IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

TARs overview for SMRs, MSRs and HTGRs, TSO point of view

WPEC/SG46 “Target Accuracy Requirements meeting”, April 14, 2021

IRSN/FRM-296 ind 5

MEMBRE DE

ETSON | EUROPEAN TECHNICAL SAFETY ORGANISATIONS NETWORK

Outline

Introduction
- scope of study, collaboration and schedule

V&UQ from the TSO point of view
- TARs as a step toward a science-driven validation

TARs from basic principles to methodology
- Separating validation and application domain

SMRs
- The groups of SMRs
- an analysis through a taxonomy

MSRs
- MSFRs
- Systematic approach to TARs studies

Summary and schedule
- Status of LWR and non-LWR SMRs
- Status and collaboration on MSR
- Status of SMRs and non-SMRs HTGR
- drawbacks, lessons learned and recommendations

The scope of IRSN contribution in TARs study

Concerned parties

- Scientific community focusing on R&D prioritization and on a support of SRL, etc.
- Design organization, operator and vendors oriented to perform feasibility study, TRL assessment and development and to facilitate a licensing process, etc.
- **Regulatory bodies and technical support organizations interested in a conformity with rules and criteria, confident statements and relevant knowledge management**

Concepts and systems to be assessed

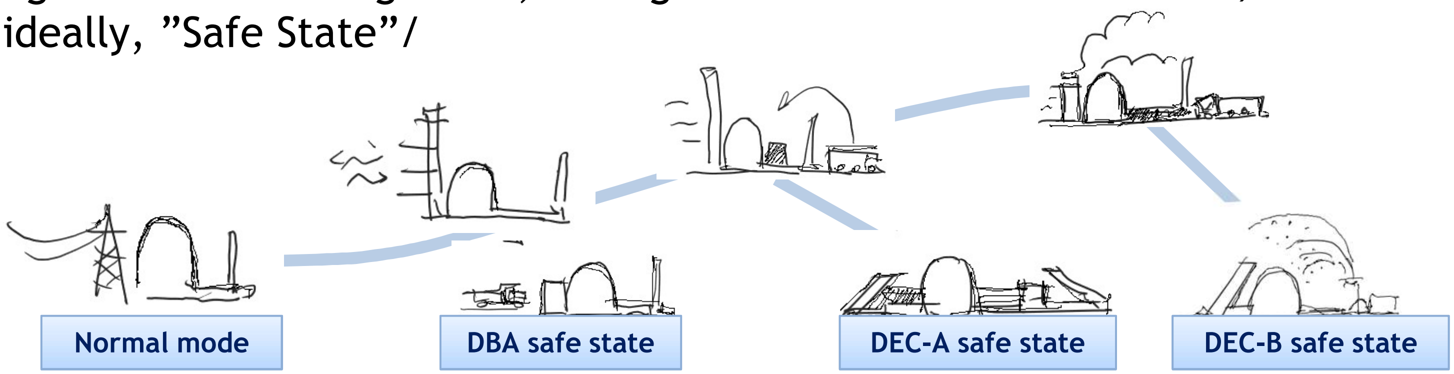
- LWR Small Modular Reactors
- High Temperature Gas cooled Reactors (GT MHR, HTGR GEMINI, VHTR)
- Molten Salt Fast Reactors (Molten fuel Salt circulating Fast Reactors)
- Other advanced non-LWRs Small Modular Systems

Assessment matrix

- Design parameters, control system efficiency, burnup and time between outages
- Transient behavior, mechanical energy release, accidental and safety state characterization and source term evaluation
- Enablers for predictive management, relevant surveillance, instrumentations and measurements

Subjects of interest for regulatory bodies and TSOs

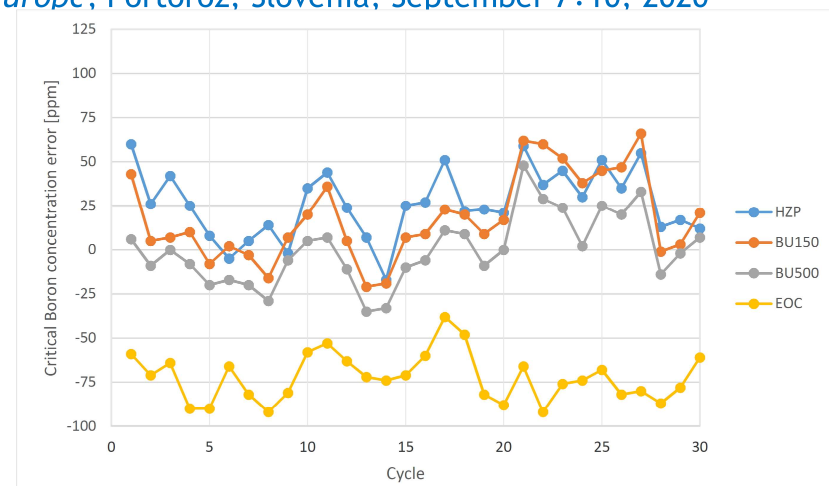
- Concerned party : regulatory body and technical support organization
- Tracing from an initiating event, through a set of “accidental states”, to an End-State (ES)/ideally, ”Safe State”/



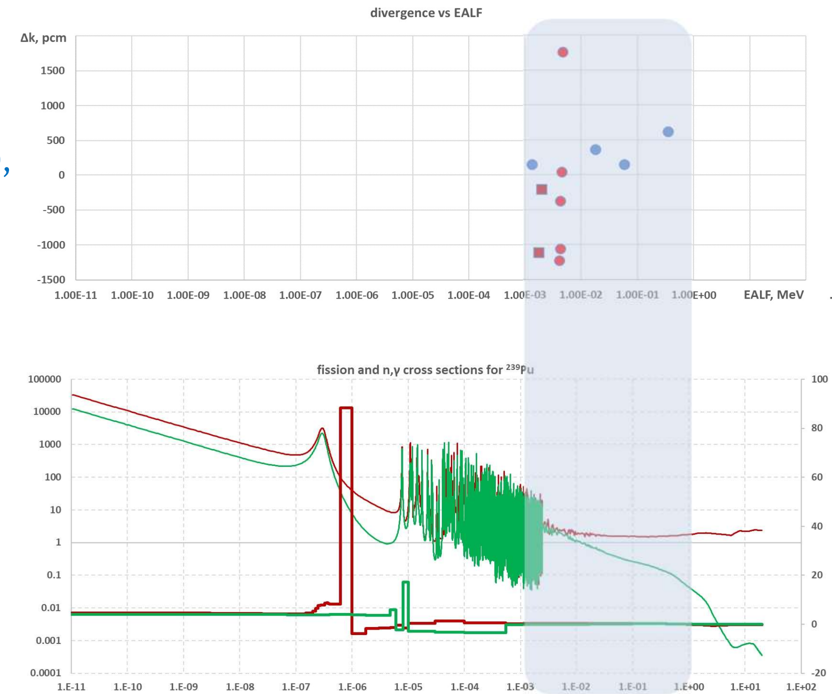
- Two axes of a safety assessment
  - Forward => an assessment of scenario and sequences from the initiating events to an ultimate set of consequences
  - Backward => an assessment of safety of the end-state, if achievable, and measures/conditions needed to reach the ES avoiding any public overburden
- Single-physics – reactor physics - as an input for other physics => TARs to be established from the global sensitivity analysis
- <u>No one experimental program might cover the application domain !</u>

Involving IE in a scientific turnover using Data Assimilation

- Data assimilation to prioritize problem-oriented basic research programmes [C. De Saint-Jean, E. Ivanov, V. Sobes, Nuclear Data Assimilation, basis and status, *EPJ-N, 2021*]
- Data Assimilation and zero power experiments with EALF in keV allowed identifying an issue with the fission resonance of ^{239}Pu.
- Marjan Kromar, Bojan Kurinčič, Comparison of the ENDF/B-VII.0, ENDF/B-VII.1, ENDF/B-VIII.0 and JEFF-3.3 Libraries for the Nuclear Design Calculations of the NPP Krško with the CORD-2 System, *International Conference Nuclear Energy for New Europe*, Portorož, Slovenia, September 7÷10, 2020



TF "The implementation of burnup calculations for nuclear data validation activities", SR, 01.27.2021



DA and critical experiments helped revealing an issue related to a wide range of application

1) the discrepancy with the recent comprehensively validated library appeared due to classical "Texas sharpshooter fallacy" when evaluators relied on the subjectively pre-selected benchmarks,

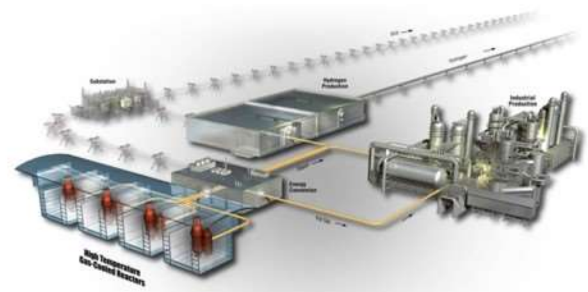
2) the physics responsible for such observation would be in a compensated Doppler component (some meso-scope effects) in the field of the right wing of the resonance

Specificity of an advanced concepts pre-licensing analysis

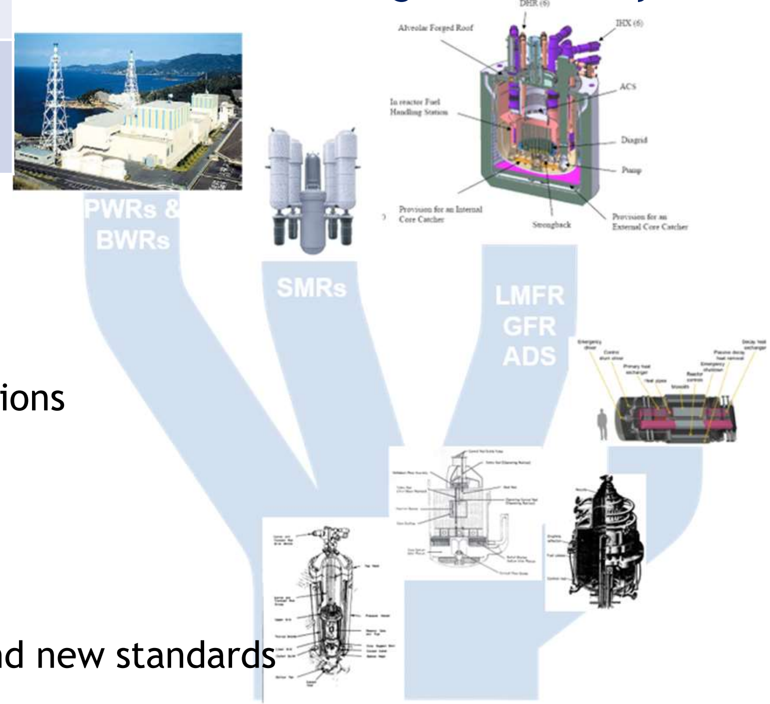
Use of Nuclear Fuel Resources for Sustainable Development – Entry Pathways, UNECE Report, 2021 (UNECE, IAEA, OECD-NEA and WNA consensual view)

Size	Likely setting	Applications
Microreactors <20 MW (thermal)	Off-grid Industrial facility Mining operations Remote communities Oil and gas platforms Off-grid agriculture	Electricity Heat
SMRs 20-300 MW (electric)	On or off-grid Large developed grids Small or non-developed grids Industrial processing, e.g. data centers Off-grid agriculture	Electricity Hydrogen production Desalination District and industrial heating
Medium to Large Reactors >300 MW (electric)	On-grid (large developed)	Electricity Hydrogen production Desalination District heating

nuclear energy system as an entity



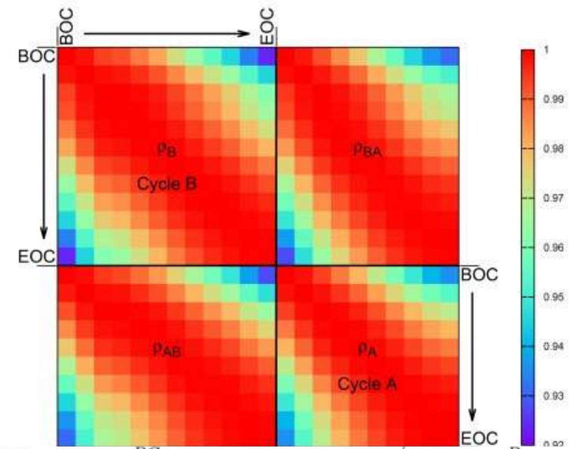
nuclear technologies’ taxonomy



- Paradigm-shift technologies => paradigm-shift assessment
- Enhanced safety => “better” than commonly adopted rules
- Limited or absent operation experience and regulation background => reliance on modeling and simulations
- Multi-units consideration and system thinking
- SMRs as “a consumer” of innovations
- SMRs as “a polygon” to approbate the innovations
- Science-driven assessment process to combining existing and new standards

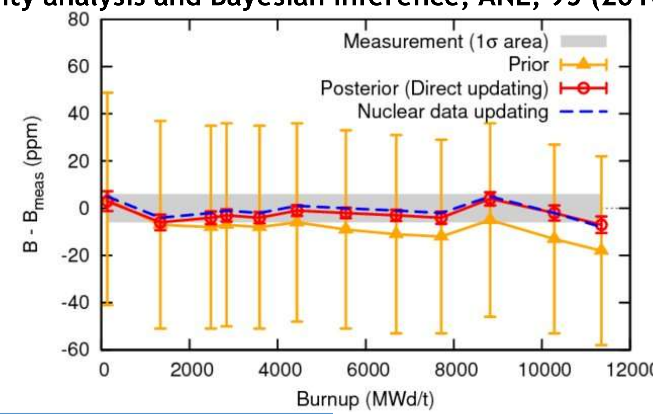
SMR LWR vs Large LWRs

- Note that not all factors to be simulated from scratch
  - Example for a large LWR => Data Assimilation to adjust the campaign operational support
  - In case of SMRs => no preceding cycle available but extended campaign required
- An increased role of modeling and simulations
- HA-LEU and ATF potential implementation:
  - Increased uranium density, extended burn-up and complexing of the fuel behavior
  - Advanced materials (coating and clad, fuel matrices, etc.)
- Advanced reactor control and predictive accidents' management
  - Solvable boron-free and long-life control bodies
  - Advance algorithms and physics behind the control
- Advanced safety assessment methodologies
  - Probabilistic Risk Analysis and Probabilistic Safety Assessment
  - Best Estimate Plus Uncertainties => requirements and informativeness
- Advanced instrumentation in terms of needed reactor physics inputs
- Diversity of the concepts => to be considered by groups and in a generalized manner



Burnup (GWd/t)	BC_{prior}	σ_{prior}	$BC_{posterior}$	$\sigma_{posterior}$	$\sigma_{prior}/\sigma_{posterior}$	$B_{measured}$
0.13	986	46	986	4.2	11	983
1.34	867	45	868	3.3	13	874
2.49	763	44	767	2.7	16	771
2.84	733	44	737	2.6	17	740
3.59	664	43	668	2.4	18	672
4.44	590	43	595	2.3	18	596
5.55	487	42	494	2.2	19	496
6.69	383	42	391	2.4	18	394
7.72	290	42	298	2.6	16	402
8.82	197	41	206	2.8	15	202
10.28	74	41	85	3.2	13	87
11.35	-15	40	-4	3.5	11	3

E. Castro, C. Ahnert, O. Buss, N. García-Herranz, A. Hoefer, D. Porsch, Improving PWR core simulations by Monte Carlo uncertainty analysis and Bayesian inference, ANE, 95 (2016)

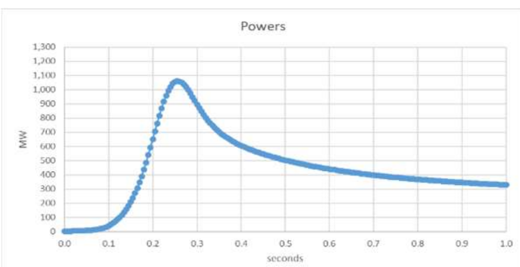


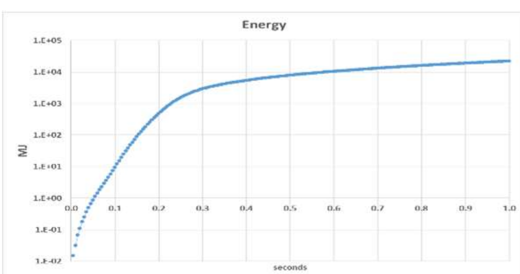
LWR transient => sensitivity analysis

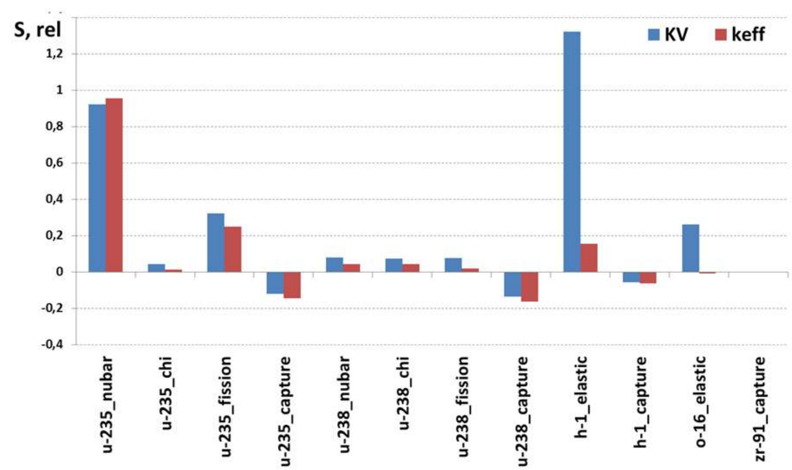
Key parameters:

- Reactivity worth to assess the risk of reactivity insertion: control groups, fuel assemblies
- Reactivity feedbacks to assess the core behavior
- Power-peak and mechanical energy releases to assess an amount of affected elements
- Source term to assess the consequences

nuclide-reaction	K_V	k_{eff}	nuclide-reaction	K_V	k_{eff}
u-235_nubar	0.92057	0.95636	u-238_nubar	0.079487	0.043366
u-235_chi	0.043341	0.013113	u-238_chi	0.074213	0.041447
u-235_fission	0.32312	0.25003	u-238_fission	0.077251	0.019996
u-235_capture	-0.12035	-0.14511	u-238_capture	-0.13711	-0.16236
h-1_elastic	1.3208	0.15373	o-16_elastic	0.25968	-0.0080381
h-1_capture	-0.055627	-0.064138	zr-91_capture	-0.0028652	-0.0035515







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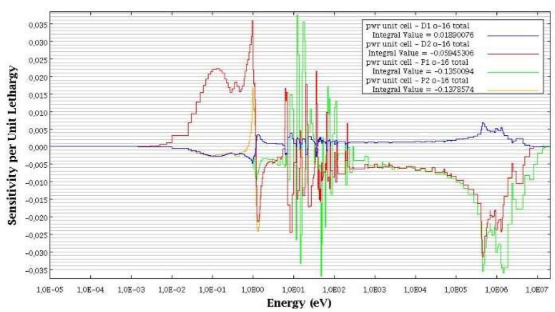
LWR transient => uncertainty propagation (prior)

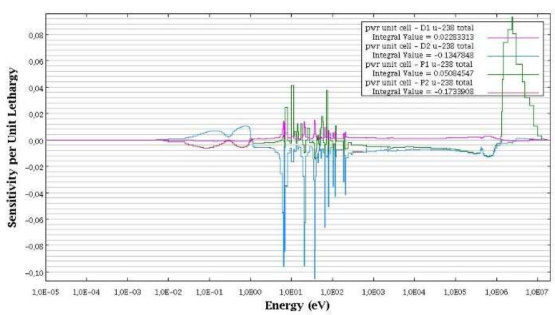
Best estimate and uncertainties required

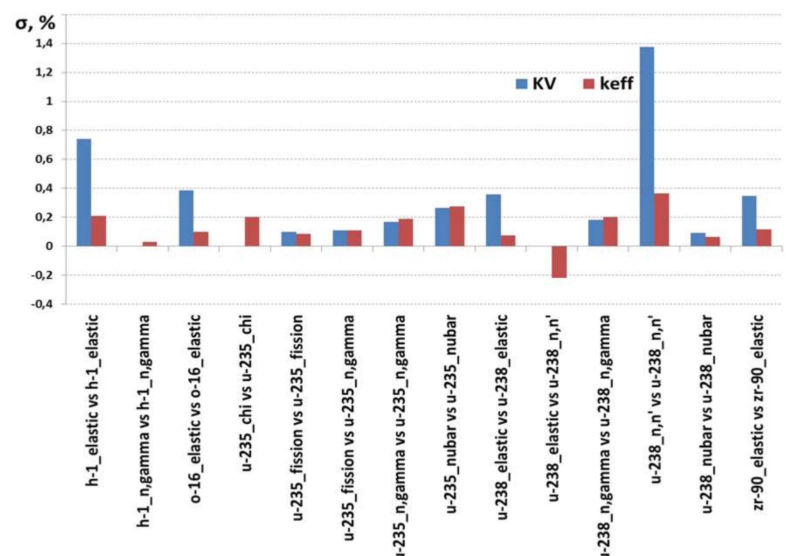
- Implementing probabilistic risks analysis and safety assessment
- Characterizing informed conservative criteria and safety margins
- Prioritizing oriented basic research programs

Non-trivial => how to translate the given (multi-physics) limits into single-physics TARs

matrix element	K_V	k_{eff}
h-1_elastic & h-1_elastic	7,41E-01	2,08E-01
h-1_n,gamma & h-1_n,gamma	-	3,08E-02
o-16_elastic & o-16_elastic	3,86E-01	9,75E-02
u-235_chi & u-235_chi	-	2,01E-01
u-235_fission & u-235_fission	9,72E-02	8,47E-02
u-235_fission & u-235_n,gamma	1,10E-01	1,09E-01
u-235_n,gamma & u-235_n,gamma	1,66E-01	1,88E-01
u-235_nubar & u-235_nubar	2,65E-01	2,75E-01
u-238_elastic & u-238_elastic	3,59E-01	7,54E-02
u-238_elastic & u-238_n,n'	-	-2,19E-01
u-238_n,gamma & u-238_n,gamma	1,80E-01	2,01E-01
u-238_n,n' & u-238_n,n'	1,38E+00	3,66E-01
u-238_nubar & u-238_nubar	9,34E-02	6,26E-02
zr-90_elastic & zr-90_elastic	3,46E-01	1,18E-01



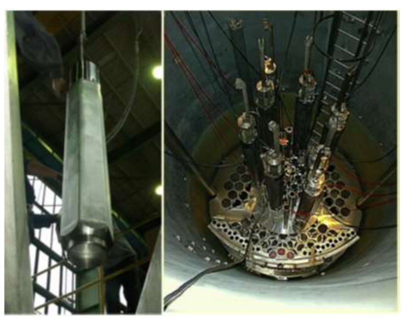




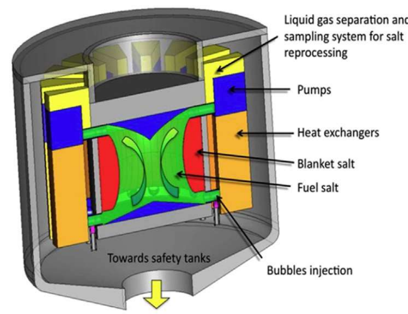
Molten fuel Salt Fast systems

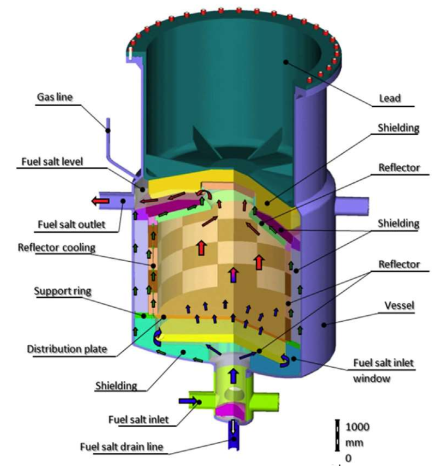
Major peculiarities to be taken into account studying the TARs (reactor physics and criticality aspects)

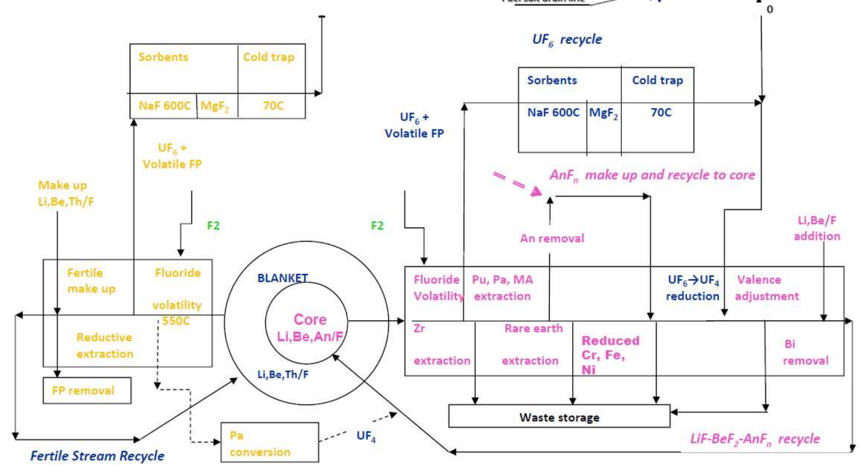
- High-temperature and an enhanced sensitivity to the density and temperature feedbacks
- variable kinetic parameters and
- therefore, no reactivity as a controlling parameter
- Sophisticated control of nuclide evolution and fissile materials inventory control
- System behavior and source terms dependences on a details of fuel treatments
- Experimental infrastructure to be included in a design project



An example: MSFR and MOSART => molten circulated fuel salt reactor concepts







Jérôme Serpet al, The molten salt reactor (MSR) in generation IV: Overview and perspectives, PNE, 77 (2014)

Molten Salt Fast Reactor functional TARs

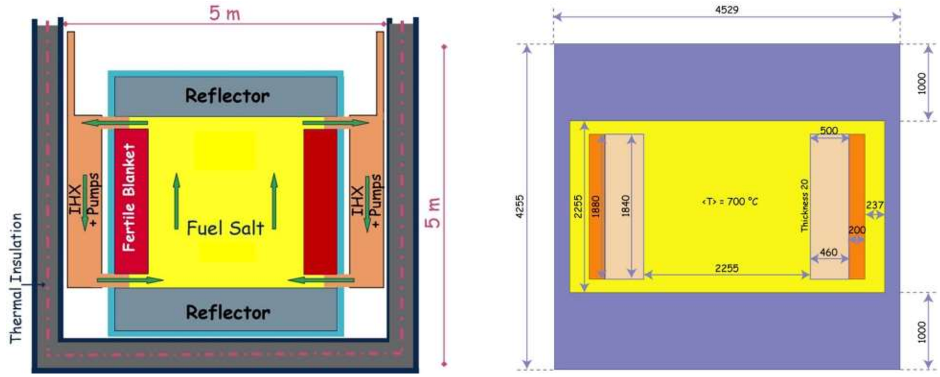
TARs: controllability

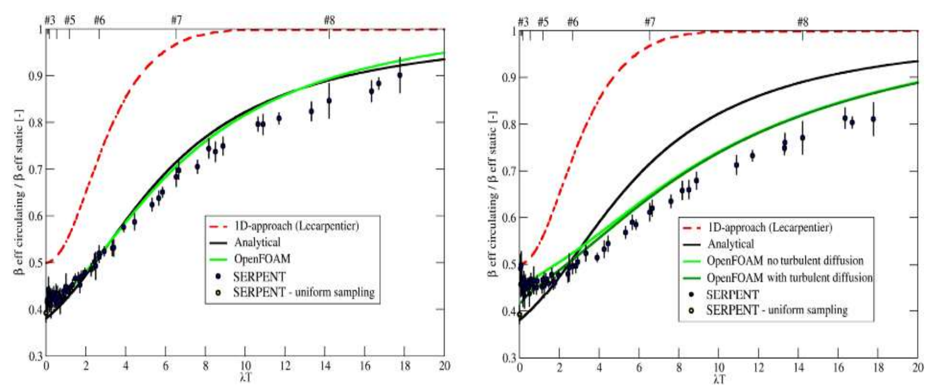
TARs have been established basing on the physics behind principles of the entire system control

Peculiarity of MSR => no dedicated power output

- Δk_{eff} ~ 1.0 % if $\omega = 0.0\ m/sec$ with f.p.
- Δk_{eff} ~ 0.2 % if ω: $\beta_{eff} \cong 0$ & circulating f.p.
- $\frac{c_{232}}{k_{eff}} \frac{\Delta k_{eff}}{\Delta c_{232}}$ ~ 2 % for static case
- $\frac{c_{233}}{k_{eff}} \frac{\Delta k_{eff}}{\Delta c_{233}}$ ~ 3 % for static case
- $\frac{c_{238}}{k_{eff}} \frac{\Delta k_{eff}}{\Delta c_{238}}$ ~ 2 % for static case
- $\frac{c_{239}}{k_{eff}} \frac{\Delta k_{eff}}{\Delta c_{239}}$ ~ 7 % for static case
- $\frac{c_{Zr.Mo.Ce}}{k_{eff}} \frac{\Delta k_{eff}}{\Delta c_{Zr.Mo.Ce}}$ ~ 12 % for static case

Calculational model





MODEL FOR SENSITIVITY STUDIES

Mariya Brovchenko, Jan-Leen Kloosterman, Lelio Luzzi, Elsa Merle, Daniel Heuer, Axel Laureau, Olga Feynberg, Victor Ignatiev, Manuele Aufiero, Antonio Cammi, Carlo Fiorina, Fabio Alcaro, Sandra Dulla, Piero Ravetto, Lodewijk Frima, Danny Lathouwers, Bruno Merk, Neutronic benchmark of the molten salt fast reactor in the frame of the EVOL and MARS collaborative projects, EPJ Nuclear Sci. Technol. 5 2 (2019)

Summary

- Basic principles in TARs assessment => an explanation combining traditional TARs and safety-related TARs =>
  Done

- SMRs by groups
  (will be drafted to the next meeting)
  - LWR SMRs : traditional TARs, transient analysis demonstrated
    to be analyzed => PSA and BEPU basis, and ATF implementation
    Non-LWR SMRs

- High-temperature systems
  (will be drafted to the next meeting)
  - HTGR : combining traditional TARs
    to be extended => PSA and PRA needs in the Best Estimate calculations
  - MSRs : in collaboration with CNRS
    to be confirmed and extended => Source Term analysis

- General statements and reasoning (to be discussed)

Thank you for your time and attention

Questions?