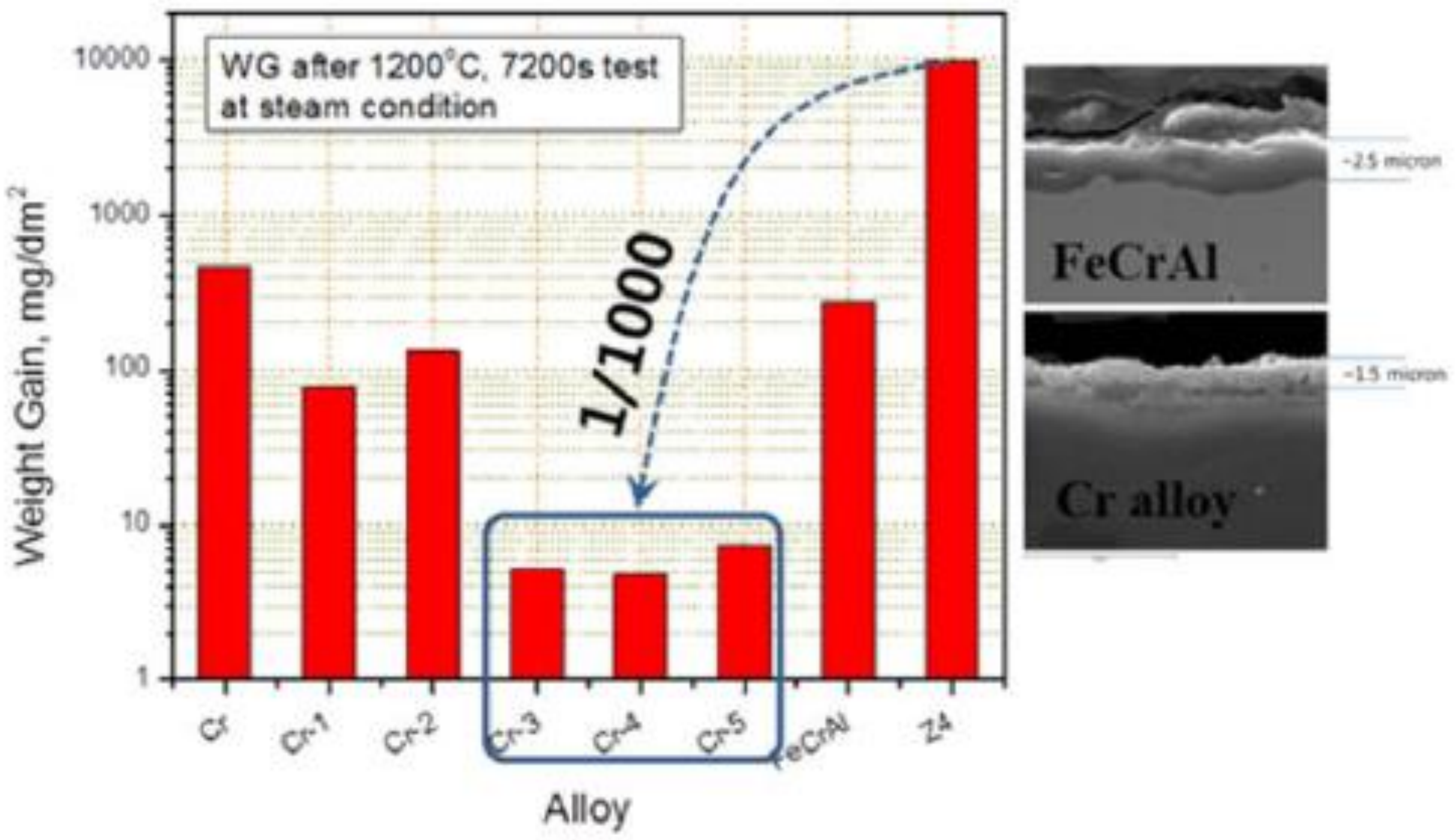
1. Proof of concept.
2. Proof of principle.
3. Proof of performance.

Examples of ATF cladding candidates.

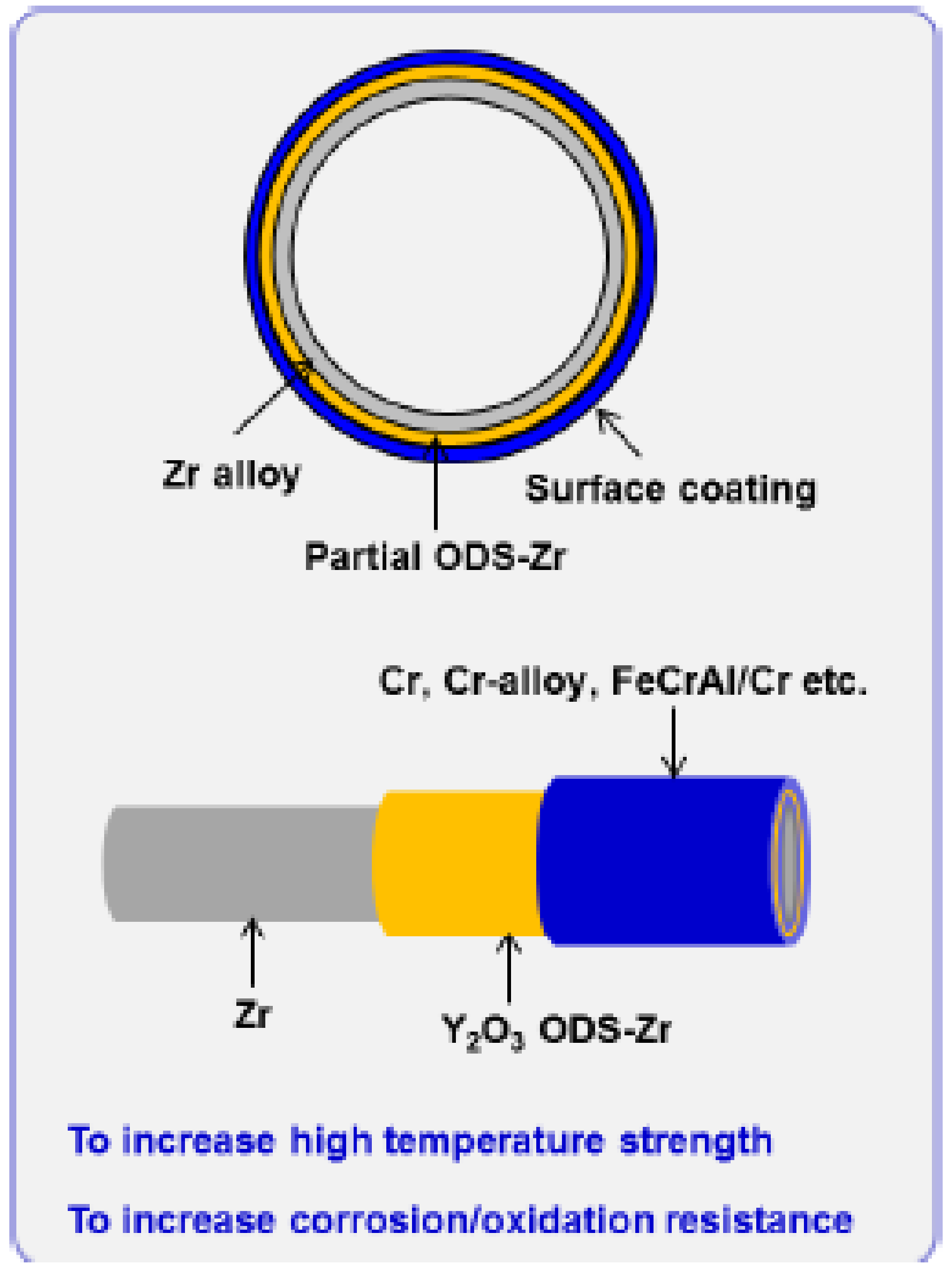


- Coated and improved Zr-alloys (Metallic or Ceramic coatings- FeCrAl, CrN, TiN, TiAlN, CrAlN)





Source: Park et al., 2015.

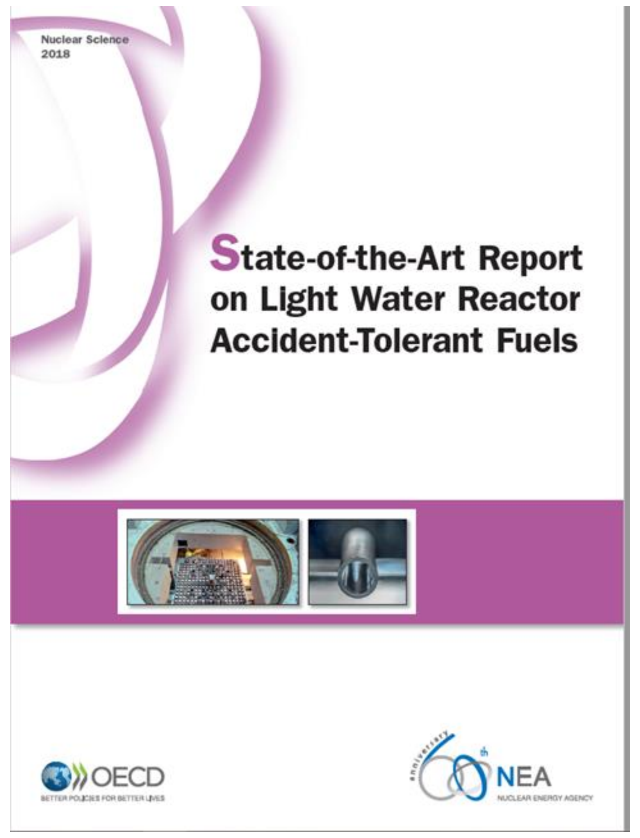


Weight gain results from HT steam oxidation tests at 1 200°C for the Cr, Cr-Al and FeCrAl for the KAERI coated concepts

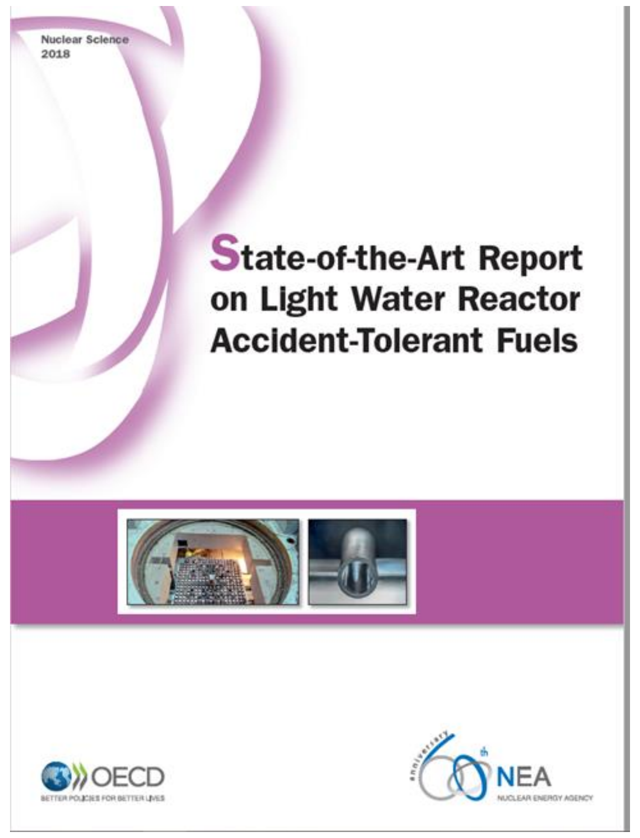
Source: Kim et al., 2016.

Coated and improved Zr-alloys

Institution	Coating system	Fabrication	Normal operation	Accidental behaviour
AREVA-CEA-EDF	Cr (5-20 µm)	PVD Full-length prototype ongoing	Extremely low corrosion + H pickup Similar mechanical behaviour as uncoated Very good adherence Cr-Zr interface stable under ion irradiation Increased wear resistance	Significantly reduced HT steam oxidation Increased post-quench ductility Strengthening effect of Cr – reduced HT creep, reduced ballooning Very adherent and no or very limited cracking after significand clad creep/balooning Zr-Cr eutectic (1 330°C) behaviour TBD
KAERI	Cr Cr-Al FeCrAl (40-80 µm)	PVD (ion plating) Three-dimensional laser coating	Extremely low corrosion + H pickup Increased strength and reduced ductility Very good adherence Increased wear resistance	Significantly reduced HT steam oxidation (up to 1 400°C) Increased post-quench ductility Strengthening effect of Cr – reduced HT creep, reduced ballooning Fe-Zr eutectic around 900°C (use of barrier layer)
IFE-Halden/ CNL	CrN (1-4 µm)	PVD Commercially available (full-length)	Extremely low corrosion + H pickup Good adherence Increased wear resistance Minor cracking of coating observed after irradiation	Reduced HT steam oxidation Some cracking of coating observed during HT steam oxidation Very adherent during HT bust test but significant cracking at burst/balloon location
	TiAlN CrAlN (1-4 µm)	PVD Commercially available (full-length)	Dissolves in water Poor adherence	Cracking and delamination observed after HT steam oxidation
KIT	MAX phases (Ti_2AlC; Cr_2AlC) (~5 µm)	PVD Difficult to obtain correct stoichiometry + microstructure	No data Potential dissolution of Ti_2AlC in water (Al_2O_3)	Similar HT steam oxidation resistance of Ti_2AlC to uncoated Zy4 Reduced HT steam oxidation of Cr_2AlC
UIUC	Cr-Al (~1 µm) FeCrAl (~1 µm)	PVD	Difficult to interpret results (deposits) Reduced corrosion but weight loss for FeCrAl (dissolution of Al_2O_3)	Slight reduction in HT steam oxidation at 700°C Negligible effect at 1 200°C steam (too thin) Fe-Zr eutectic ~900°C
PSU	TiN / TiAlN (~10 µm)	PVD (multi-layer coating)	Low corrosion + H pickup if surface TiN	No data



Coated and improved Zr-alloys



Main advantages:

• significantly reduced HT steam oxidation leading to reduced heat and hydrogen production;

• increased post-quench ductility;

• strengthening effect at high temperature leading to reduced creep and ballooning and to increased time to rupture.

Challenges to be monitored:

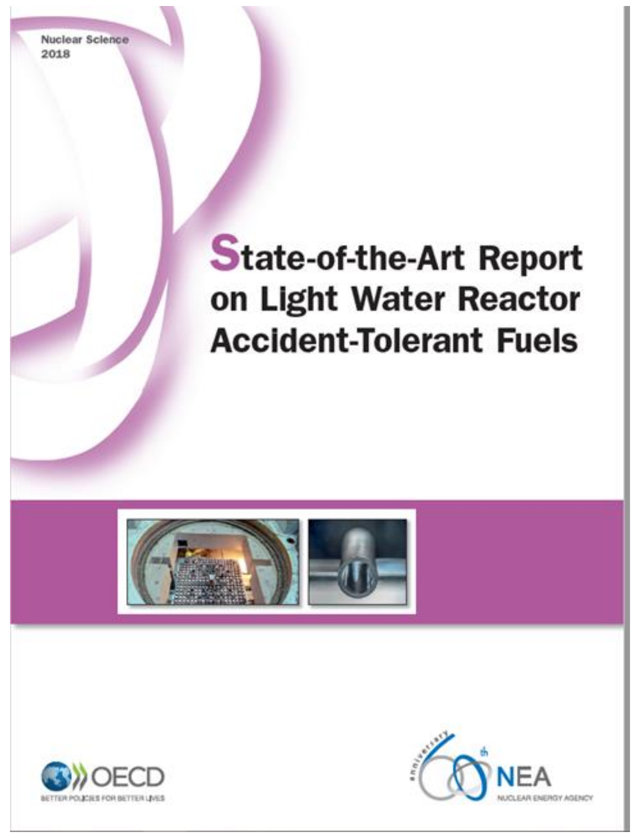
• coating has to be thick enough to provide significant reduction in HT steam oxidation;

• potential eutectic formation (especially for metallic coatings);

• coating has to be thin enough to limit the extent of potential eutectic formation for metallic coatings;

• few data exist for HT behaviour (mechanical and oxidation) of ceramic coatings.

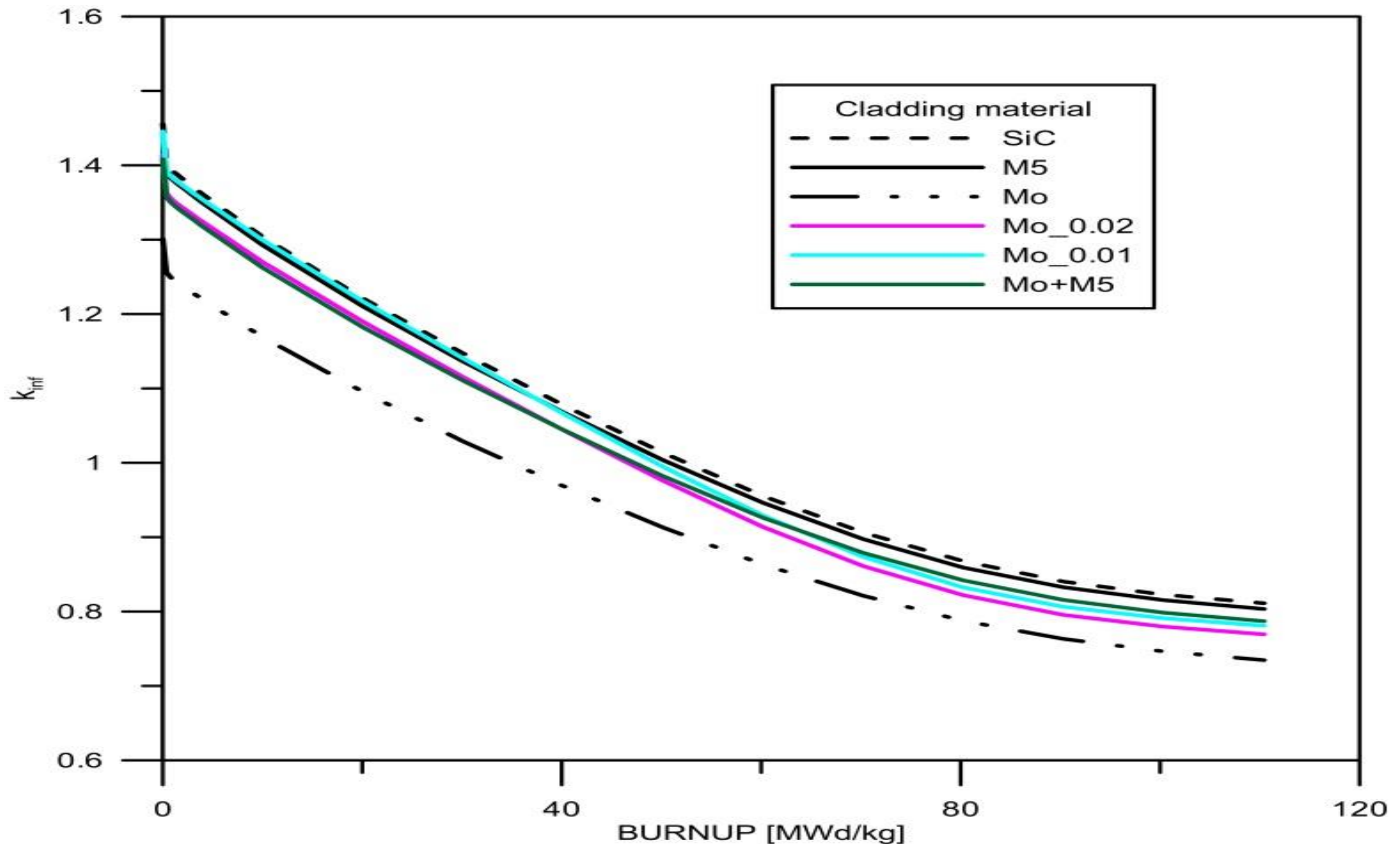
Examples of ATF cladding candidates.



Material	Melting point [°C]	Absorption cross section for thermal neutrons [barn]	Thermal conductivity [W/(m·K)]
SiC	~2800	0.019	~20÷350
Mo	2623	2.6	138
Zr alloy	~1800	~0.19	22
ZrO_2	2715	~0.18	2-3

Christina A. Back, Advanced Fuel Technologies at General Atomics, OECD – NEA Meeting; December 10, 2012

- Advanced steels: FeCrAl.
- Metals: Lined Mo-alloy cladding
- SiC/SiC-composite cladding

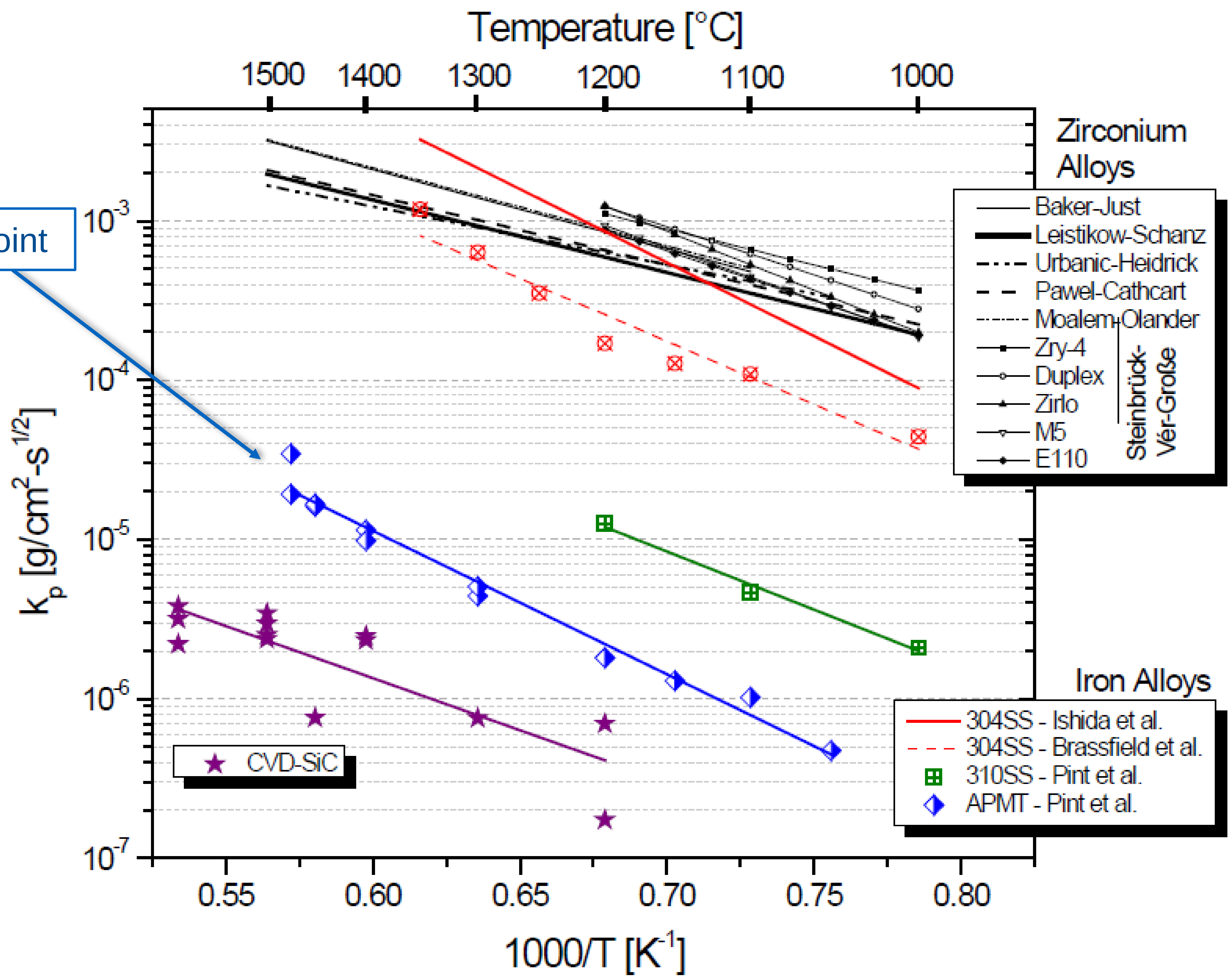


Multiplication factor (k_{inf}) as a function of burnup

A. Boettcher, Z. Marcinkowska, Annals of Nuclear Energy 2018

Examples of ATF cladding candidates.

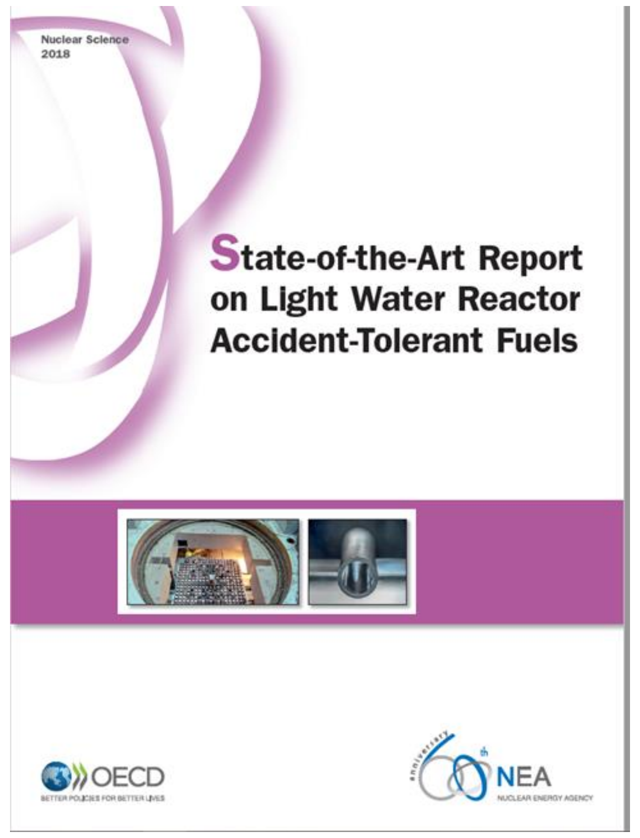
Melting point



Kinetics of oxidation of APMT is three orders of magnitude lower than the kinetics of oxidation of zirconium base alloys.

*AMPT iron-chromium-aluminium alloy

Summary



Candidate fuel and cladding system should seek to preserve or improve upon:

- burn-up limit/cycle length (while maintaining criticality and fuel performance);
- operational parameters (power distribution, peaking factors, safety margins, etc.);
- reactivity coefficients and control parameters (shutdown margin, rod worths);
- handling, transport and storage (consideration of fuel isotopics, handling dose, mechanical integrity);
- compatibility with existing infrastructure (e.g. core loading, in-core operations, post-irradiation handling and storage, etc.).

Proposed literature

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Thank you!

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