

FEASIBILITY STUDIES AND SCOPE ANALYSES FOR A SUPERSTAR DEMONSTRATOR NEUTRONICS DESIGN



SARA BORTOT*, MARCO E. RICOTTI
 Politecnico di Milano, Department of Energy, Nuclear Engineering Division - CeSNEF
 Via la Masa, 34; 20156 Milano, Italy
 sara.bortot@mail.polimi.it, marco.ricotti@polimi.it



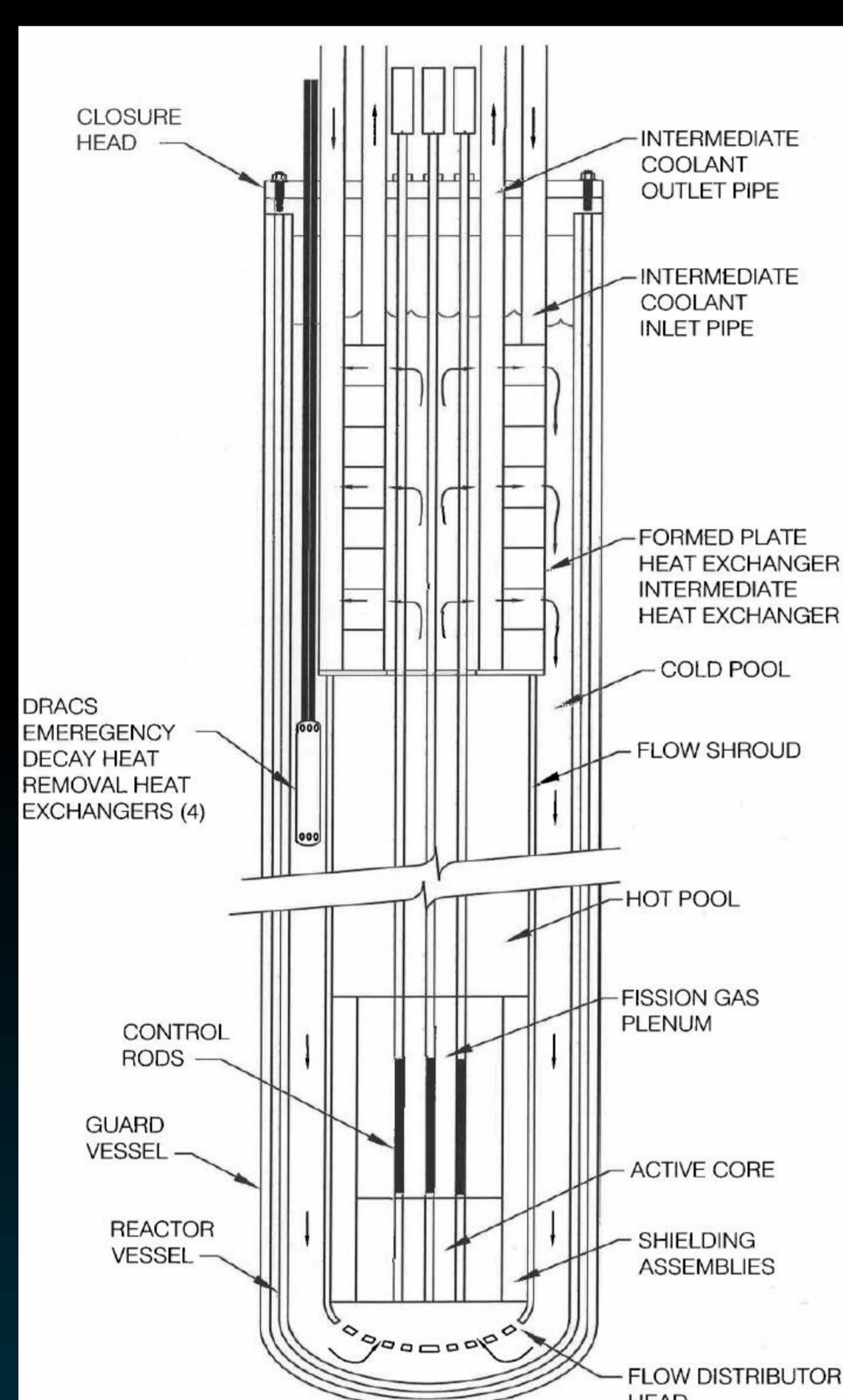
CARLO ARTIOLI
 National Agency for the New Technologies, Energy and Sustainable Economic Development (ENEA)
 Via Martiri di Monte Sole, 4; 40129 Bologna, Italy
 carlo.artioli@enea.it

ABSTRACT

A preliminary feasibility study and scope analysis for a demonstrator (demo) of the Sustainable Proliferation-resistance Enhanced Refined Secure Transportable Autonomous Reactor (SUPERSTAR) has been performed. Preliminary core design studies have been carried out focused on maximizing the power level compatibly with natural circulation cooling and transportability requirements, while meeting the foremost goals of (i) providing energy security and proliferation resistance thanks to a long life core design, (ii) minimizing the reactivity swing over the core lifetime, and (iii) flattening the radial power profiles, as demanded by the choice of wrapper-less fuel assemblies and by the stringent technological constraints imposed by the short-time-to-deployment feature. Once established appropriate geometrical pin and fuel assembly specifications, a suitable active height allowing the system to be cooled by free-flowing lead has finally been set through parametric T/H analyses. Fuel cycle calculations have been then performed to optimize both the fresh fuel composition and the radial enrichment zoning. Moreover, the use of several absorbing materials has been investigated in order to guarantee enhanced safety by incorporating control elements having a net density greater than that of the surrounding lead coolant. A complete static neutronic characterization of the resulting core has been finally accomplished.

SUPERSTAR REACTOR CONCEPT

Sustainable Proliferation-resistance Enhanced Refined Secure Transportable Autonomous Reactor



DESIRED PERFORMANCE

- International or remote deployment
- Small power level (~ 100 MW_e)
- Transportability → radial constraint
- Energy security → long lifetime core
- Proliferation resistance → $\rho_{\Delta cycle} < 1 \text{ \$}$
- Enhanced safety → $\rho_{\Delta cycle} < 1 \text{ \$}$
- Autonomous operation

- Economic performance maximization
- Highest power level compatible with:
 - Natural circulation cooling
 - Dimensional constraints

NEED OF A NEAR-TERM DEPLOYABLE DEMONSTRATION REACTOR (demo)

SUPERSTAR DEMONSTRATOR REFERENCE CRITERIA

FUEL FORM:	Particulate-based metallic fuel (U-Pu-10Zr alloy)
FUEL LIFETIME:	15 years (13.5 EYFP with capacity factor $f_c = 0.9$)
CLADDING MATERIAL:	T91 → 550 °C peak cladding temperature → 1 m s ⁻¹ peak coolant speed → 4·10 ²³ cm ² peak fast neutron fluence
COOLANT:	Pure lead → 400 °C coolant inlet temperature
FA DESIGN:	Wrapper-less square → flat power distribution ($f_R = 1.2$ maximum)
CONTROL SYSTEM:	Innovative Finger Absorber Rods (FARs) FARs denser than lead for enhanced safety 10 \$ safety margin

CORE DESIGN RATIONALE

REFERENCE PARAMETERS and PERFORMANCE → ELSY-BASED LFR DEMO

- Power density reduction to respect the limit on the neutron fluence
Maximum acceptable peak flux: $\phi_{(E>0.1 \text{ MeV})} = 8.46 \cdot 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$
- Determination of fuel pin diameter accordingly (incorporation of 2σ HC factors)
- FA XY dimensions optimization respecting the core radial constraints
- T/H Optimization → Determination of the fuel pin pitch (power maximization; natural circulation; flux reduction)
→ Determination of the core active height
- Fuel cycle analyses → Optimization of fresh fuel composition and core zoning

MAJOR COMPLEMENTARY SCOPING ANALYSES:

- Impact of Pu vector choice
- Alternative absorbing materials (W, W-Re, Ta)
- Different B₄C enrichments in ¹⁰B and FAR design
- Grid spacers and FA design study

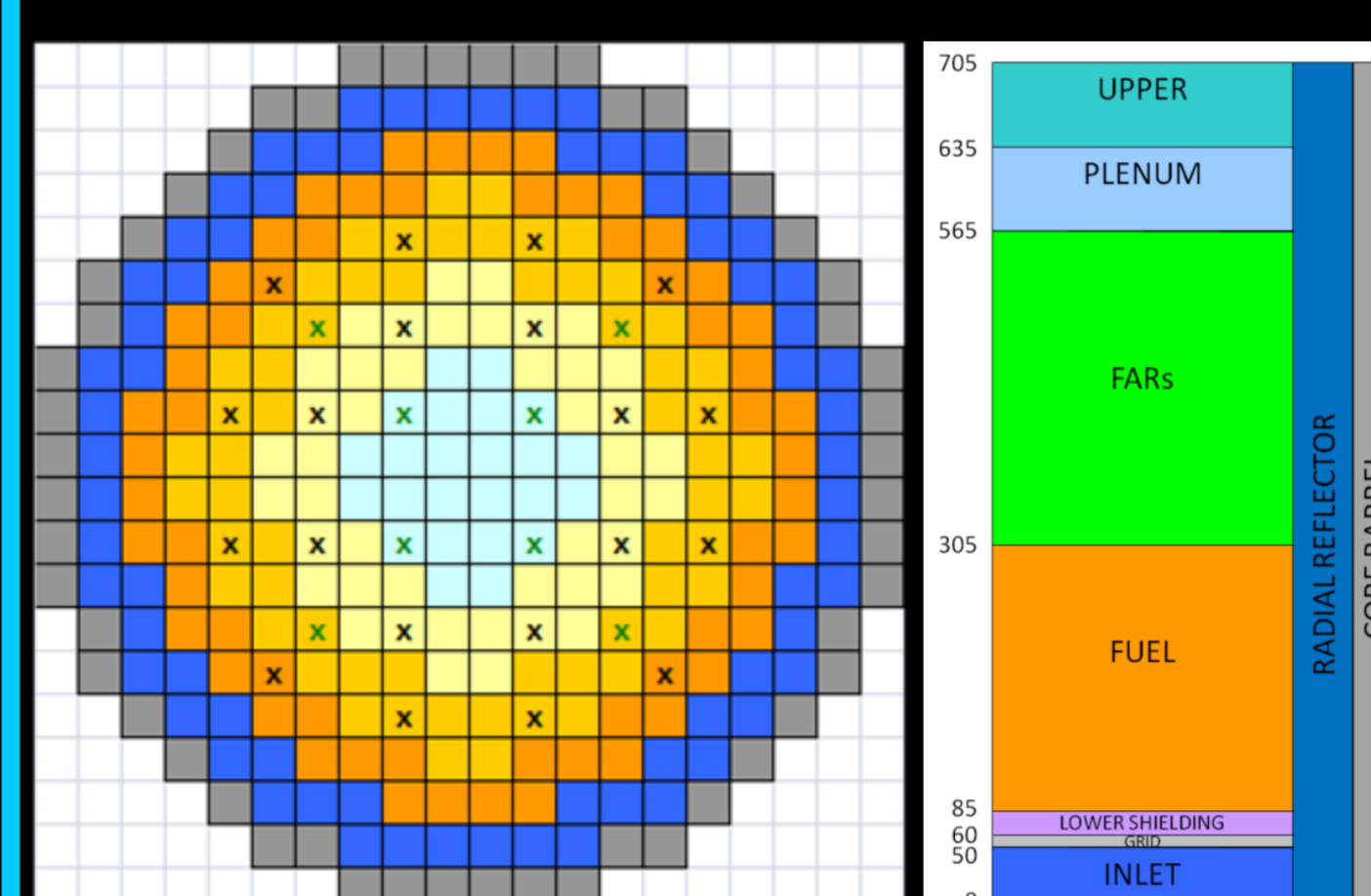
Isotope	Depleted U [wt.%]	WG Pu [wt.%]	RG Pu [wt.%]
²³⁸ U	0.003	-	-
²³⁵ U	0.404	-	-
²³⁹ U	0.010	-	-
²³⁸ U	99.583	-	-
²³⁹ Pu	-	0.050	2.333
²⁴⁰ Pu	-	93.600	56.873
²⁴¹ Pu	-	5.900	26.997
²⁴² Pu	-	0.400	6.104
²⁴³ Pu	-	0.050	7.693

TOOLS AND MODELING

- ERANOS (European Reactor ANalysis Optimised System) ver. 2.1
- JEFF 3.1 nuclear data library
- Cross section generation → ECCO (European Cell COde)
- Criticality calculations → nodal transport calculations (TGV module)

RESULTS

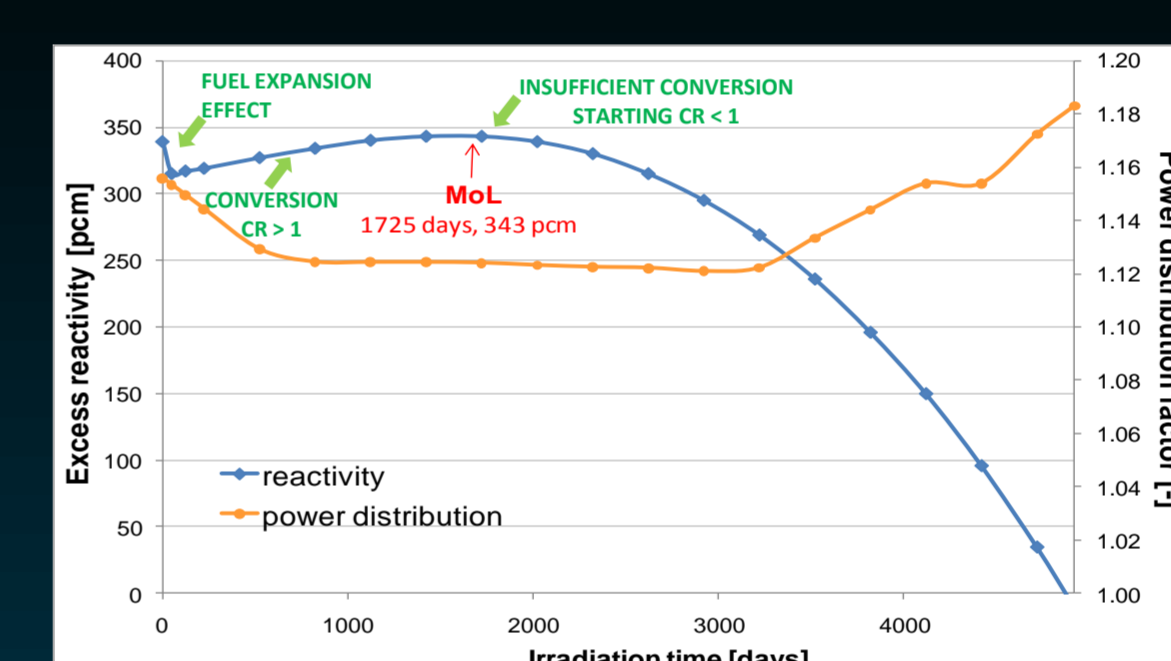
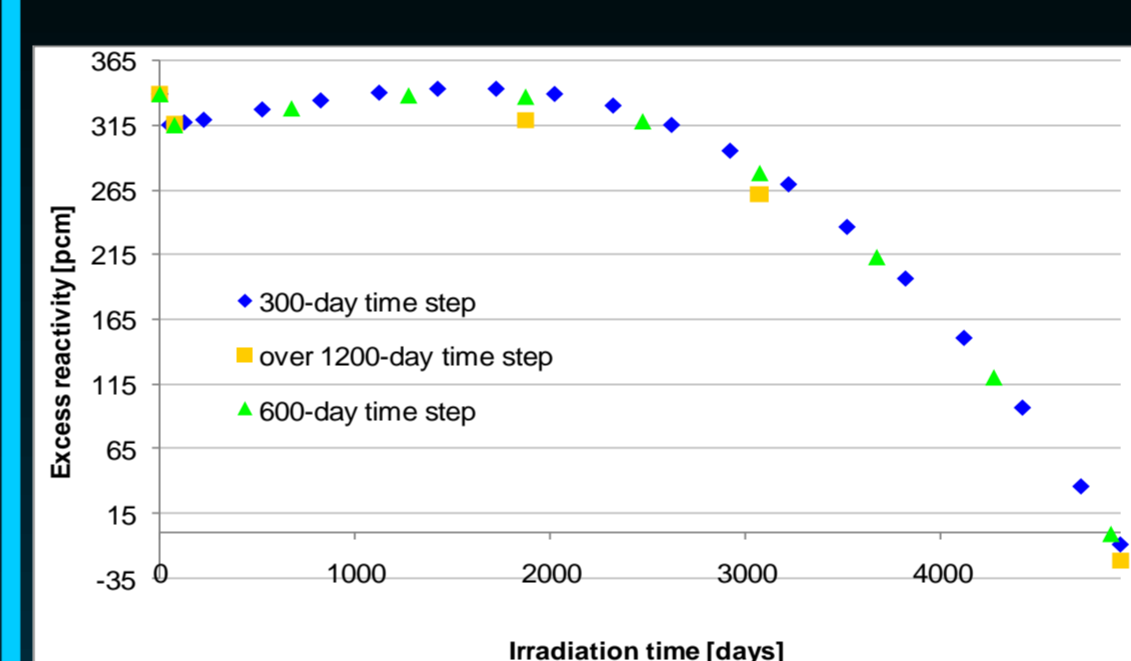
CORE LAYOUT



- 300 MW_{th} metal-fuelled core
- 188 ductless square FAs
- 4 radial enrichment zones
- Innovative FAR design

Enrichment zone	# FAs	Pu fraction [wt.%]	U fraction [wt.%]	Zr fraction [wt.%]
A	24	7.01	82.99	10
B	44	8.20	81.80	10
C	60	9.81	80.19	10
D	60	11.97	78.03	10

FUEL CYCLE ANALYSES

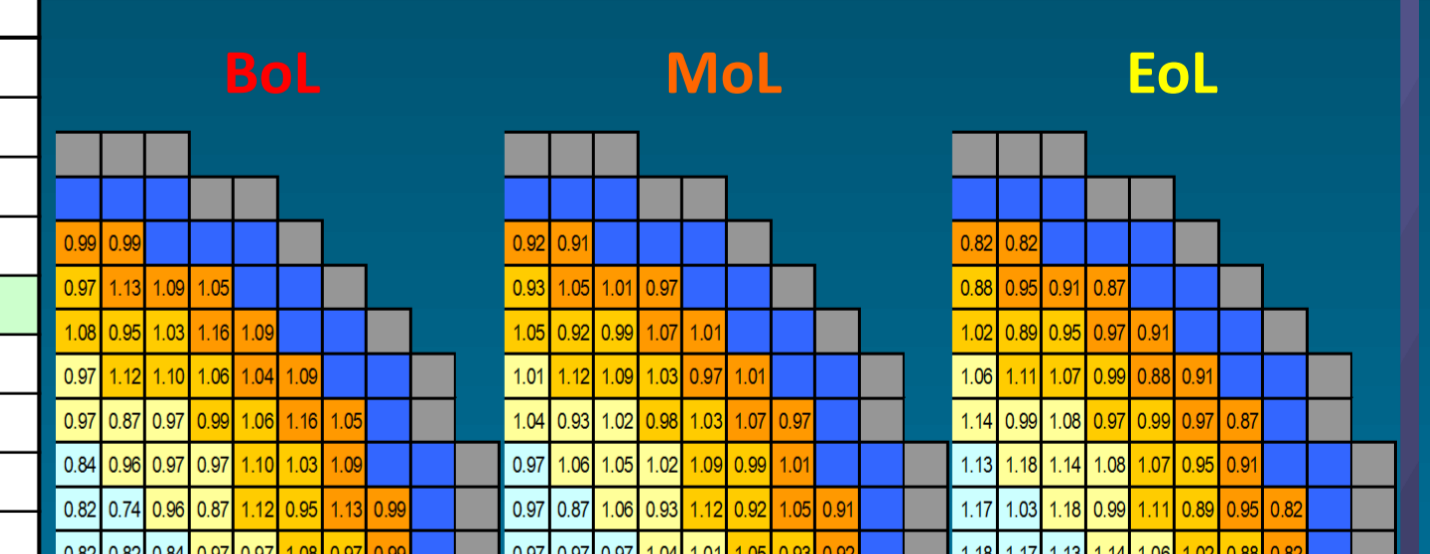
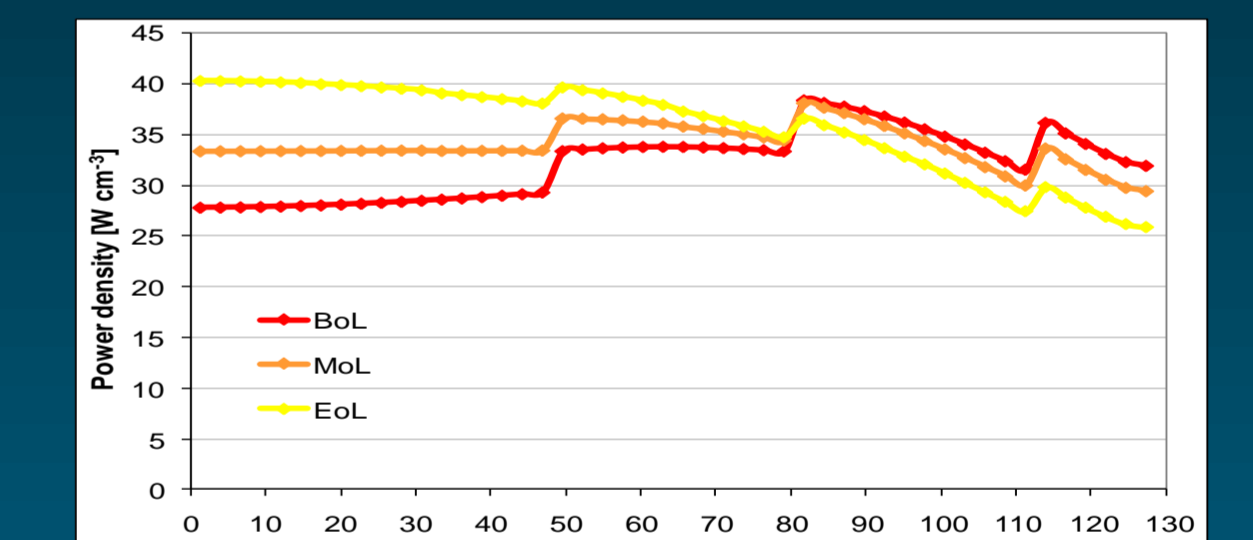


- Slight impact of the Δt choice (~ 12 pcm)
- Small spectral effect on microscopic cross-sections

KEY CORE PERFORMANCE

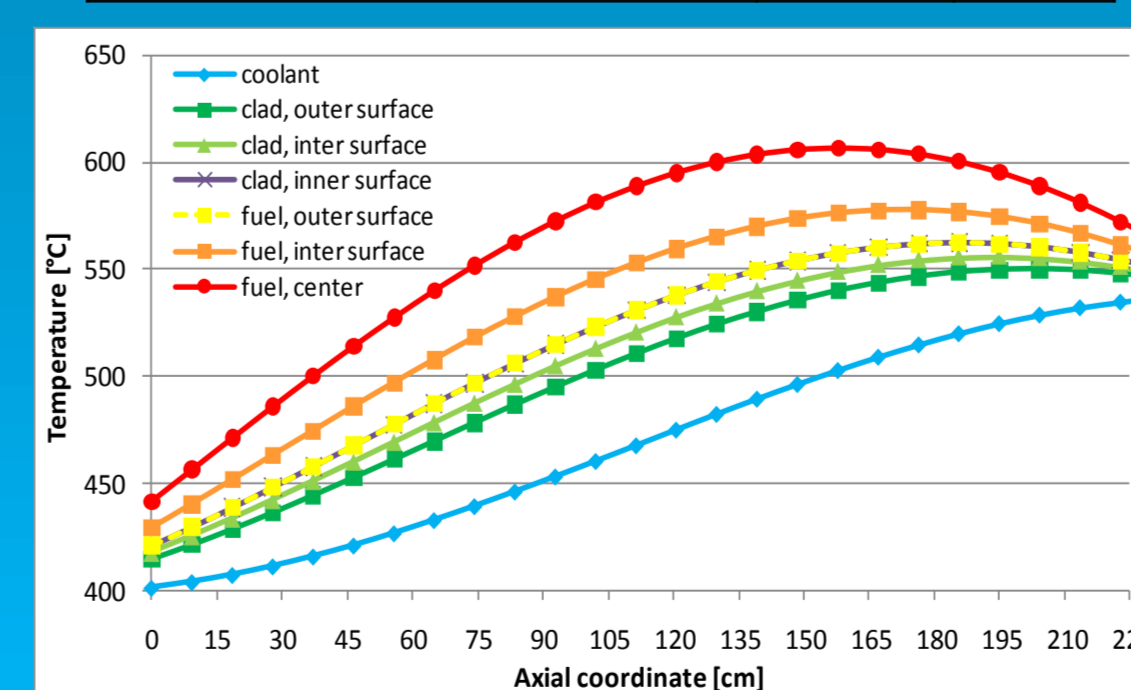
Parameter	Value	Units
Core lifetime	15	Years
Capacity factor	0.9	-
Core average burn-up	55	MWd kg ⁻¹ (HM)
Core peak burn-up	90	MWd kg ⁻¹ (HM)
Peak fast neutron fluence	3.22·10 ²³	cm ²
Maximum reactivity swing	343	pcm
k_{eff}	BoL: 0.99988, MoL: 0.99994, EoL: 0.99990	-
Reactivity, ρ	-12 (-0.03), -6 (-0.02), -10 (-0.03)	pcm (\$)
Primary FAR set insertion share	35, 40, 0	cm
Total peaking factor	1.64, 1.54, 1.60	-
Power/FA peak distribution factor	1.16, 1.12, 1.18	-
Average power density	25.6, 25.6, 25.6	W cm ⁻³
Average linear power	91, 91, 91	W cm ⁻¹
Peak total neutron flux, ϕ	1.03·10 ¹⁵ , 1.08·10 ¹⁵ , 1.21·10 ¹⁵	cm ⁻² s ⁻¹
Peak fast flux (E>0.1 MeV)	6.47·10 ¹⁴ , 6.75·10 ¹⁴ , 7.53·10 ¹⁴	cm ⁻² s ⁻¹

Satisfactory radial power profiles



T/H PRELIMINARY ANALYSES

Parameter	Value	Units
Core Hot Channel (HC)		
Peak pin power	27.87	kW
Max coolant temperature rise in core	135.40	°C
Max coolant temperature	550.00	°C
Max cladding temperature	550.00	°C
Max fuel-clad interface temperature	562.27	°C
Max fuel temperature rise (HC)	71.77	°C
Max fuel temperature	606.53	°C
Min fuel temperature margin	250	°C
Coolant max speed in HC	0.810	m s ⁻¹
Coolant speed in HC grid spacers	1.099	m s ⁻¹



Core Hot Channel axial temperature profiles.

REACTIVITY COEFFICIENTS

- Direct calculations
- Perturbation theory

Parameter	BoL	MoL	EoL	Units
Doppler constant, α	-496	-453	-395	pcm
Doppler coefficient	-0.55	-0.51	-0.44	pcm K ⁻¹
Lead density coefficient (active core)	0.67	0.68	0.69	pcm K ⁻¹
Lead density coefficient (whole system)	0.21	0.28	0.36	pcm K ⁻¹
Axial expansion coefficient (linked)	-0.75	-0.79	-0.41	pcm K ⁻¹
Axial expansion coefficient (not-linked)	-0.85	-0.89	-0.50	pcm K ⁻¹
Radial expansion coefficient	-0.68	-0.68	-0.68	pcm K ⁻¹
Delayed neutron fraction, β	328	324	316	pcm
Prompt neutron lifetime, λ	1.0715·10 ⁻⁶	9.4676·10 ⁻⁷	8.3659·10 ⁻⁷	s

- favorable buckling ($H_{core}/D_{core} \approx 0.8$)
- significant leakage reduction
- positive coolant density coefficient

CONCLUSIONS

Development of a completely new LFR preconceptual design

- Design goals satisfactorily achieved
- Technological constraints and design criteria respected with good margins
- Key improvement: innovative CR design aimed at enhanced safety (essential issue concerning HLMS systems)
- OPEN ISSUES:
 - Possibility to further extend the fuel lifetime to attain a more effective utilization of fissile resources
 - Acceptability of a positive coolant density feedback coefficient