Systematic approach to TA establishment: major findings

In the frame of « Target Accuracies establishment »

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Layout

General statements

- Briefly about the concepts

MSR concepts

- MSFR, current status
- others: MOSART, MUSE

SFR and LFR

- Breeder, burner, izo+

Outline

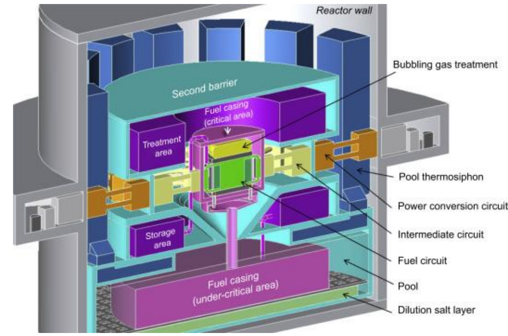
- TAs by concepts and tasks

Challenge Impacting Phenomena and FOMs

Subject	CIP or/and FOM
Design and critical parameters; assembling and reloading;	Criteria => half of SA for zone of flattening
Reactivity and power control; feedbacks; measurements	CR worth in dependence on power flattening, AU/RN
Reactivity swing, fuel cycle optimization, pre-D&RDM	Reactivity swing => to identify power history (around 5-10%)
Accidental states assessment; and instrumentation	Reactivity spatially spanned worth profiles

TAGs to be considered in a context of a Decision Making process

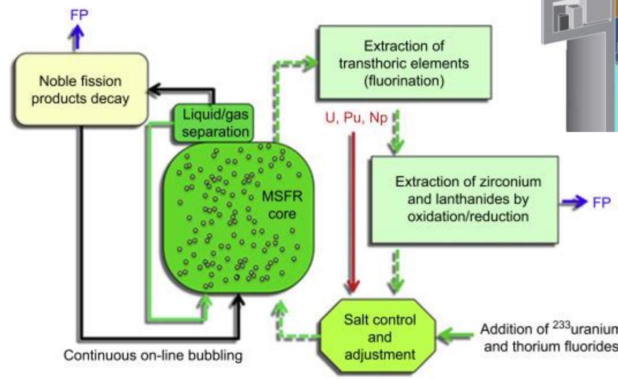
MSFR: design features and role in the power generation fleet

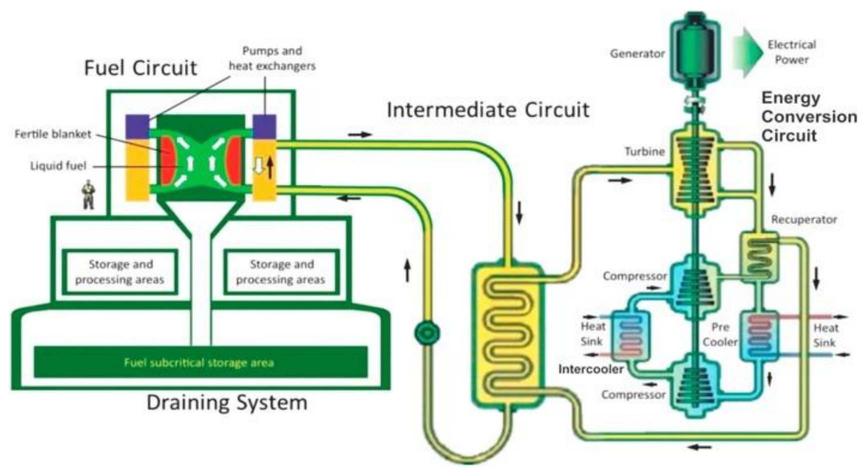


Features and motivations

- Flexible tool to deploy new options in fuel cycle
- Bed-kind system
- Comprises three areas: nuclear heater, draining tank and storage and reprocessing plant
- To be controlled: multiplication, isotopic inventory and delay, inputs for other physics => freezing, residual heat, REDOX, gas-bubble as a control body
- The fundamentally multi-physics modeling

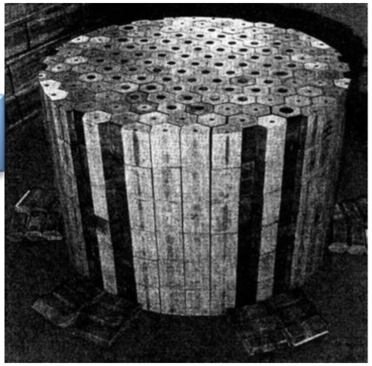
Solutions





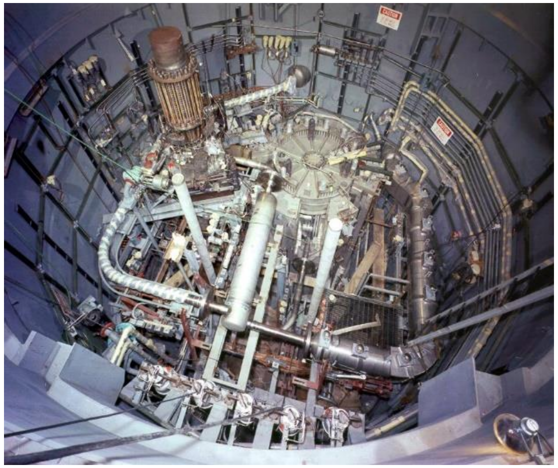
Historical overview, some notes

- 1954 : **Aircraft Reactor Experiment (ARE)**
  Operated during 1000 hours
  Power = 2.5 MWth



Not considered : fission gas storing tank, reprocessing control

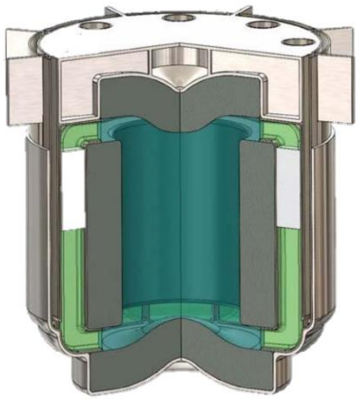
- 1964 – 1969: **Molten Salt Reactor Experiment (MSRE)**
  Experimental Reactor
  Power: 7.4 MWth
  Temperature: 650°C
  U enriched 30% (1966 - 1968)
  ^{233}U (1968 – 1969) - ^{239}Pu (1969)



- 1970 - 1976: **Molten Salt Breeder Reactor (MSBR)**
  Never built
  Power: 2500 MWth
  Thermal neutron spectrum

Note: MSRE zero power test to be published in IRPhE Handbook

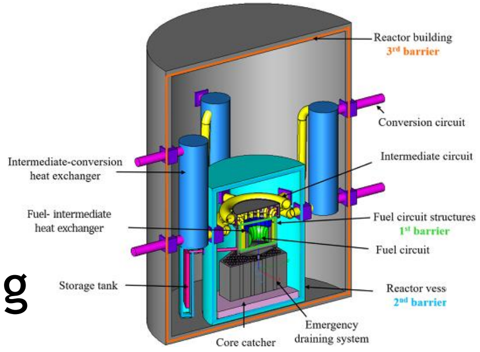
Different concepts => same CIPs

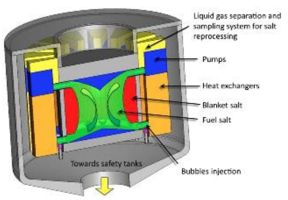


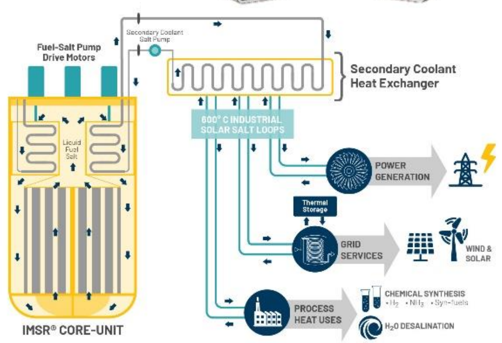
Concepts and CIPs

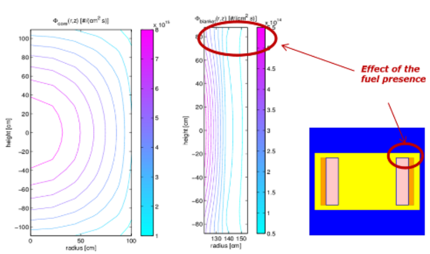
- Bed-type or channel-type
- High-temperature
- Circulating/solid fuel
- Continuous/discrete processing
- Fundamental non-linearity
- Bubbles, rods, circulation velocity as “control bodies”
- Zoning:
  - Active “core” and HX
  - Draining tank
  - Fission gas collector
  - Reprocessing plant

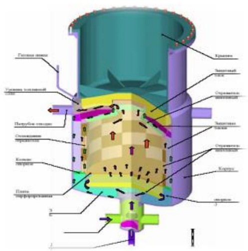
Comments

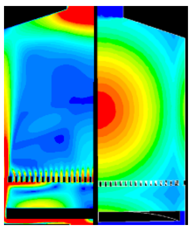










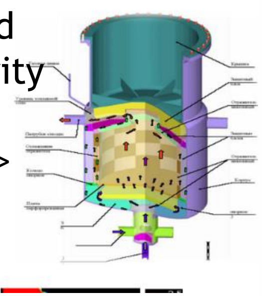


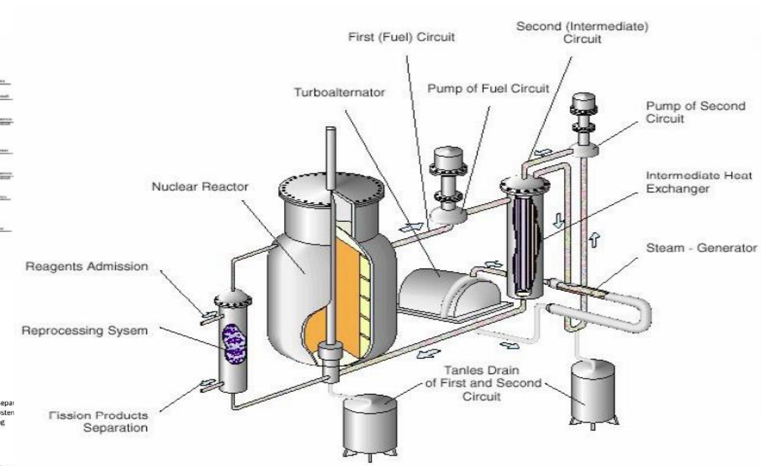
Coupled reactor + fuel cycle

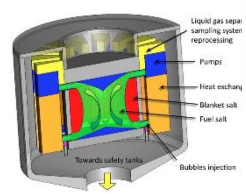
Options and CIPs

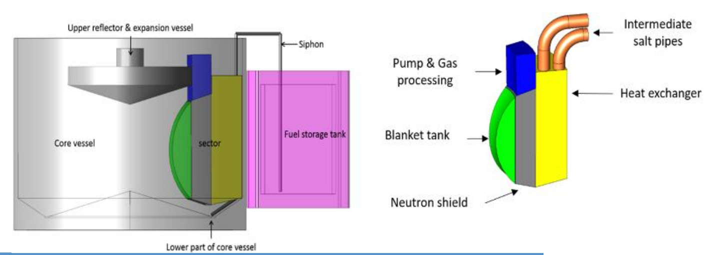
- Bed-type U/Th system
  - Narrow operating REDOX range (band control by Bi, Th, Zr etc.) => reactivity issue
  - ^{233}Pa decay: breeding and capture => neutron and nuclide components of reactivity and balance
- Bed-type Pu/U system
  - Fine nuclide balance control => spatially spanned material worth
  - ^{239}Np caused fluctuations etc. => nuclide and neutron reactivity
- Both cases:
  - Correlations between critical size and inventory => specific slow feedbacks => nuclide and neutron reactivity
- Radiation-induced corrosion =>
  - Φ, rad and Q along the circuit => ~ 10%

Comments







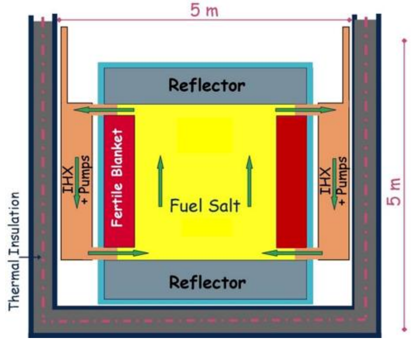


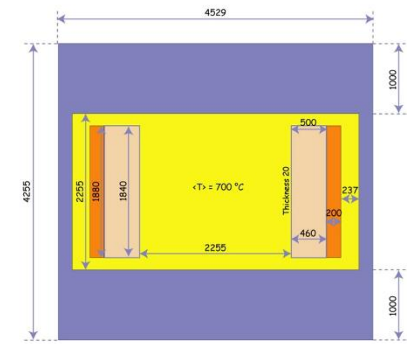
Circulating fuel peculiarities

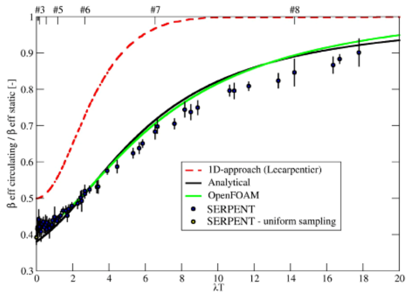
Phenomena

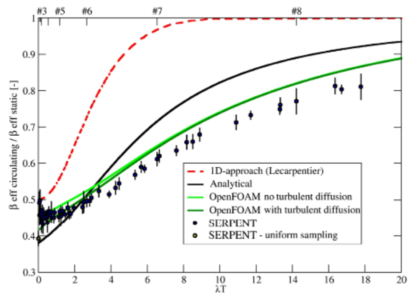
- Circulating fuel in normal operation while static salt in a start-up
  - an elimination of ≥ ½ min precursors
  - all precursors in core
- CIPs =>
  - detection of state zones
  - control and power stabilization
- Summary
  - accuracy for start-up ~ 2%
  - accuracy for operation ~ 5%

Comments & illustrations









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)

LMFRs paradigm dependent

Concepts and physics

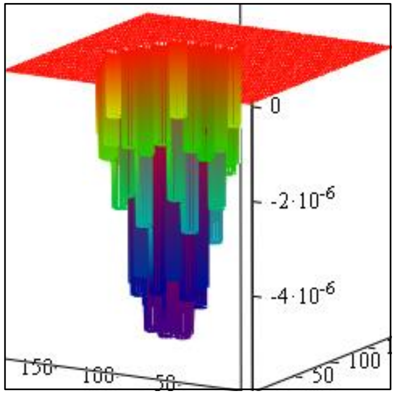
- Burner
  - Operation with “dirty Pu vector”
- Breeder
  - Breeding in blankets optimizing the spectra
- ASTRID-like = LFR
  - Objective => an exclusion of a large non-compensated reactivity
  - Low reactivity swing and low CR worth

CIPs and main issues

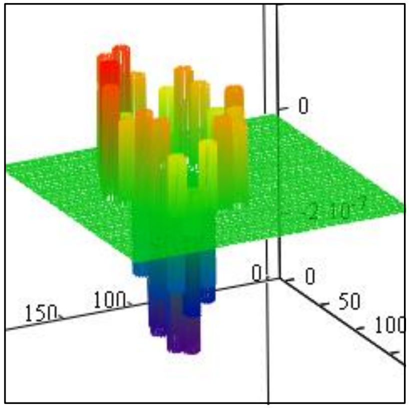
- Design goal => low impact <= Pu
  - Sensitivity for Q and Φ distributions <= driven by CRs
- TH and safety issues
  - Fine reactivity and Q(R,Z,t) TA to $\rho_{MAT}(R) \leq$ 5-10%
- Control ρ and Q and Φ by CRs
  - Reactivity swing < \$, an associated TA better than \$
  - TA(CRs) <3% (influence on in-core BG)
  - Replacing TA to $\Phi(x)$ by $\rho_{MAT}(R) \leq$ 5-10%

An application object for Levels 1-3 [the most penalized configuration]

Phénix sodium worth distribution

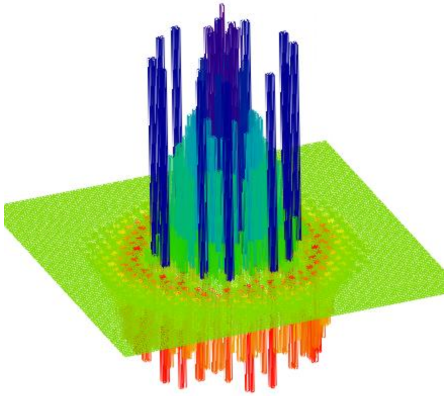


DISTR

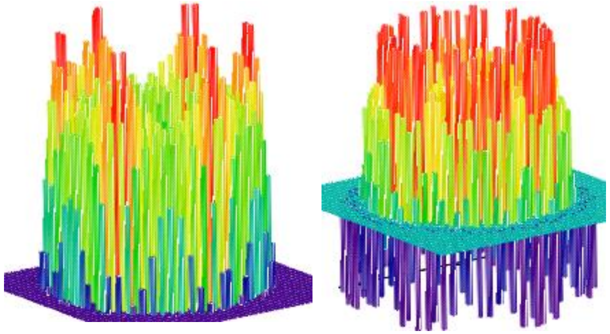


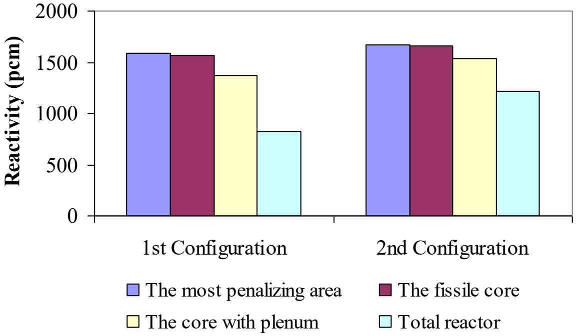
MARG

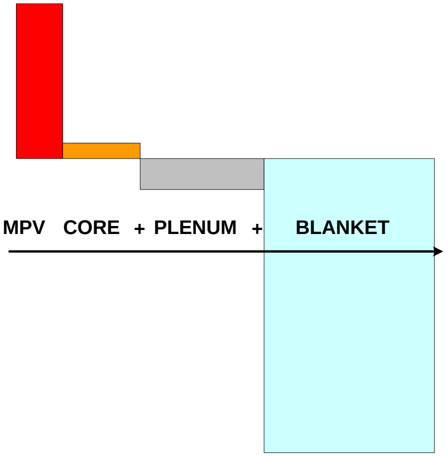
SNR-300 sodium worth distribution



Core without blankets, sodium worth distribution







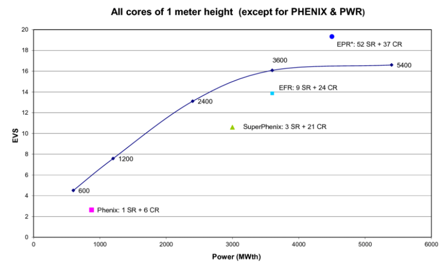
IRSN MEMBRE DE ETSON

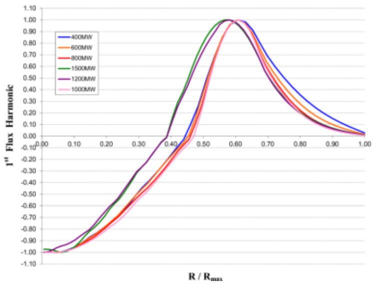
LMFR EVS issue and a local worth

Facts and statements

- EigenValue Separation used as a criteria of reactivity measurement consistency
  - ASTRID-like system should have high EVS => should be “decoupled”
  - Deeply subcritical ADS => no fundamental mode => decomposition is needed
- Alternative form is in coupled system
  - To address the sensitivities for “local” parameters

Comments



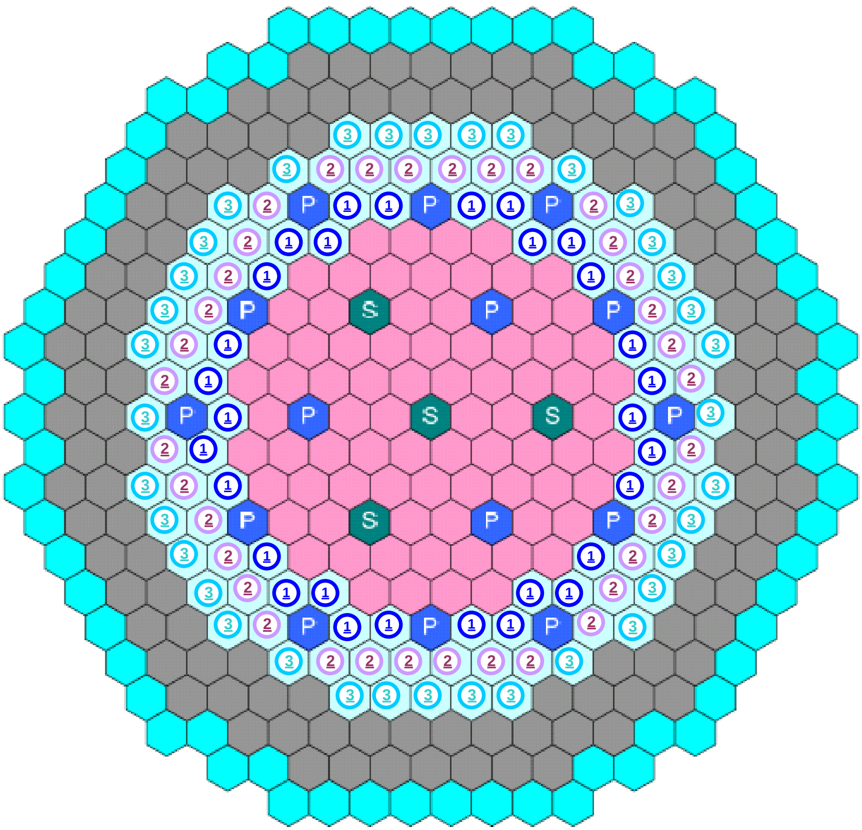


$$P(t)\cdot\Delta t = (A_1\cdot e^{\alpha_1\Delta t} + A_2\cdot e^{\alpha_2\Delta t})\cdot\Delta t \neq A_0\cdot e^{\alpha_0\Delta t}\cdot\Delta t$$

$$\begin{cases} \dfrac{dq_c}{dt} = \dfrac{\rho_c-\beta_c}{\Lambda_c}\cdot q_c + \dfrac{k_{bc}}{\Lambda_c}\cdot q_b + \sum_i \lambda_i\cdot c_{c,i} \\ \dfrac{dc_{c,i}}{dt} = \dfrac{\beta_c}{\Lambda_c}\cdot q_c - \lambda_i\cdot c_{c,i} \\ \dfrac{dq_b}{dt} = \dfrac{k_{cb}}{\Lambda_b}\cdot q_c + \dfrac{\rho_b-\beta_b}{\Lambda_b}\cdot q_b + \sum_i \lambda_i\cdot c_{b,i} \\ \dfrac{dc_{b,i}}{dt} = \dfrac{\beta_b}{\Lambda_b}\cdot q_b - \lambda_i\cdot c_{b,i} \end{cases}$$

IRSN MEMBRE DE ETSON

Example: SVR in the 2-nd zone



ABR Metallic-Fuel Core

1
2
3

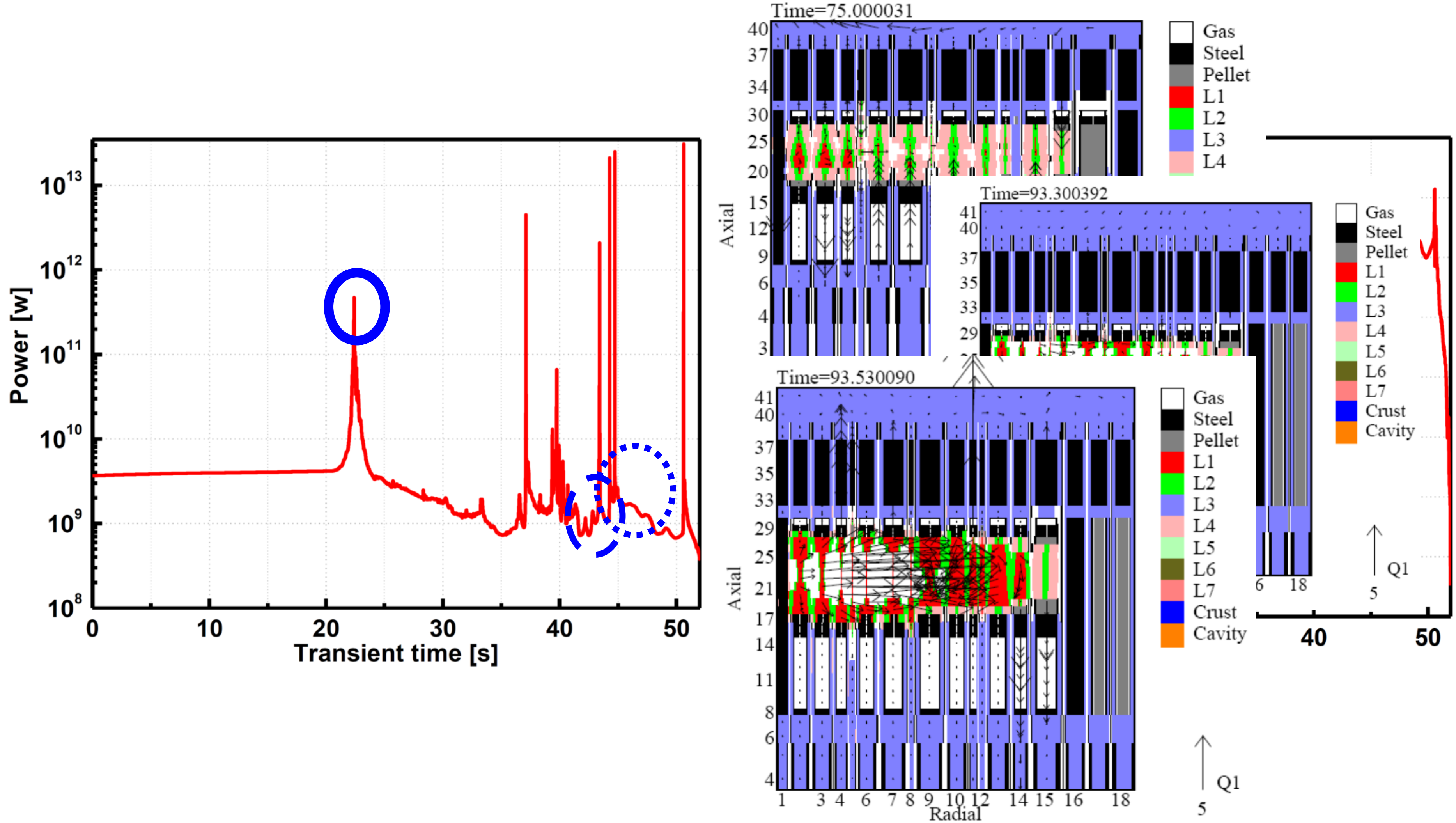
Voided S.A.

$\Delta\rho=\Sigma \mathbf{a}_i\times\gamma_i+\Sigma \mathbf{b}_{ij}\times\gamma_i\times\gamma_j$

γ_i is a volumetric part of void

$\mathbf{a}_i$, $\mathbf{b}_{ij}$ are coefficients to be found

Accidental state concept => snapshots

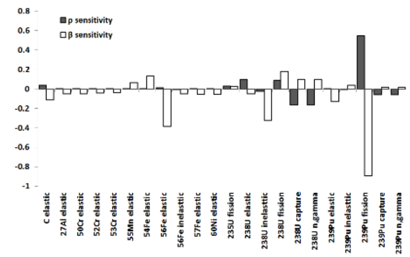


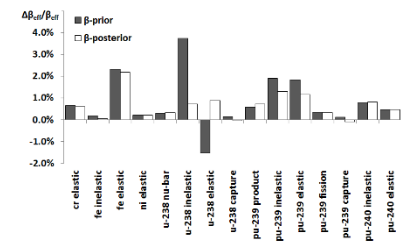
Specificity of correlated data and correlated phenomena

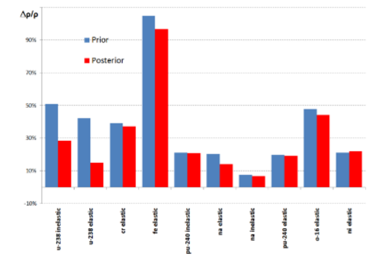
Application objects

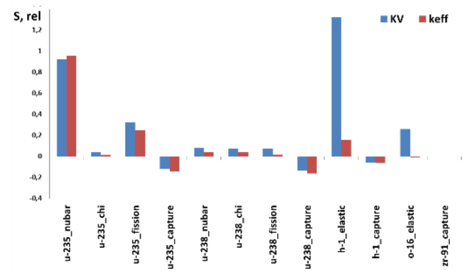
- LMFR => instrumentation
- LMFR => kinetic parameters
- LMFR => subsequent accidental states
- LWRs reactivity analysis
- LWRs unflattening factors

Sensitivity ⇔ uncertainty









Summary (a part of one)

Subjects

- MSR: start-up and operational regimes
- MSR: input for multi-physics
- MSR: storage tank and shut-down state
- LMFRs (izogenerator)
- LMFR instrumentation
- LMFR assembling and reloading

TA to be established

- Total and reduced beta βtotal≤3%, β<min≤3%, λdel≤7%
- Worth(**x**) (HMs, void, etc.) ≤10%
- Criticality and worth (traditional => fp, HMs, …)
- CRs interferences etc. ≤5%
- Local kinetic (AO specific)
- Criticality ~ ≤ 0.3 %

Some additional remarks

MSFR benchmark

- MSFR => $^{233}U/Th$ concept with an option of Pu/U/Th commissioning
- Reactivity, power distribution, BR and BG, kinetic parameters for circulating fuel
- Published in M. Brovchenko, Jan-Leen Kloosterman, et al, 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)

Available data

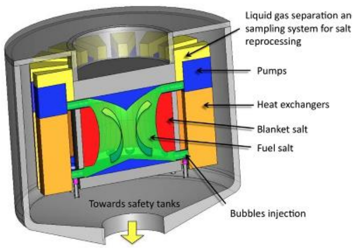
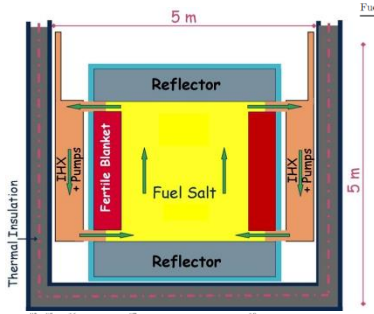
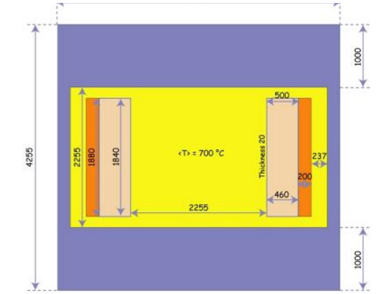
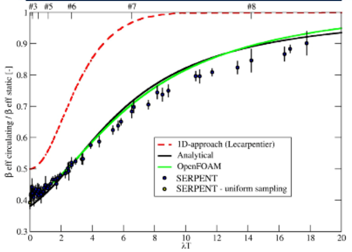


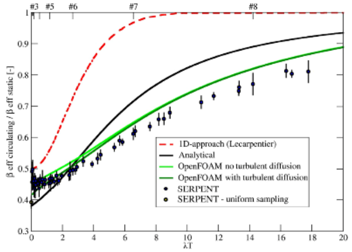
Table 3. Characteristics of the MSFR simulated in the neutronics benchmark.

Thermal power (MWth)	3000				
Electric power (MWe)	1500				
Fuel molten salt initial composition (mol%)	LiF-ThF_4-$^{233}UF_4$ or LiF-ThF_4-(Pu-MA)F_3 with 77.5% LiF				
Fertile blanket molten salt initial composition (mol%)	LiF-ThF_4 (77.5–22.5%)				
Melting point (°C)	565				
Inlet/outlet operating temperature (°C)	650–750				
Initial inventory (kg)	^{233}U-started MSFR		TRU-started MSFR		
	Th	^{233}U	Th	Actinide	
	38 300	5 060	30 600	Pu	11 200
				Np	800
				Am	680
				Cm	115
Density (g/cm^3)	4.1249				
Dilatation coefficient (g/(cm^3 K)) [29]	8.82×10^{-4}				
Core dimensions (m)	Radius: 1.1275				
	Height: 2.255				
Fuel salt volume (m^3)	18				
	9 out of the core				
	9 in the core				
Blanket salt volume (m^3)	7.3				
Fuel salt cycle time in the system (s)	4.0				







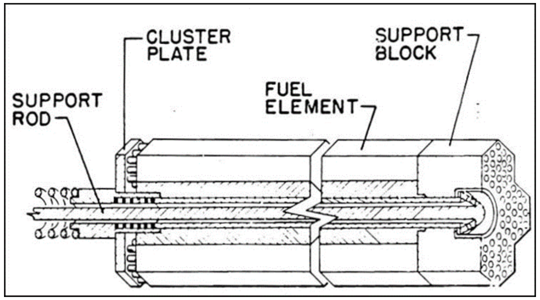


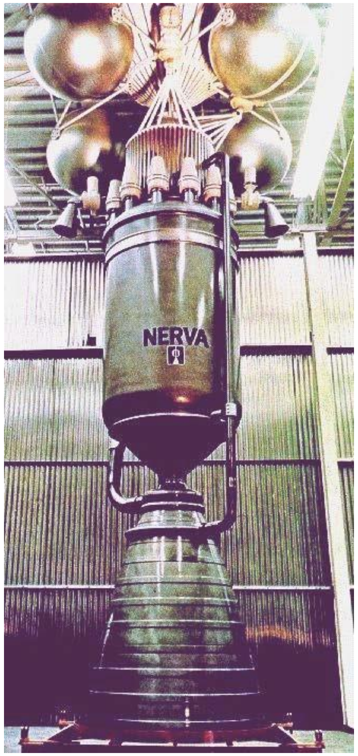
Technological families and "common mode" issues

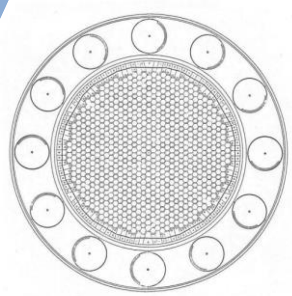
NERVA program

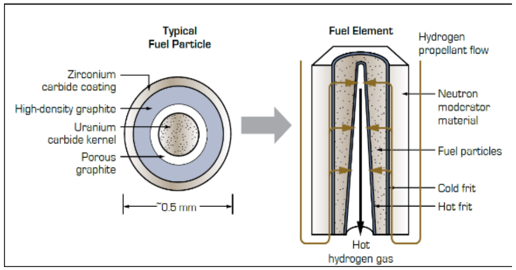
HTGR, VHTR, GFR => Gas cooled systems

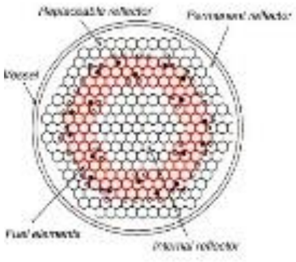
Gas leaks

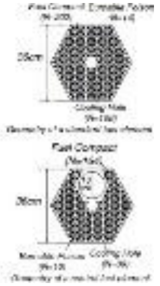


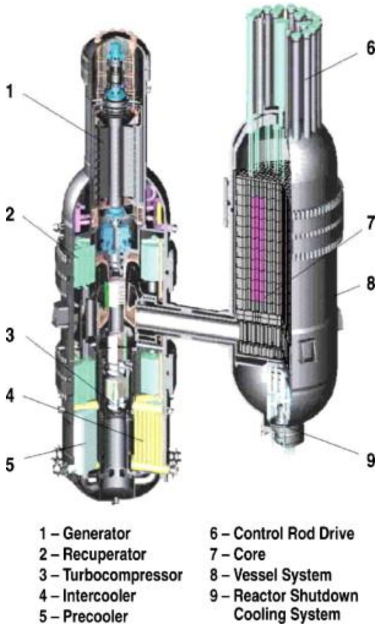






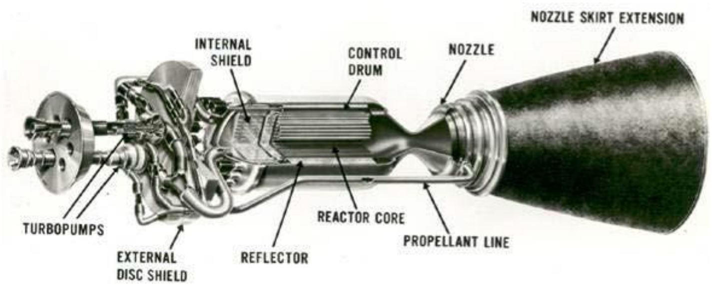






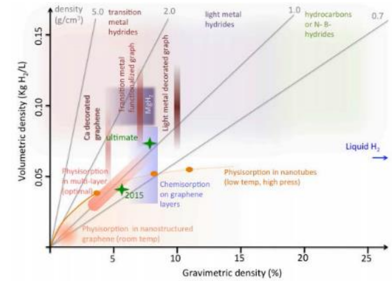
The Nuclear Engine for Rocket Vehicle Application (NERVA)

Nuclear Thermal Propulsion (NTP)

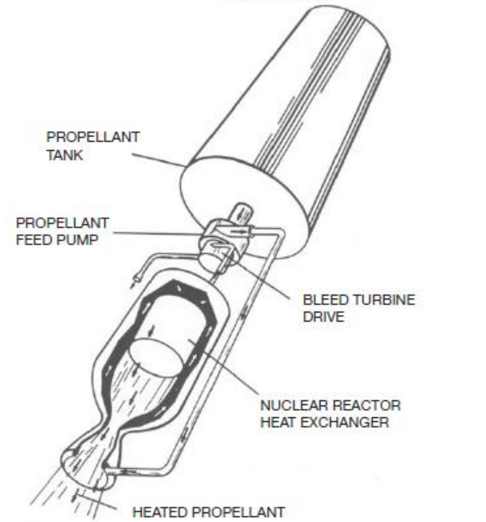


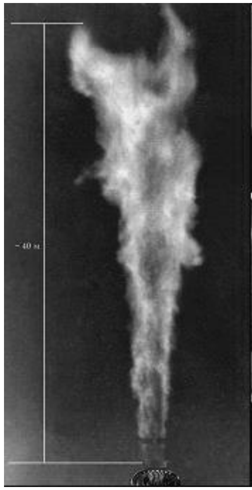
$$I_{sp} = \frac{F}{\mathring{W}} = \frac{V_j}{g}$$

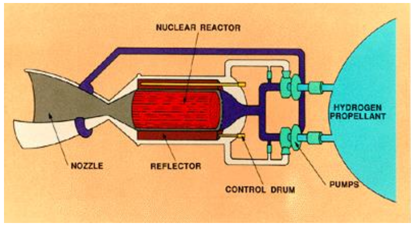
$$F = \frac{\mathring{W}}{g} V_{ex} + (p_e - p_o) A_e$$

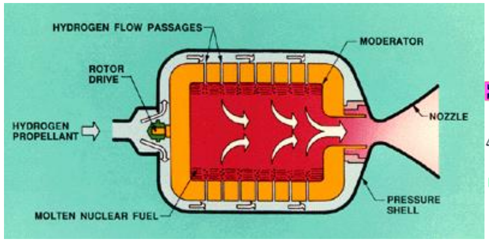


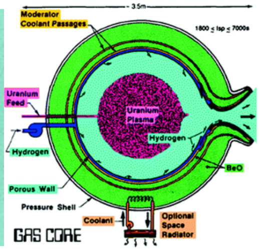
Propulsion	Specific energy (J/kg)	Specific impulse (s)
Chemical, $H_2(g) + 1/2O_2(g) \rightarrow H_2O(g)$	1.3×10^{7}	<520
Nuclear, fission of ^{235}U	8.8×10^{13}	800÷9000

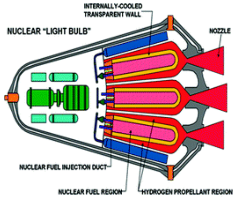








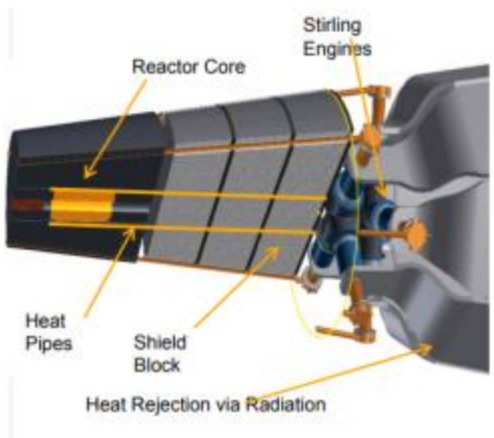


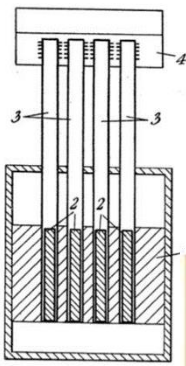


IRSN MEMBRE DE ETSON

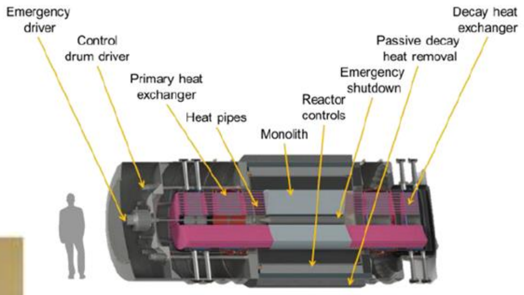
Technological families and “common mode” issues

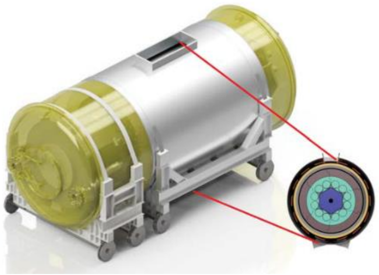
Kilopower: KRUSTY etc.

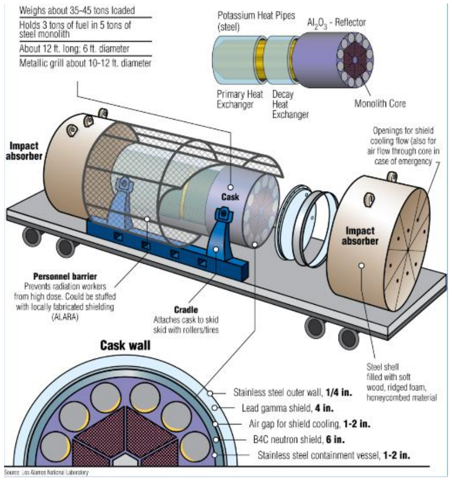




Micro power heat pipe systems: eVinci etc





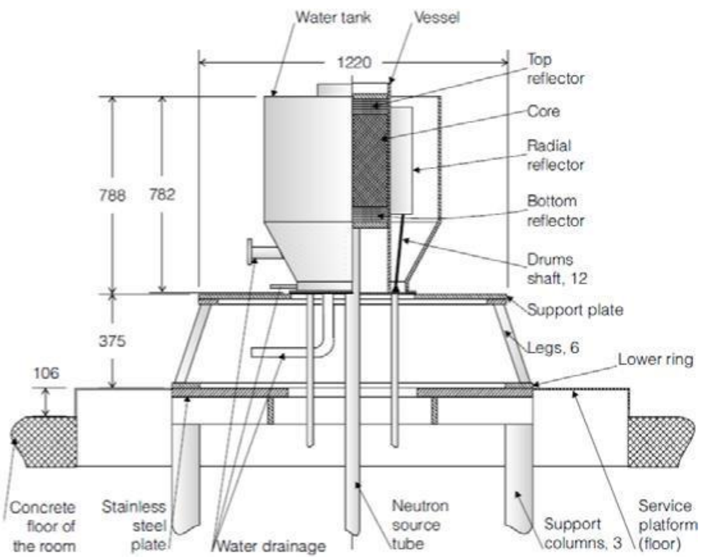


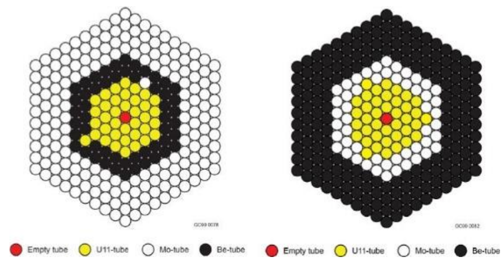
the Kilowatt Reactor Utilizing Stirling TechnologY, or KRUSTY

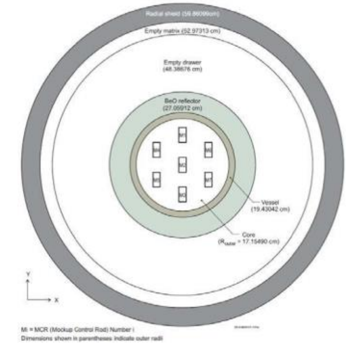
Thank you for your time

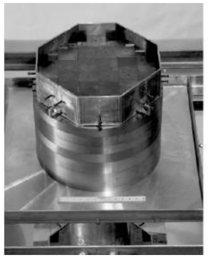
Questions?

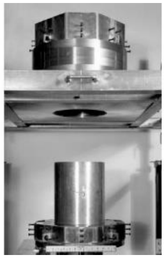
Data preservation: IRPhE collection

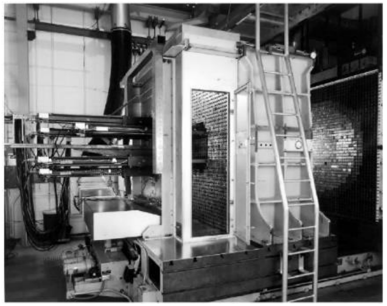


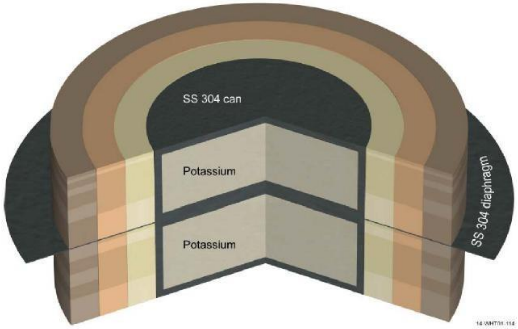




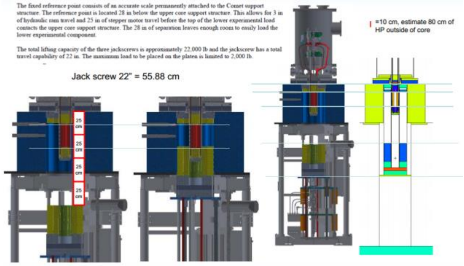






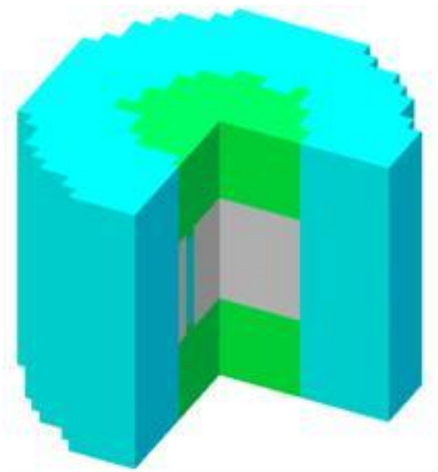


KRUSTY is ongoing

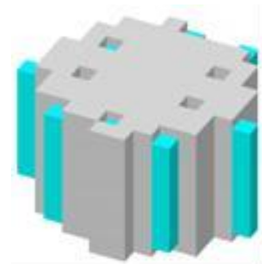


IRSN MEMBRE DE ETSON

Decomposition of SNEAK 7A Model



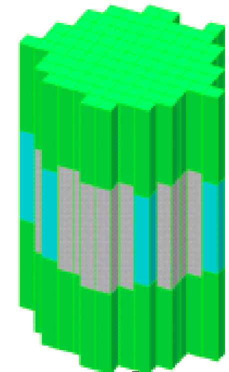
C-R



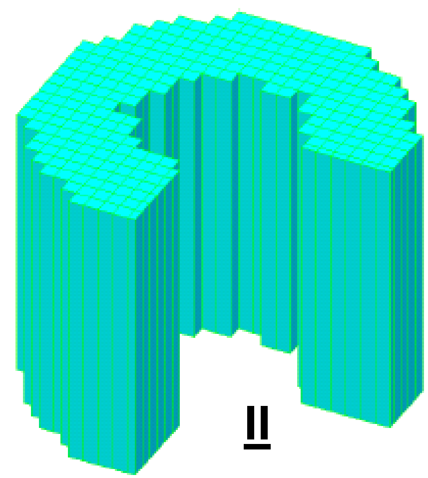
Core

Reflector

I-II



I



II

	C-R	I-II	
β_{rec}, pcm	412.9	411.4	
$\Delta\beta_{exp}/\beta_{Cf}$, %	-4.6	-4.6	before
$\Delta\beta_{noise}/\beta_{Cf}$, %	-0.02	-0,39	after