Liquid metal cooled fast reactors

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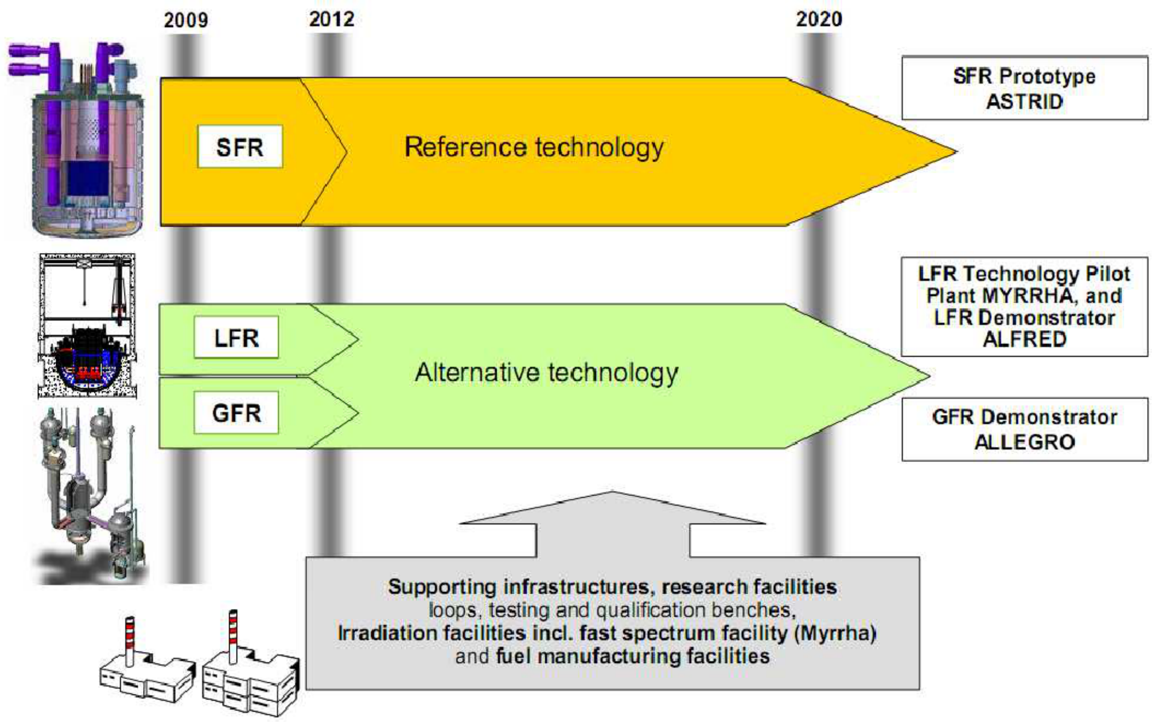
  - Turbulent transport (momentum,energy)
  - Engineering –Pumps, Materials
- System dynamics – safety
- SUMMARY

with input from the KIT groups
Nuclear Plant Safety, Reactor Physics and Dynamics - INR
Karlsruhe Liquid Metal Laboratory –KALLA –IKET
Transmutation- KALLA –IKET
Programm Nukleare Entsorgung und Sicherheit– NUSAFE @ KIT

ROADMAP-European Sustainable Nuclear Industrial Initiative



ESNII roadmap

➡ **Most mature technology SFR**

Roadmap- Generation IV Forum (GIF)

Criteria

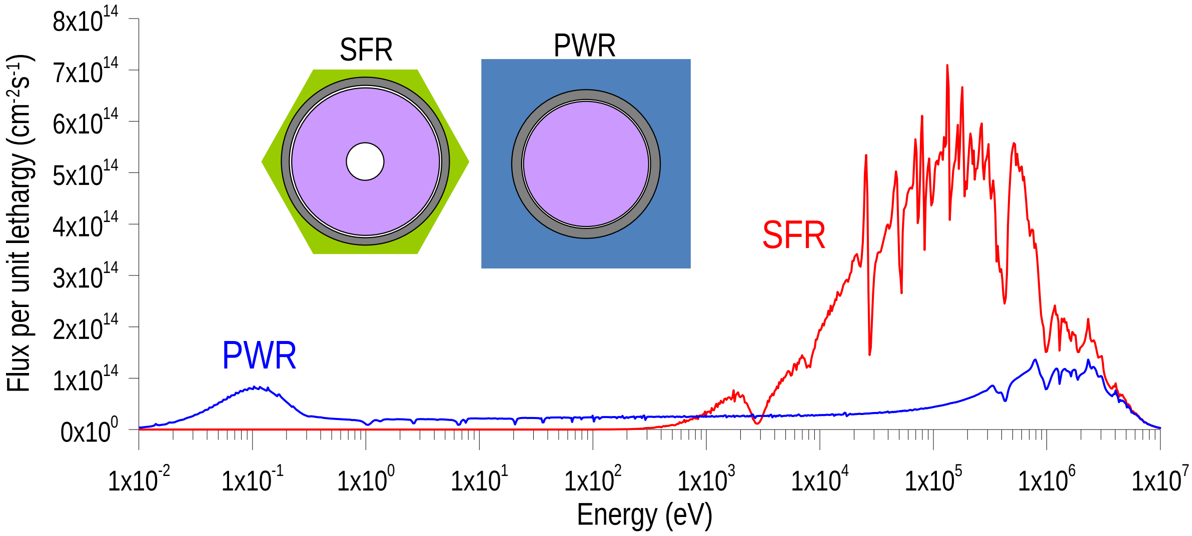
- Sustainability
  - improved fuel utilization - capacity of breeding
  - minimization of waste - recycling (capability of Minor Actinide (MA) recycling with minor impact on core safety parameters, -homogeneous core configuration or Minor Actinide Breeding Blanket (MABB) option)
- Economics
  - comparable to other energy sources (reactor + fuel cycle)
    - Long cycle lengths ➡ high loading factors (low reactivity swing, steady power shape)
    - Improved lifetimes for fuel & absorbing elements (material performance, optimized fuel pin, absorbing materials with low efficiency)
    - Compact core size
- Safety (➡see safety last chapter)
  - high level of safety and operational reliability
  - Very low probability of core damage accidents (CDA)
  - Elimination of need for off-site emergency response
- Proliferation :
  - Low susceptibility to diversion & physical protection against deliberate aggression

➡ **FAST SPECTRUM REACTORS**

Roadmap- Generation IV Forum (GIF)

FAST SPECTRUM REACTORS

- fission chain reaction sustained by fast neutrons
- no need for neutron moderator, but
- requires fuel highly rich of fissile material (>>10%)



KEY FEATURES of FAST REACTORS

- **higher flux (factor 10)** ➡ **material damage**
- **higher volumetric power** ➡ **high temperature gradients,**
- **Fast in all views (neutronics -many groups, TH- TM transients)**

Fast reactors

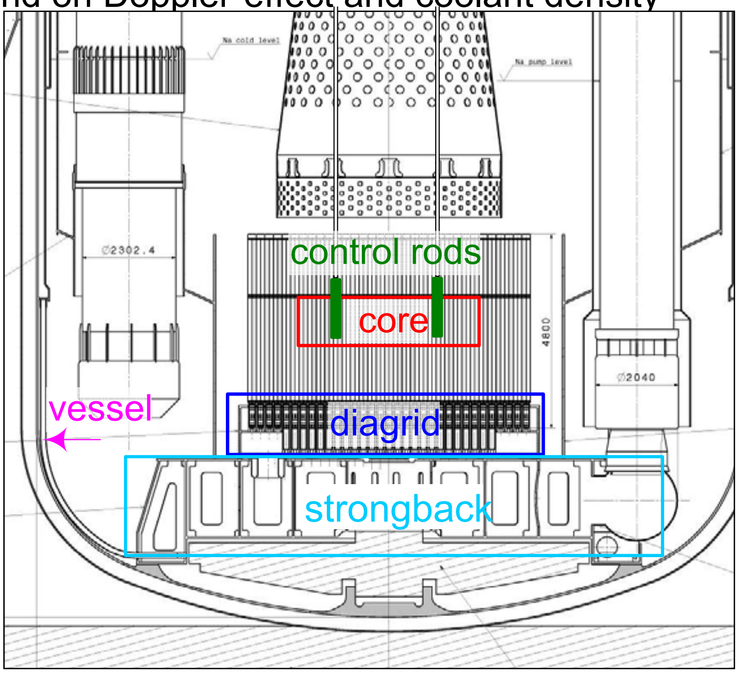
Why power density and dynamics are so important ?

- Feedback does not only depend on Doppler-effect and coolant density

- *Thermal changes*
- ➡ thermal expansion of structures
- ➡ Impact on reactivity (+ or minus)

Most relevant ones

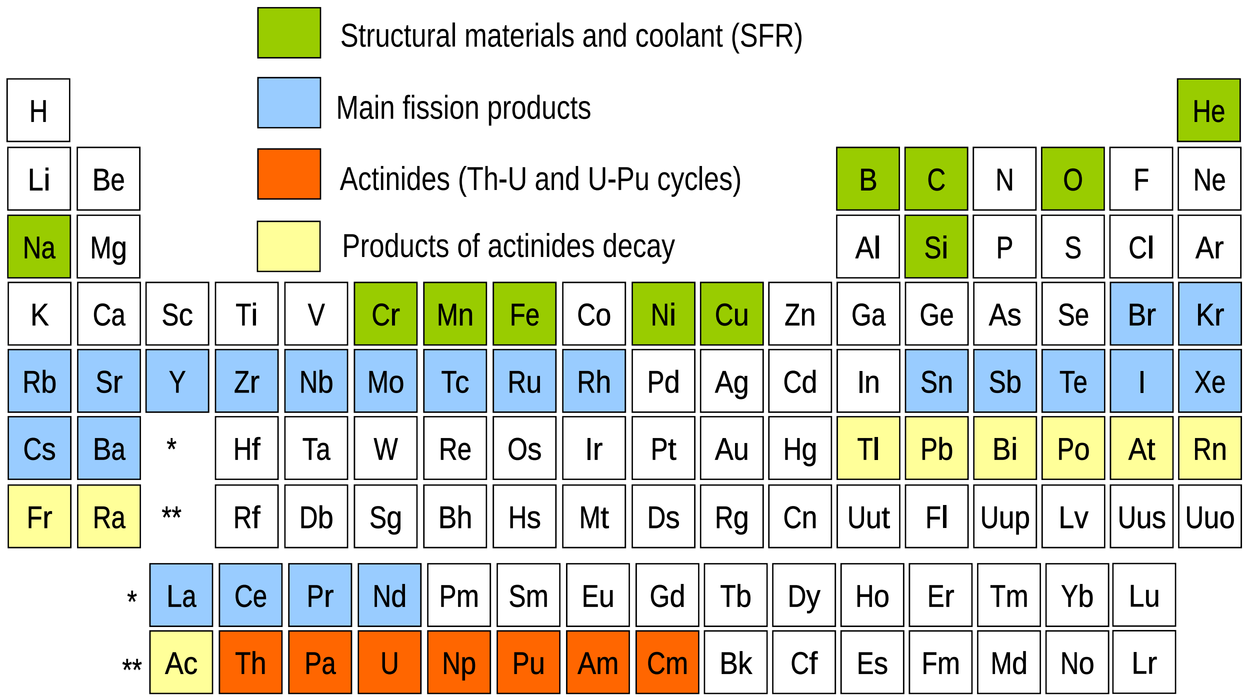
- Fuel expansion (–)
- Clad expansion (+)
- Diagrid expansion (–)
- Strongback expansion (–)
- Vessel expansion (+)
- CR driveline expansion (+ /–)



➡ detailed representation mandatory for reliable safety analysis

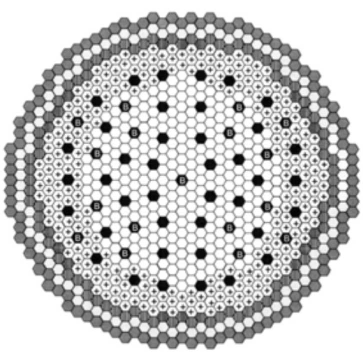
Not considered in this context in depth

Fast Reactors – Nuclide composition neutronics



Fast reactors- principle design

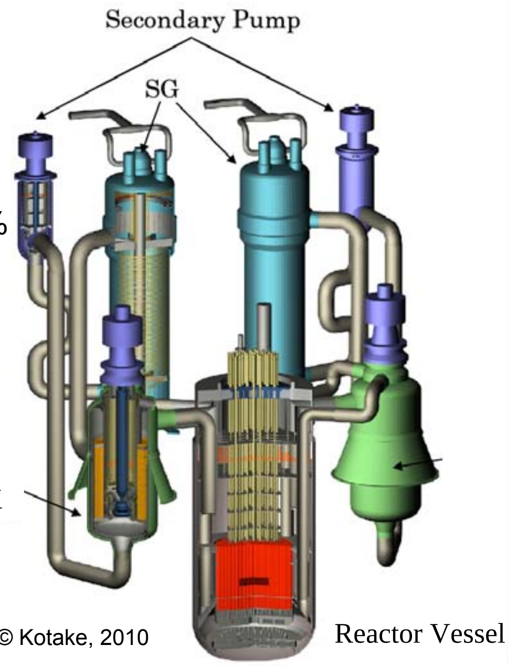
- **Loop type system**
  - seismic resistance ↑
  - Safety performance ↓



Core Zone	Inner Core	288
	Outer Core	274
Radial Blanket		96
Control Rod	Primary Control Rod	40
	Backup Control Rod	17
Radial Shield	SUS	102
	Zr-H	108

(JSFR,Japan)

P_{el} 750MW/η=40%
Core T_{in}/T_{out} 352°C/520°C
$u_{0,mean}$, $u_{0,max}$ 2.9, 4.1m/s
Core Δp 3 bar

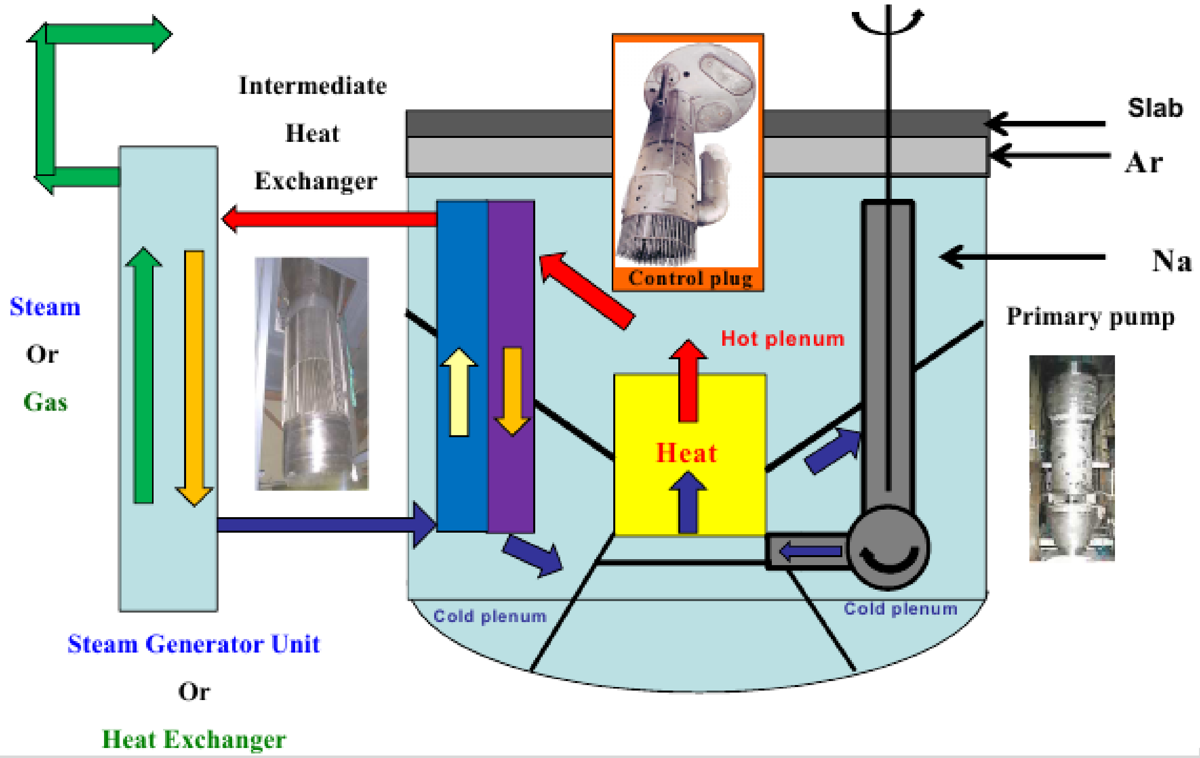


© Kotake, 2010

- Most advanced **Pool Type Design**

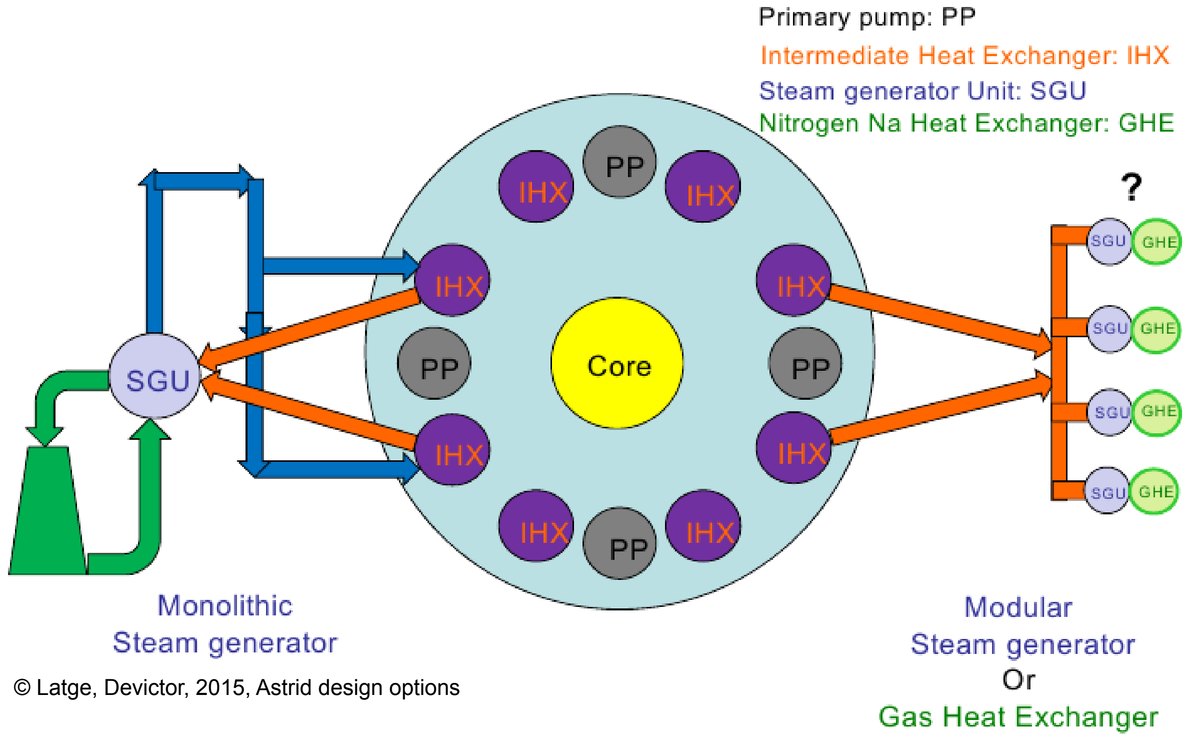
Fast reactors- principle design

- Functional layout – pool (vertical cut)



Fast reactors- principle design

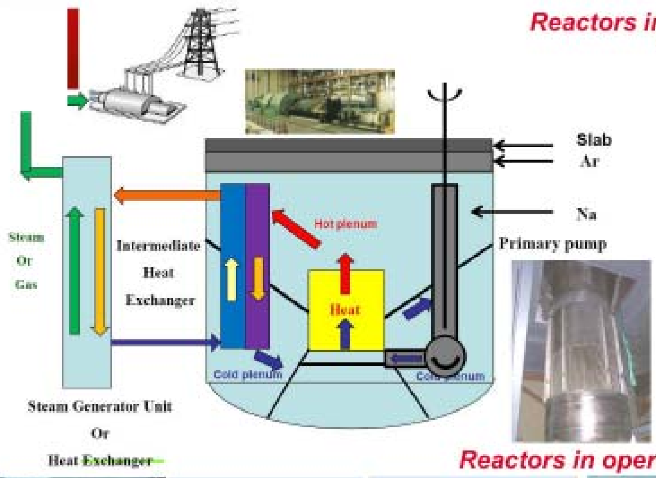
- Functional layout – pool (vertical cut)



© Latge, Devictor, 2015, Astrid design options

SFR- several thousand reactor years accumulated

- First reactor in world EBR-I –sodium cooled -20.Dec. 1951, **net power 800W !!!**



Reactors in start-up phase

BN800
(Russia)
800 MWe

PFBR
(India)
500 MWe

Reactors in operation

- and new projects under way worldwide as JSFR, CDFR, PGSFR, CFBR, **ASTRID**, BN1200

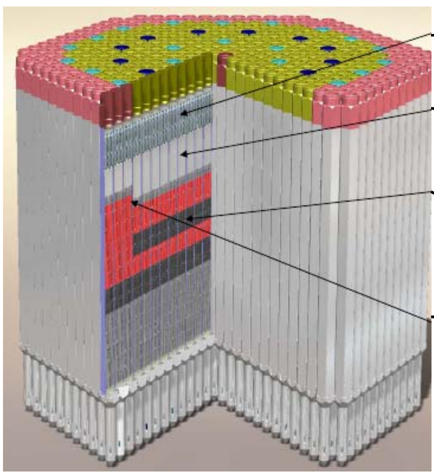
SFR- ASTRID

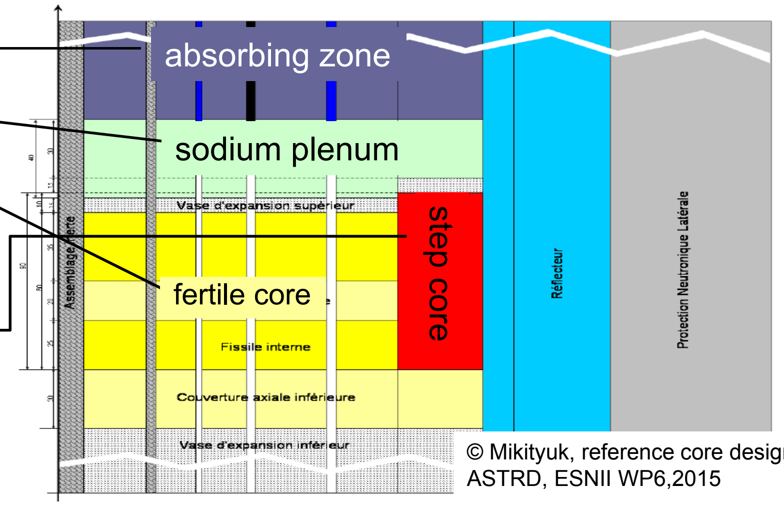
General features SFR

- introduction of sodium plenum (enhanced leakage- void worth ↓)
- reflectors at top and bottom/
- low coolant/fissile ratio

Modifications for ASTRID

- Innovative core design
  - Heterogeneous axial enrichment
  - Separation in two cores (inner/outer)





© Mikityuk, reference core design ASTRD, ESNII WP6,2015

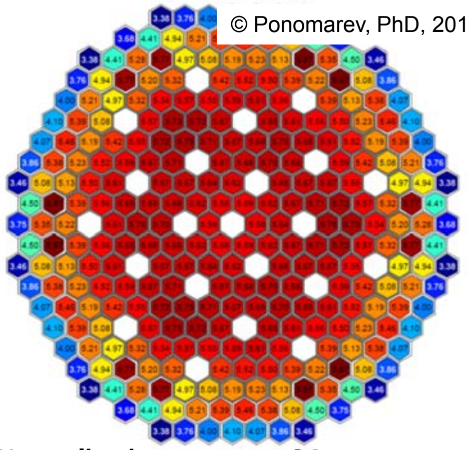
SFR- ASTRID

Core calculations for ASTRID

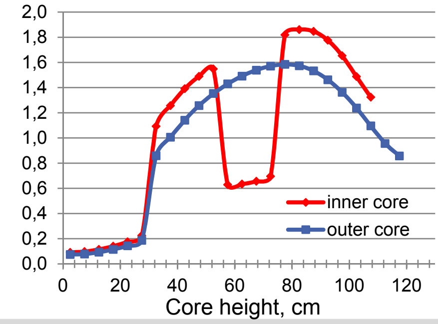
- heterogeneous power distribution across core
- enlarging control rod worth, reducing void worth
- ➡ enhanced safety performance

Parameter	Value	
	IC	OC
Total core power, MW	1500.00	
Subcore powers, MW	973.98	526.02
SA number in subcores	177	114
Subcore volumes, m^3	5.27	3.70
Average SA power in subcores, MW	5.503	4.614
Subcore radial peak.factor (for SA)	1.045	1.273
Maximum power density in core, W/ccm	360.4	
Average power density, W/ccm	167.2	
Volumetric peak.factor	2.156	
Maximum power density, ccm	360.4	287.5
Average power density in subcores, W/ccm	184.8	142.1
Volumetric peak.factors in subcores	1.950	2.024
Maximum linear power, W/cm	446.1	355.9
Average linear power, W/cm	228.8	175.9
Maximum power density in av.SA, W/ccm	343.9	225.2

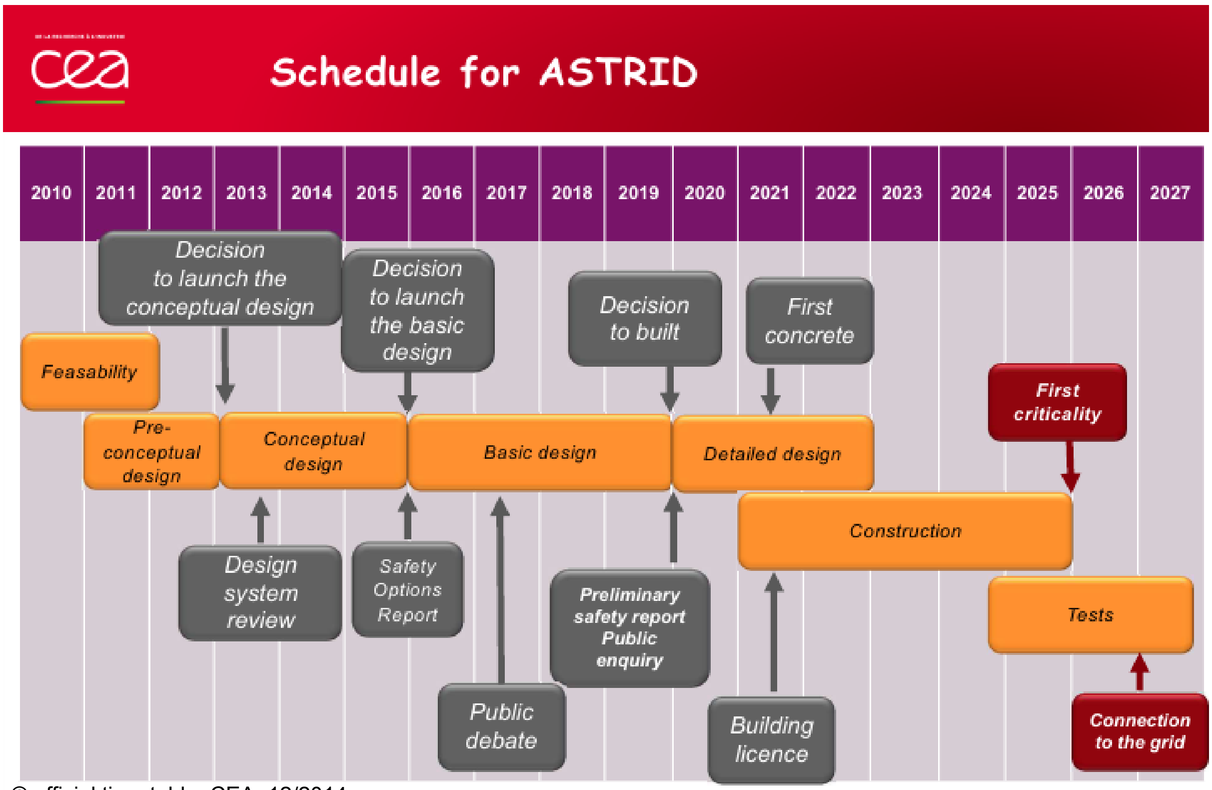
SA power map, [MW]



Normalized power at av.SA



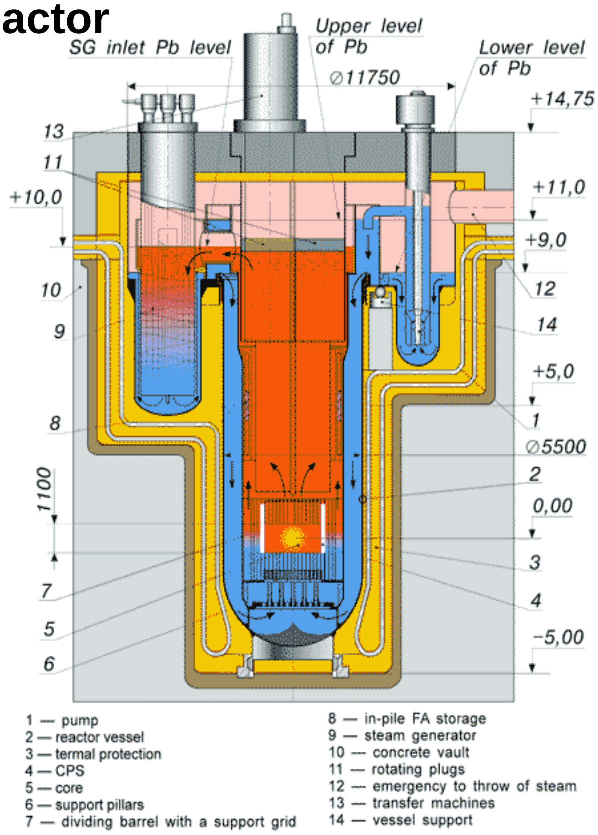
SFR-ASTRID



LFR :BREST-300 Prototype Reactor (Nikiet, Russia)

KEY DATA

Thermal power	700 MW
Gross electric power	300 MW
Net plant efficiency	43%
Coolant	pure lead
Core inlet temperature	420°C
Core outlet temperature	540°C
Coolant velocity in the core	<1.67m/s
Core coolant pressure drop	1.55 bar
4 coolant loops, 4 pumps 500kW each	
Feedwater temperature	355°C
Steam temperature	525°C
Steam pressure	27 MPa
Refuelling intervals	300 days
Vessel material	Cr16Ni10
Vessel air preheaters	420 - 470°C



BREST−300 reactor. Vertical section

LFR : BREST-300 Core Design

Fuel: PuN-UN

Max. enrichment: 16.1%

Avg. burn-up: 61.5 GWd/t

Pu content: 2260 kg

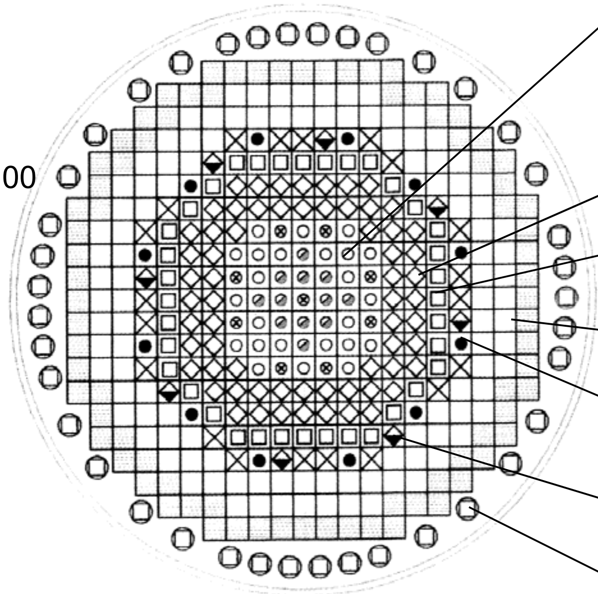
Active core height: 1100 mm

Inner Core Diameter: 1280 mm

Outer Core Diameter 2296 mm

Assembly width: 166.5 mm

Fuel pin diam. 9.4 to 10.5mm



45 Inner Fuel Assemblies with Shutdown Rods (BC; 20%^{10}B)

64 Intermediate Fuel Assemblies

36 Outer Fuel Assemblies

148 Reflector Blocks

20 Control Rods

8 Reflector Blocks with Shut Down Rods

38 Storage Locations

Peak core power density	835 MW/m^3
Average core power dens.	510 MW/m^3

Max. cladding surface temp: 650°C

Reactor applications- LFR- FA design

Reactor type	SVBR	BREST	JNC	ELSY	PDS-ADS	EFIT
Coolant	LBE	Pb	LBE	Pb	LBE	Pb
Lattice	Δ	□	Δ	□/Δ	Δ	Δ
Spacer types	honey	tube	wire wrap	Honey	honey	honey
Pin ∅ (mm) *P*	12	10.4	7.6	10.6	8.2	8.5
Pin/Pitch *P/D*	1.42	1.4	1.21	1.415	1.58	1.54
W/D	1.32	1.2	1.48	1.7	1.69	1.4
Active height *H* [mm]	1000	1100	700	1200	870	775
H/D	83.	106	92.1	113.2	106	91.1
Power density [W/cm^3]	140	510	420	200	300	100
q''_{mean} [W/cm^2]	31	60	92	69.8	38	100
u_0 [m/s]	1.2	0.6	1.6	2	0.3	1.1
Re_D	$7\cdot10^{4}$	$4\cdot10^{4}$	$5.5\cdot10^{4}$	10^{5}	$2.5\cdot10^{4}$	$6\cdot10^{4}$
Pr	0.02	0.023	0.02	0.023	0.02	0.023
Pe	$1.4\cdot10^{3}$	920	$1.1\cdot10^{3}$	$2.3\cdot10^{3}$	500	$1.38\cdot10^{3}$
Gr_x	$7.04\cdot10^{15}$	$2.7\cdot10^{16}$	$1.56\cdot10^{16}$	$7.6\cdot10^{16}$	$9.02\cdot10^{15}$	$1.9\cdot10^{16}$
Gr_D	$2.56\cdot10^{7}$	$9.2\cdot10^{6}$	$7.1\cdot10^{5}$	$1.5\cdot10^{7}$	$8.1\cdot10^{6}$	$2.2\cdot10^{7}$
$0.3\cdot Re/(Gr)^{0.5}$	4.15	3.9	10.15	7.7	2.64	3.75

Reactor applications- SFR -FA design

Reactor type	SPX	BN600	JSFR	EFR	PBFR	SNR300
Configuration	pool	pool	loop	pool	pool	loop
Lattice	Δ	Δ	Δ	Δ	Δ	Δ
Spacer types	wire	wire	wire	wire	spacer	spacer
Pin ∅ (mm)	8.5	6.9	10.4	8.2	6.6	7.6
Pin/Pitch *P/D*	1.14	1.19	1.14	1.18	1.3	1.26
W/D	1.2	1.19	1.23	1.19	1.32	1.28
Active height *H* [mm]	1000	1030	1000	1000	1000	950
H/D	117.6	149.3	96.2	122.0	151.5	125
Power density [W/cm^3]	279	353	144	242	208	300
q''_{mean} [W/cm^2]	112	129	77	101	138	97
u_0 [m/s]	6.1	7.5	3	6.7	7.7	5
Re	$2\cdot10^{4}$	$3.82\cdot10^{4}$	$1.2\cdot10^{4}$	$2.5\cdot10^{4}$	$3.9\cdot10^{4}$	$2.5\cdot10^{4}$
Pr	0.007	0.007	0.007	0.007	0.007	0.007
Pe	140	267	84	175	273	175
Gr_x	$1.53\cdot10^{12}$	$1.67\cdot10^{12}$	$1.53\cdot10^{12}$	$1.53\cdot10^{12}$	$1.53\cdot10^{121.}$	$1.31\cdot10^{12}$
Gr_D	$9.4\cdot10^{5}$	$5.1\cdot10^{5}$	$1.7\cdot10^{6}$	$8.4\cdot10^{5}$	$4.4\cdot10^{5}$	$6.7\cdot10^{5}$
$0.3\cdot Re/(Gr)^{0.5}$	6.2	16	3.2	8.1	17.6	9.2

- **Nominal cond´s:**
  - **turbulent, forced convective flow**
- **Challenges:**
  - **loss of flow → transition to buoyant convection,**
  - **tight lattices (*P*/*D*) → strong secondary flows**

Transmutation – 2 Modes

Homogeneous mode

- MA diluted in small fraction in driver fuel

Advantages
- high neutron flux available
- fuel behavior slightly affected by some % of MA
- acceptable MA global quantities higher than heterogeneous mode

Drawbacks
- core safety parameters affected by MA insertion (max. MA content SFR 3-5%, reduced Doppler constant (SFR -15 % for 3% MA), coolant coefficient (-5%), delayed neutron fraction (-5%)
- entire fuel supply chain affected by transmutation

Heterogeneous mode :

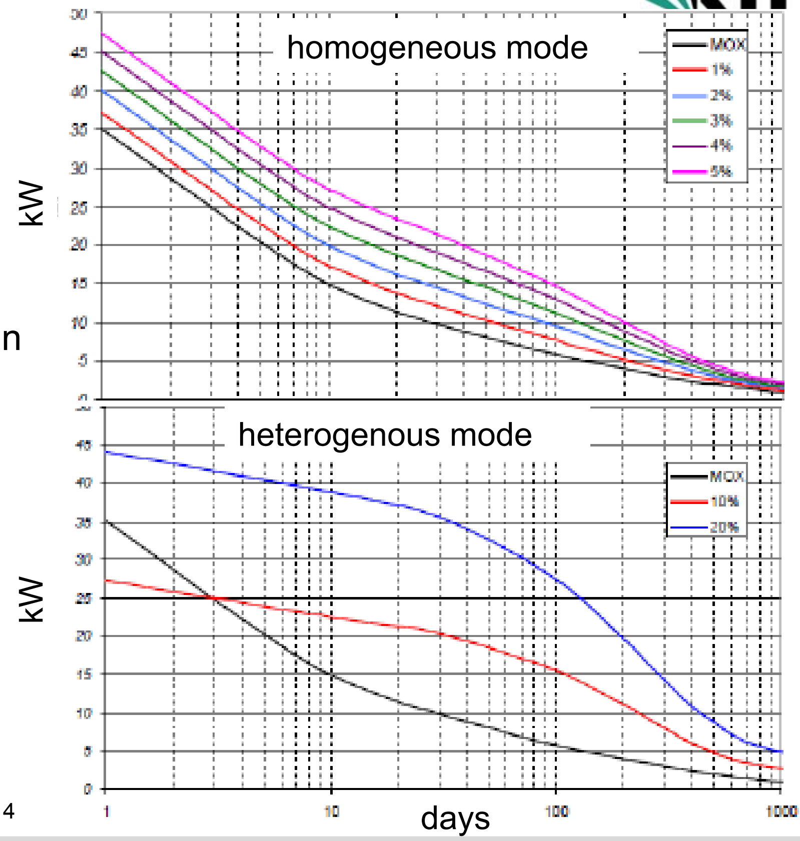
- MA concentrated in specific devices, apart from driver fuel

Advantages
- transmutation targets placed in neutron weak importance
- ➔ marginal impact on core safety parameters
- limited numbers of transmutation element to manage
- management of driver fuel / transmutation targets not coupled

Drawbacks
- lower neutron flux level @ periphery
- high concentration of MA in targets important neutron sources and decay heat to manage, lacks in material behavior knowledge

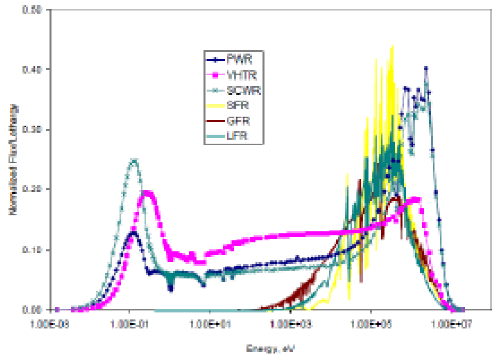
Transmutation - Impact of MA content

- decay heat in homogeneous mode increasing with MA content
- decay heat in heterogeneous substantially lower than in homogeneous option



Transmutation performance- key core options

- neutron spectra (f = (material, coolant, structural materials))
  - ➡ affects fission/capture cross-section ratio



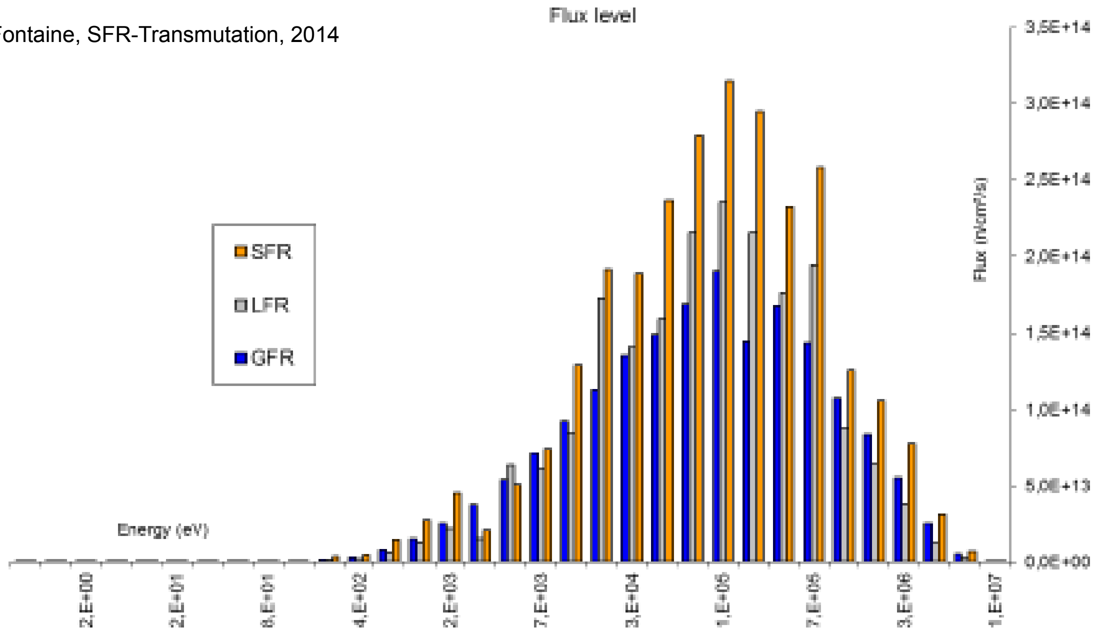
- Power density [MW/m³]
  - ➡ determines global MA mass in fuel cycle
- Heavy nuclide inventory [kg/MW]
  - ➡ affects neutron flux level

	SFR	LFR	GFR
HN inventory (kg/MWe)	50 kg/MWe	85 kg/MWe	60-70 kg/MWe

- Maximal acceptable MA content , which depends on
  - fuel material
  - safety parameters (coolant is essential)

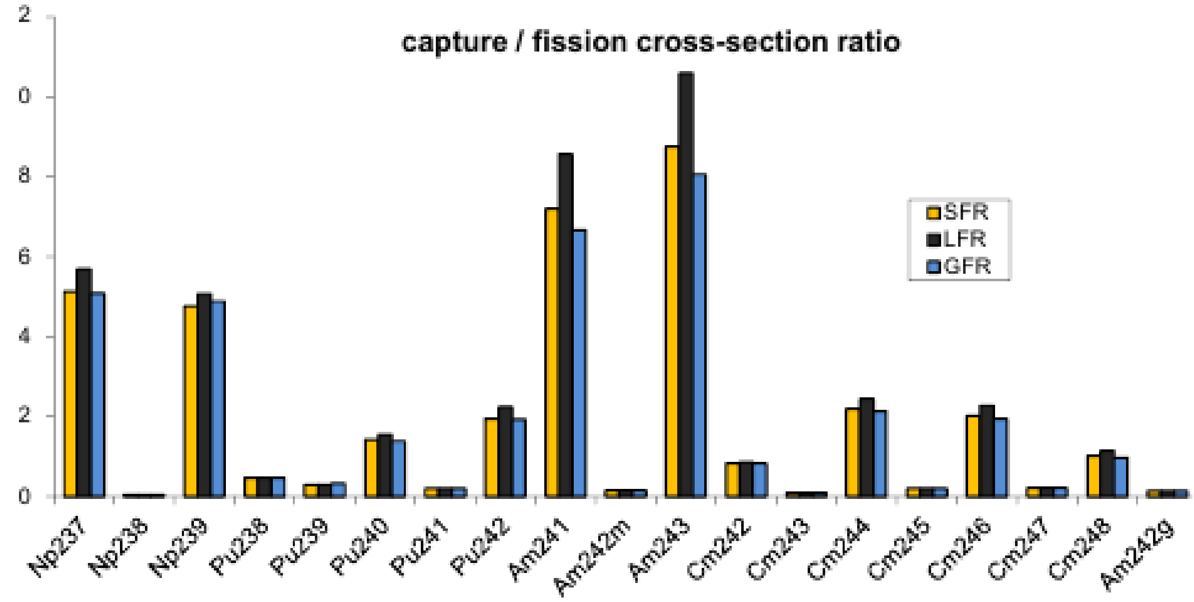
Transmutation performance-Comparison of different FR‘s

© B. Fontaine, SFR-Transmutation, 2014



- SFR flux level higher than LFR/GFR in nearly all energy groups !!!
- ➡ cladding/core internals challenge

Transmutation performance-Comparison of different FR's



- almost similar for GFR/SFR, little penalty for LFR (large coolant fraction)

Transmutation performance - SFR

MA balance (kg/TWhe)	SFR No transmutation	SFR homogeneous 1%	SFR homogeneous 3%	SFR heterogeneous MABB 10% Am
Np	+0.5	-0.6	-2.9	
Am	+3.3	-0.9	-9.2	
Cm	+0.9	+1.4	+2.5	
AM	**+4.7**	**-0.1**	**-9.6**	**-3.7** (MABB) **+1.4** (MABB+core)

© Verwaerde, CP-ESFR, WP-3, Final report,2013

- in homogeneous mode, auto-recycling is achieved near 1%
- 💣in heterogeneous mode, MABB+Core has to be considered !
- in any case Curium production is not stopped

More details for SFR
Gabrielli, Rineiski et al. , 2015, Energy Procedia, ASTRID-like Fast Reactor Cores for Burning Plutonium & Minor Actinides, Vol. 71, p.130ff

Transmutation ability

	SFR	LFR	GFR
Transmutation capabilities	High flux, fast spectra		
MA balance	Around -10 kg/TWhe (homogeneous mode)		
Cycle impacts	moderate MA inventory in cycle		High MA inventory in cycle (low neutron flux)
Flexibility	Homogeneous mode Heterogenous mode	Potentially the same than SFR	Only homogeneous
MA integration capacities	3 % (hom.)	Same than SFR ? Higher margins on coolant void	5% (hom.)
Technology maturity for transmutation	Existing experiments in SFR	Use of SFR experience ?	No experience

FR- Summary- Reactors & Core Design

Use of liquid metals in fast nuclear systems

- Ensures good neutron economy ➡ efficient fuel utilization (CR≥1)
- Transmutation capability limited (type and concept dependent)
- Safe reactor concept requires more advanced computational effort (neutronics , TH-TM and their interaction)
  BUT: physically not impracticable
- higher thermal efficiency (high temperatures for power conversion system)
- compact design
- necessitates high Pu enrichment but allows for high burn-up (mostly material limiting –clad/or RPV) at load cycles comparable to LWR

➡ **Why liquid metal cooled fast reactors (FR) are not standard today ?**

- technology gaps (thermal-hydraulics, material issues, instrumentation,…)
- advanced safety requirements (seismic loads, ….)
- public acceptance (or perception –“breeder“)
- ……

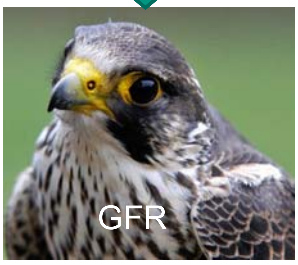
FR-Summary-Reactors & Core Design

- Different Fast Reactors = different products although owing a fast neutron-spectrum

falcon

eagle

turkey

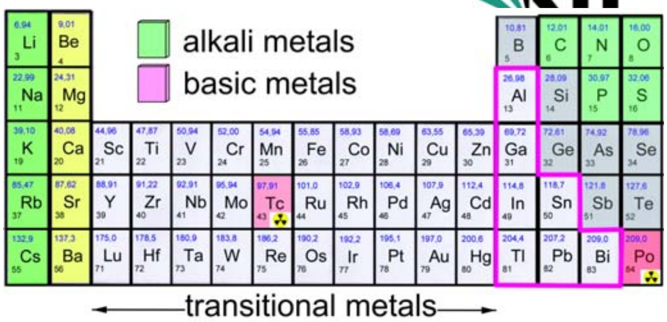


- different properties (time scales, power density, neutronics, TH-TM and safety demonstration)

What distiguishes liquid metals from other liquids ?

Elements suitable for engineering ?

- alkali-metals (Li, Na,K+alloys)
- basic metals (Pb,Ga,Sn+alloys)



	Li	Na	$Na^{78}K^{22}$	Pb	Sn	$Pb^{45}Bi^{55}$	$Ga^{68}In^{20}Sn^{12}$	Hg
T_{melt} [°C]	180	98	-11	327	232	126	11	-39
$T_{boiling}$ [°C]	1317	883	785	1743	2687	1533	2300	356
ρ [kg/m3]*	475	808	750	10324	6330	9660	6440	13534
c_p [J/(kgK)]	416	1250	870	150	240	150	350	140
ν [(m²/s)· 10^{-7}]	7.16	2.6	2.4	1.5	1.6	1.1	3.7	1.1
λ [W/(mK)]	49.7	67.1	28.2	15	33	12.8	16.5	8.3
σ_{el} [A/(Vm)·10^5]	23.5	50	21	7.8	15.9	6.6	8.6	5.7
σ [N/m·10^{-3}] @ T=300°C	421	202	110	442	526	410	460	436

* @ T=600°C, p=10^5Pa, except GaInSn, Hg (T=20°C)

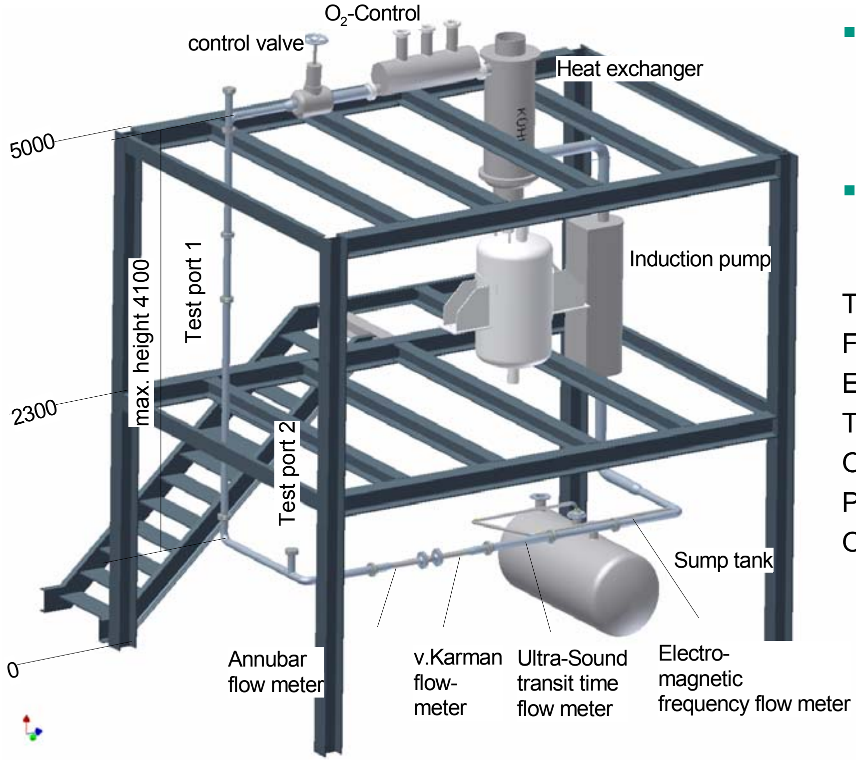
What distiguishes liquid metals from other liquids ?

General findings ➡ technical impact

- low kinematic **viscosity** ➡ turbulent flow (ν_{H2O}~10-6m²/s)
- high **heat conductivity** ➡ scale separation of thermal from viscous boundary layer (λ_{H2O}~0.6W/(mK))
  ➡ time separation of temperature and velocity fluctuations (different damping !!!!)
- high surface **tension** ➡ different bubble transport/interaction mechanisms
  ➡ scale separation of velocity field and surface statistics (high retarding moment) (σ_{H2O}~52mN/m))
- high elec. conductivity ➡ velocity field modification by strong fields due to ($\vec{v} \times \vec{B}$) (Magnetohydrodynamics)
  ➡ measurement access by electromagnetic means
  ➡ pumping (MHD-Pumps) and/or flow control
- **opaque** ➡ no optical access
- high boiling points ➡ wide operational temperature threshold (ΔT)
- Complex **chemistry** ➡ alkali metals with Group V, VI,VII elements
  ➡ exotherm. reactions
  ➡ heavy metals weak reactions with Group V-VII but
  ➡ dissolution transitional metals (structure materials !!!)

FACILITIES-TECHNOLOGY @KIT

PbBi Loop THESYS



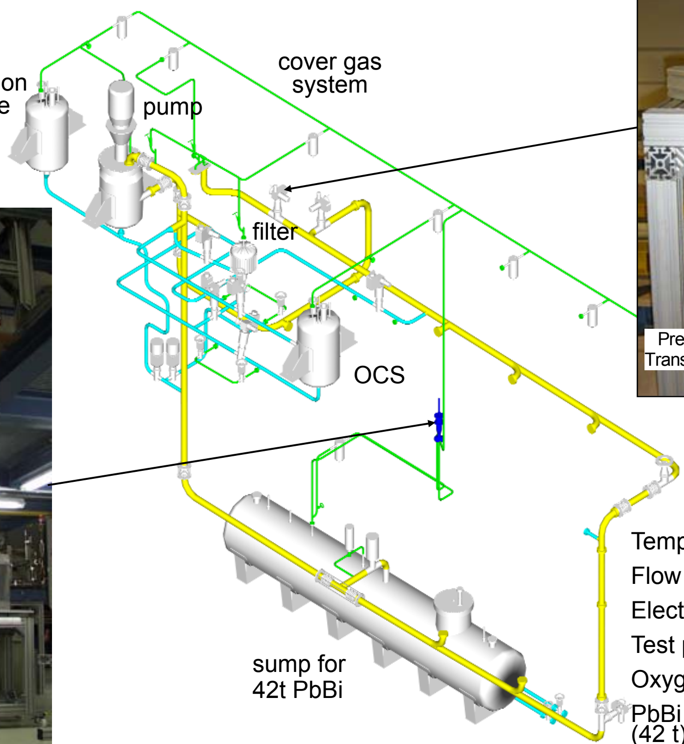
- Development of measurement techniques for flow, temperature and pressures
- Benchmark experiments

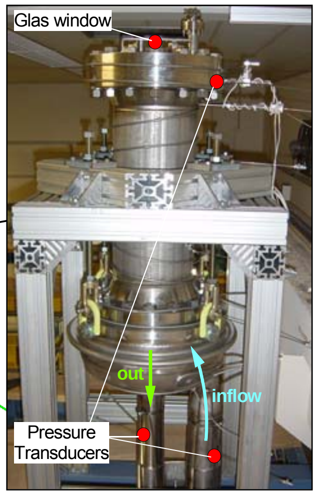
Temperature	200-550°C
Flow rate	16 m^3/h
Electr. power	250 kW
Test ports	2+2
Oxygen control	yes
PbBi inventory	300 l (3 t)
Operating hours	4000

Prototype Loop THEADES

Component Tests

MEGAPIE experiment





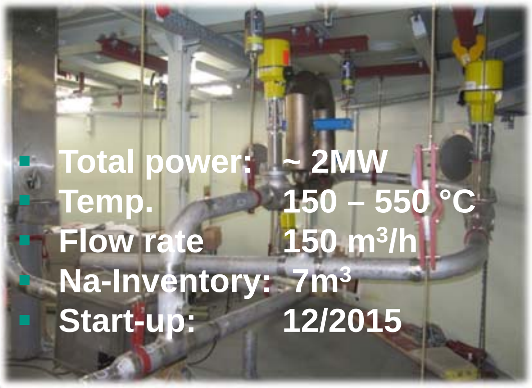
Free surface target experiment

Temp.	-400°C
Flow rate	47 m^3/h
Electr. power	1200 kW
Test ports	2
Oxygen control	yes
PbBi inventory (42 t)	4000 l
Operating hours	4000

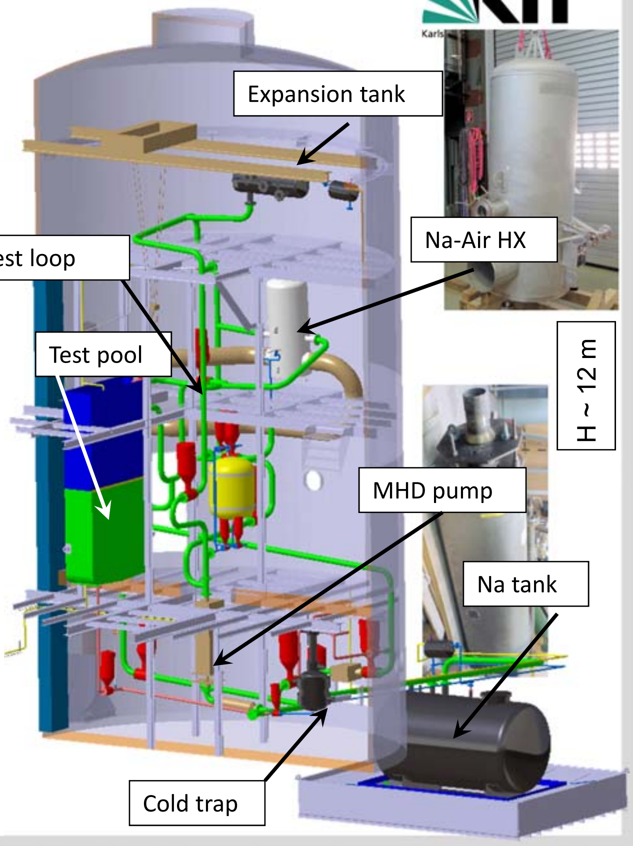
KASOLA- (KArlsruhe SOdium LAboratory

(http://www.inr.kit.edu/258.php)

- Facility planned for:
  - research activities on liquid metal (LM)
  - accelerator target development
  - studies of LM for solar applications
  - development of turbulent LM heat transfer models for CFD tools
  - system tool qualification (TRACE)



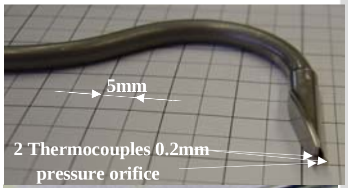
- Total power: ~ 2MW
- Temp. 150 – 550 °C
- Flow rate 150 m³/h
- Na-Inventory: 7m³
- Start-up: 12/2015

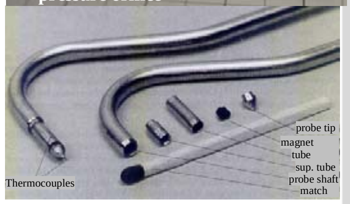


INSTRUMENTATION

How to measure in liquid metals ?

- **Flow rate** – electro-magnetic, Δp, UTT, momentum based ……..
- **Visualization techniques**
  - direct – X-Ray tomography
  - indirect – CIFT,
    Utra-sound-transient time (UTT),….



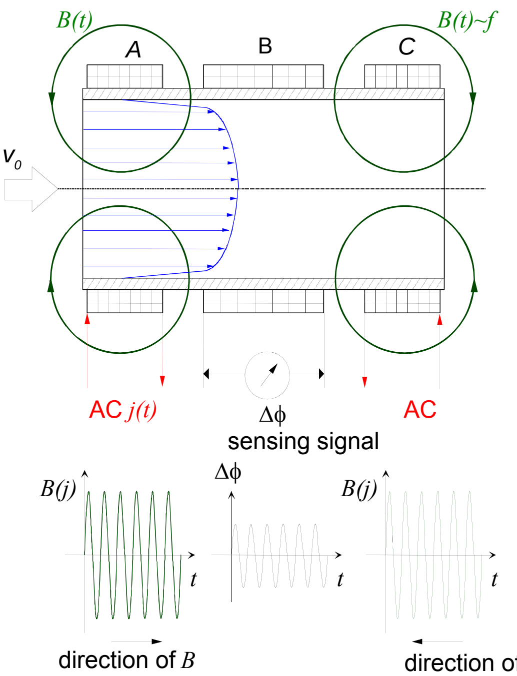


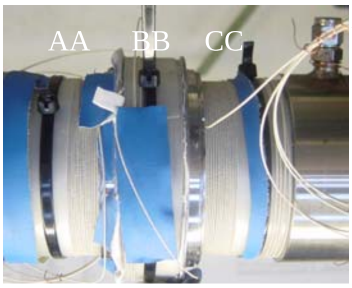
- **Velocity**
  - direct – Pitot-Tube (Δp)
    – magnetic potential probes (MPP)
    – fibre-mechanics

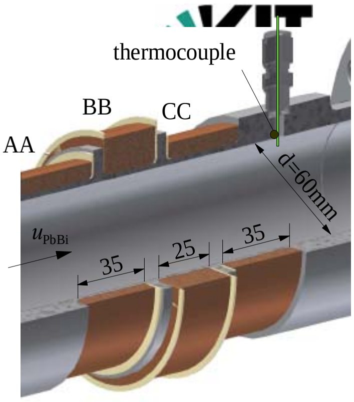
  - Non-intrusive – Ultra-sound doppler velocimetry (UDV), multi units ➡ mapping
- **Surfaces /2-phase**
  - direct – resistance probes
  - Indirect – X-ray, UTT
    – optic means for surfaces

Measurement: Flow rate

Electro-magnetic frequency flow meter (EMFM)







Measurement principle

- Dragging of magnetic fields lines by the flow (**RMS-Value ~Q**)

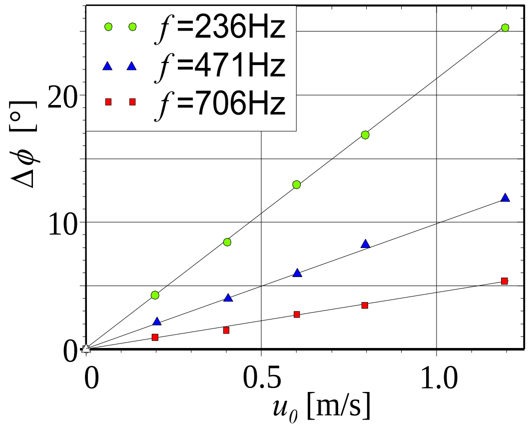
$$Re = \frac{u_0 \cdot d}{\left(\frac{1}{\mu\sigma}\right)}$$

- flow direction given by sign of signal
- time delay between Emitter-Sensor (or Phase Angle) $\Delta t \sim Q$

➡ **2 independent gross-output quantities for Q**

Th. Schulenberg, R. Stieglitz, NED 2010.

Measurement: Flow rate-EMFM



Conds. : PbBi tube flow, T_0=200°C, Pr=0.02, d=60mm, I_0=410mA

Design wishes

- High penetration depth δ of field B into duct (➡ low f f = frequency AC current supply)
- High magnetic field strength (high $\Delta\Phi_{RMS}$)
- Large amount of windings (~n n=wire turns)

Counter arguments

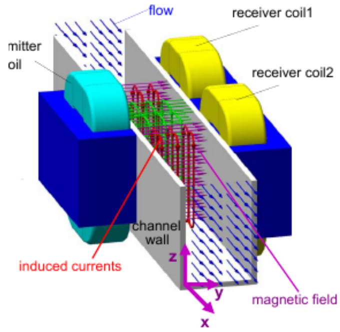
- Low f yield high sensitivity to ambient stray signals
- High B modifies the flow Hartmann number Ha<<1 (Ha=(EM-forces/viscous forces))

$$Ha = d \cdot B \sqrt{\frac{\sigma}{\rho \nu}}$$

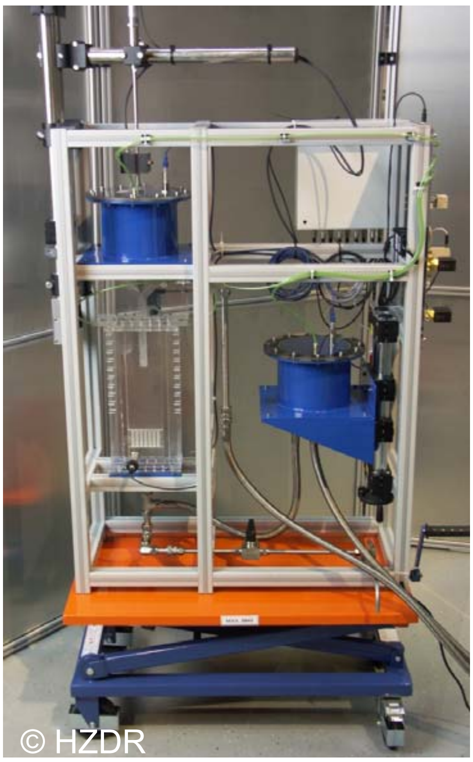
- Too large f yield skin-effect $f\, d^2\, \mu\, \sigma << 1$

Other designs

- clamp on systems



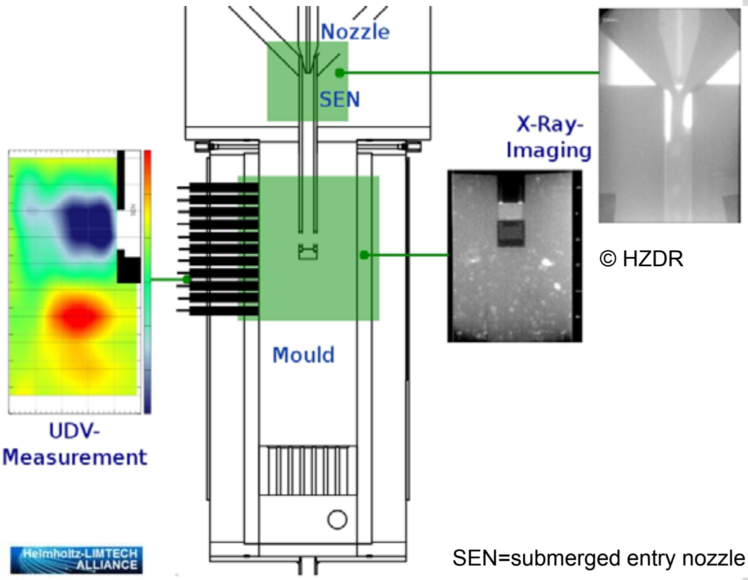
Measurement: flow visualization- 2 phase-flow



Main feature:

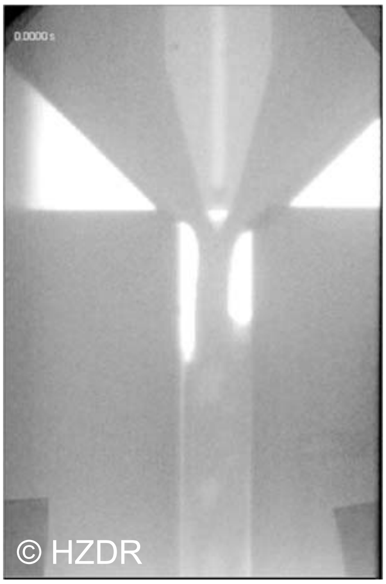
- X-ray visualization of two-phase flows
- Restriction of the mold size in beam direction

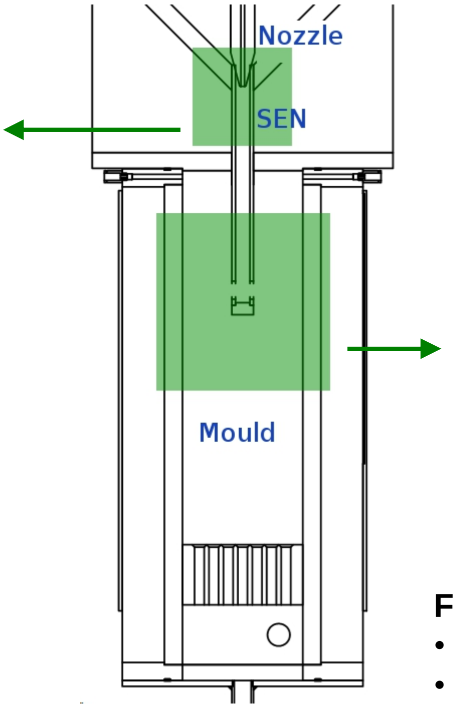
Example : LIMMCAST @ HZDR

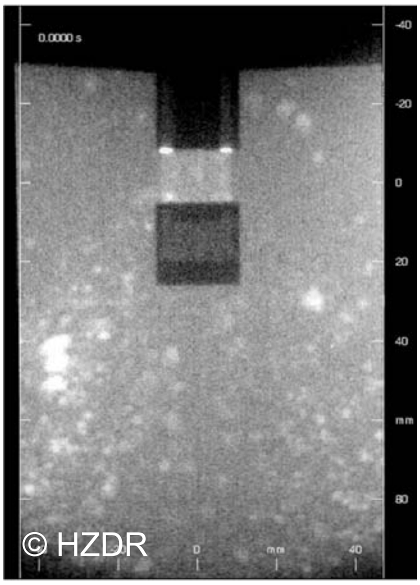


SEN=submerged entry nozzle

Measurement: flow visualization- 2 phase-flow







Complex flow regimes

Flow rates:

- Ar: 1,7 cm^3/s
- Liquid metal: 120-130 ml/s

Measurement :Flow velocity

Ultra-Sound Doppler Velocimeter (UDV)

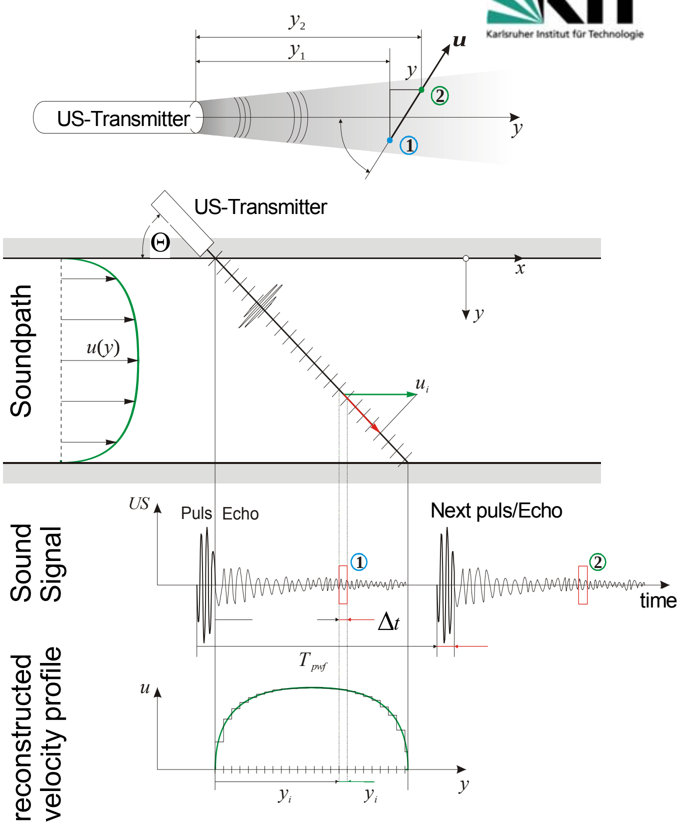
Principle (particle tracking)

- Distance change from sensor due to motion from 1→2 between two pulses.
- Determination of the time difference from the phase shift between received echoes

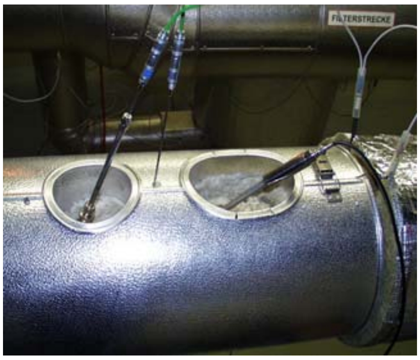
➡ Velocity at a discrete distance

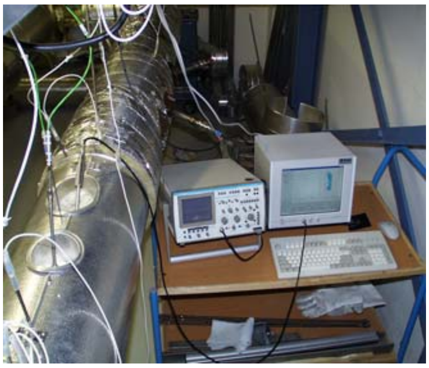
Profile

- Separation of sound path in time intervals (gates Δt) allows recording of a velocity profile. Therefore,
  - Coupling of a time t_i with a measurement position
  - Determination of the local velocity u_i in the interval i

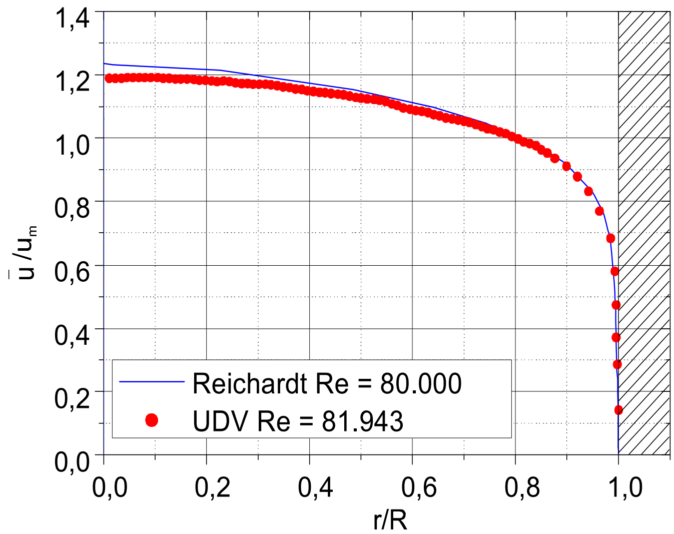


Measurement :Flow velocity





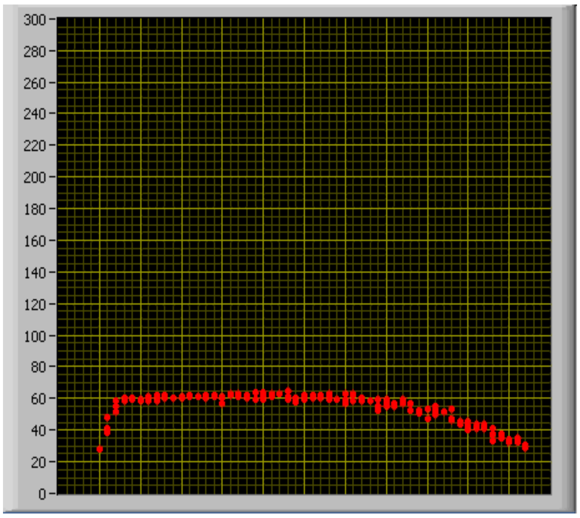
Ultra-Sound Doppler Velocimeter (UDV)-Validation



- Good agreement between measurement and literature profile
- Detailed resolution of the velocity profile
- Deviation literature profile for r/R>0.6 less than 0.5%

(Schulenberg&Stieglitz, NED, 2010)

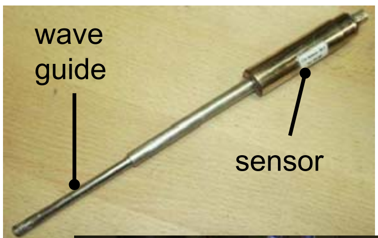
Measurement: Flow velocity



Transient start-up behaviour of EM pump in THESYS Loop

Ultra-Sound Doppler Velocimeter (UDV)

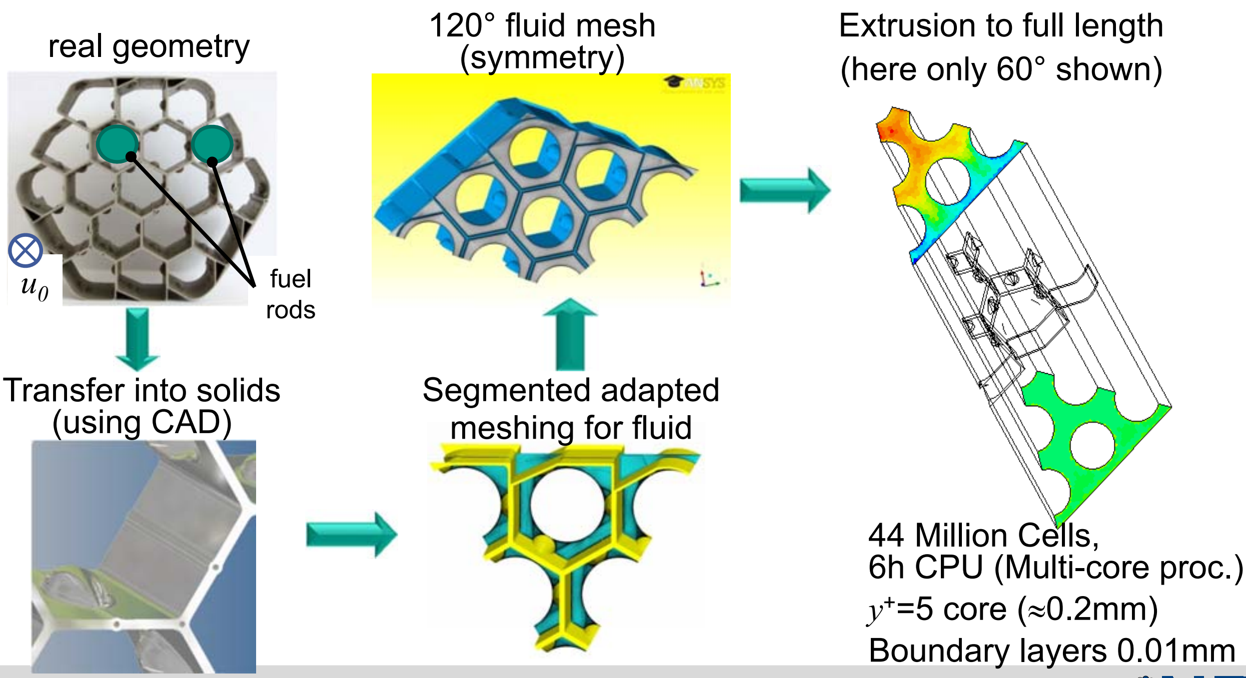
- Fluid temperature: 400°C
- Temperatur compensation durch (Wave Guide)
- Inclination angle: 45°
- Tube diameter: 60 mm



Thermalhydraulic transport in liquid metals

Momentum transfer: numerical approach

- At a first glance simple: put numerous cells (fluid, solids) in SA geometry
- But: with tremendous effort (correction terms) successful for low Re by CFD means
- **Example : Fluid assembly Flow (heated rods)**



Momentum transfer: numerical approach

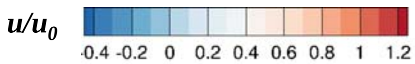
- **Momentum transport models based on averaging (e.g. $u = \bar{u} + u'$)**

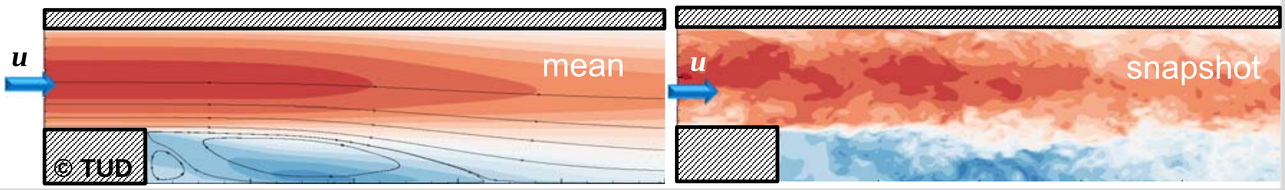
standard

in development

Order	isotropic turbulent transport	anisotropic turbulent transport	No. of transport equations
1st	Gradient models, eddy diffusivity models		
	l mixing length models	l_i mixing length models	0
	k-l, k-ε, k-ω, SST, etc.		1,2, ...
	non-linear k-ε, V2-f and branches		2
		ASM models with k-ε	2
2nd	transport equations for all second order closure moments		
		equations for complete shear stress tensor	6+2

- **Large Eddy Simulation (LES + adequate subgrid scale modelling)**
- **Direct Numerical Simulation (DNS)**
  Example: Backward facing step Re=4.800





Turbulent momentum transfer: numerical approach

- **Quality of CFD computations not defined by number of cells**

Reynolds averaged modelling of momentum transport

- Reynolds-Averaged Navier-Stokes (RANS) equations ➡ closure problem in convective term

$$\frac{\partial}{\partial x_i}\left(\overline{u_i}\cdot\overline{u_j} + \overline{u_i^{'}\cdot u_j^{'}}\right)$$

- Standard model assumption: gradient hypothesis

$$\overline{u_i^{'}\cdot u_j^{'}} = -\varepsilon_M^{ij}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

- Simplification = isotropic exchange coefficient

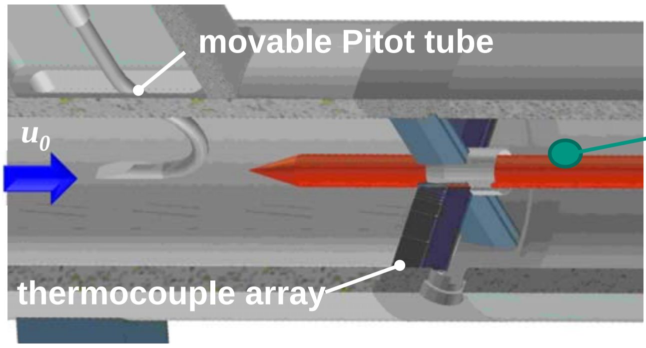
$$\overline{u_i^{'}\cdot u_j^{'}} = -\varepsilon_M\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

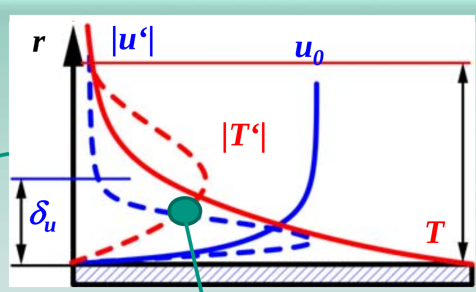
General

- Turbulent flow modelling demands qualified user (rather than computing power)
- **No substantial difference of liquid metals to ordinary liquids in bounded flows**

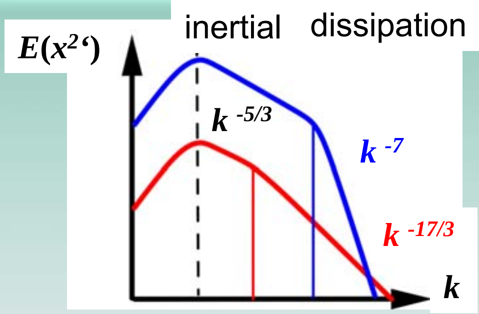
Energy transfer: some considerations

- Observation: -high heat conductivity λ





- scale separation boundary layers $\delta_T > \delta_u$
- spatial statistics $r(T_{max}') \neq r(u_{max}')$



- different transport characteristics

Consequences

- turbulent heat transport necessitates dedicated turbulence modelling for
  - heat transport and
  - dissipation
- constant turbulent Prandtl number concept (Reynolds analogy) not correct (standard CFD-models)
- if more cells do not improve the results (super-slating of a soup!!!)

Energy transfer: numerical approach

Turbulent energy equation

$$\rho c_p \left(\bar{u} \frac{\partial \bar{T}}{\partial x} + \bar{v} \frac{\partial \bar{T}}{\partial y} \right) = -\frac{\partial}{\partial y} \left(-\lambda \frac{\partial \bar{T}}{\partial y} + \rho c_p \overline{v'T'} \right) ,$$

- Analogous to turbulent viscosity $\varepsilon_M = \mu_t / \rho$ a turbulent heat flux appears and thus
- a turbulent eddy heat diffusivity $\varepsilon_H = \lambda_t / (\rho\, c_p)$ can be defined,
- the turbulent Prandt number Pr_t

$$Pr_t = \frac{\varepsilon_M}{\varepsilon_H} = f\left(Re, Pr, y/R \right) = \frac{\overline{u'v'}}{\overline{v'T'}} \frac{\frac{\partial T}{\partial y}}{\frac{\partial u}{\partial y}}$$

Consequences

- Pr_t is far of being a constant (in reality a tensor)
- Difficult to measure directly, since it is a measure of
  - dimensions and
  - available sensor sizes as well as the
  - temporal resolution)
- Involves several modelling problems
- Hydraulic diameter concept is not valid (except for forced convection)

Energy transfer: numerical approach

How to solve the closure problem of the turbulent heat flux?

- **Standard approximation: Gradient hypothesis**

$$\overline{u_i' T'} = -\varepsilon_H^i \frac{\partial T}{\partial x_i} \quad \rightarrow \quad \overline{u_i' T'} = -\varepsilon_H \frac{\partial T}{\partial x_i}$$

enforced isotropic exchange coefficient ε_H

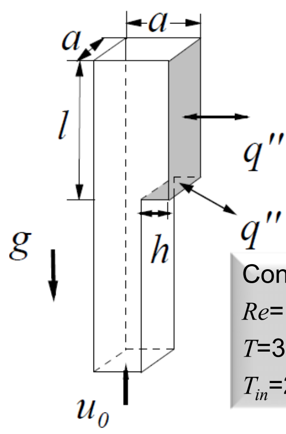
- **Reynolds – Analogy (Standard in all CFD-Codes)**

$$\overline{u_i' T'} = -\varepsilon_H^i \frac{\partial T}{\partial x_i} \approx -\frac{\varepsilon_M}{Pr_t} \frac{\partial T}{\partial x_i} \quad \text{with} \quad Pr_t = \frac{\varepsilon_M}{\varepsilon_H}$$

tensor | constant

- **Consequences & typical problems (CFD Simulation with standard Pr_t =0.9)**
  - **u and T- Statistics completely different, Pr_t is function of Pr_t =(y, Re, Pr, Gr)**
  - **no anisotropic diffusivity**
  - **Missing transport characteristics (diffusor, recirculation flows, free jets)**
  - ➡ Zero-dimensional approach is problematic only valid for forced convection (otherwise extremely qualified user required)
  - ➡ **Use of more cells and computing will not help; only advanced modelling**

Energy transfer: numerical approach



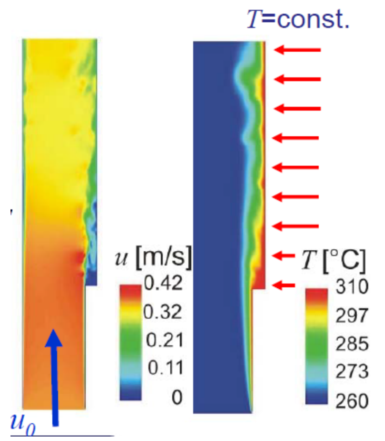
Direct numerical Simulation (DNS)
- only chance to obtain transport coefficients but
- limitation of Reynolds number (flow velocity)
- **Formulation of benchmark problems**

Backward facing step
- Stratification problem (buoyancy) at large axial ΔT
- Flow separation at geometry discontinuities

Cond's:
Re=10^4,
T=310°C=const
T_{in}=260°C

Approach
- Choice of small Pr-Fluid (Pr_{Sodium}=0.007)
- LES u-Field is DNS of T-Field

Goal
- Validity limits of CFD codes.
- Development of advanced turbulent heat flux models.
- Reliability threshold of design correlations.

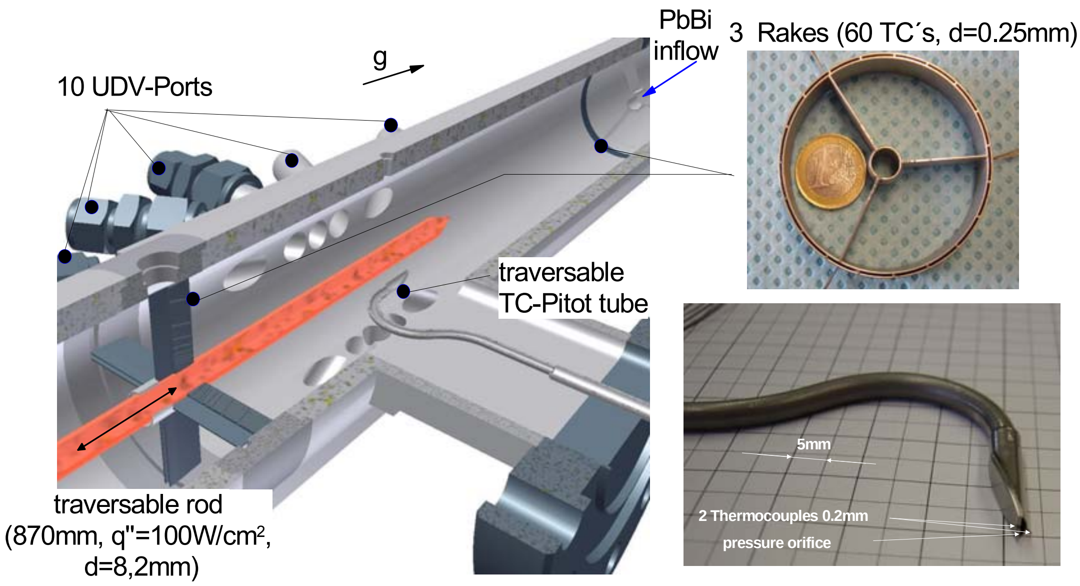


Energy transfer: Validation

Background : Pin single element of fuel assembly

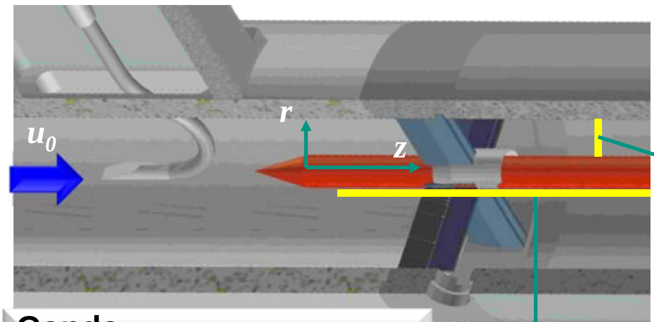
Scope : Turb. heat transfer in forced, mixed and buoyant convective flows ($Re \rightarrow 6 \cdot 10^5$)

Measure:
- Development of models for turbulent heat flux;
- Determination of Nu-correlations;
- Evaluation of transitional regimes (model validity).

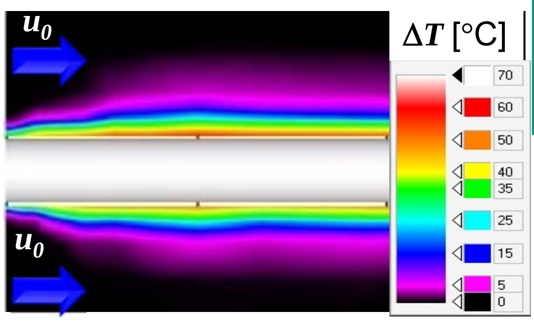


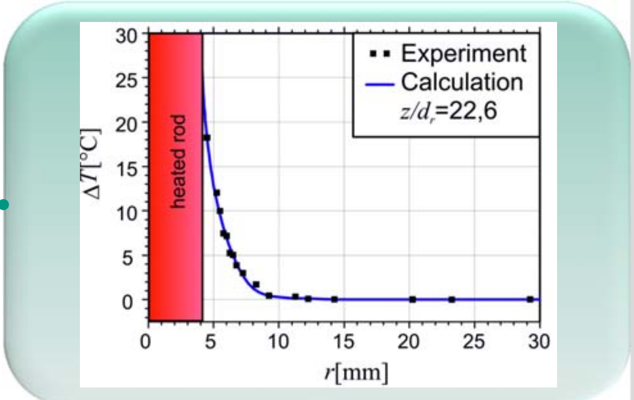
Energy transfer: "real world"

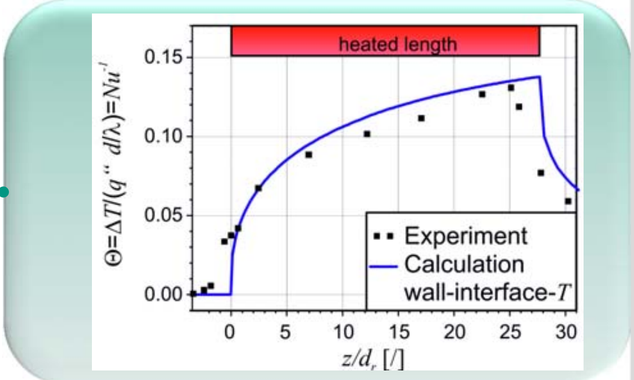
- Observation: -high heat conductivity λ



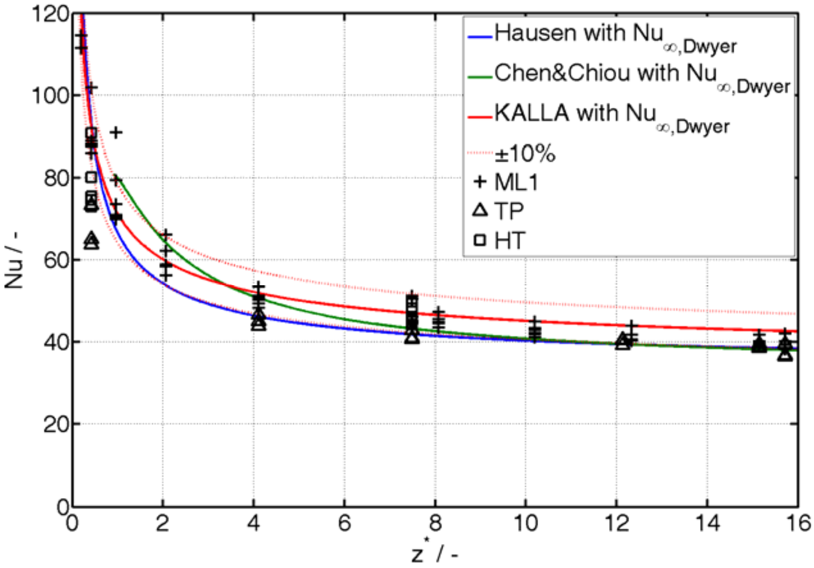
Conds:
Re = 3.1·10⁵, q''=40W/cm², PbBi @ T_{in}=300°C







Energy Transfer: Heated Rod- developing flow



$$\frac{Nu_{z,Hausen}}{Nu_{\infty}} = 1 + \left(\frac{d_h}{z}\right)^{\frac{2}{3}}$$

$$\frac{Nu_{z,Chen\&Chiou}}{Nu_{\infty}} = 1 + 2.4\frac{d_h}{z} - \left(\frac{d_h}{z}\right)^{2}$$

$$\frac{Nu_{z,KALLA}}{Nu_{\infty}} = 1 + 1.14\left(\frac{d_h}{z}\right)^{\frac{1}{2}}$$

Nu_{∞} according to Dwyer:

$$Nu_{\infty} = \left(4.63 + \frac{0.686}{b}\right) + \left(0.02154 - \frac{0.000043}{b}\right)\cdot\left(\overline{\Psi}\cdot Pe\right)^{n}$$

$$\overline{\Psi} = \left(1 - \frac{1.82}{Pr\left(0.0185 Re\sqrt{f_{wm}}\right)^{1.4}}\right) = \left(Pr_t\right)^{-1}$$

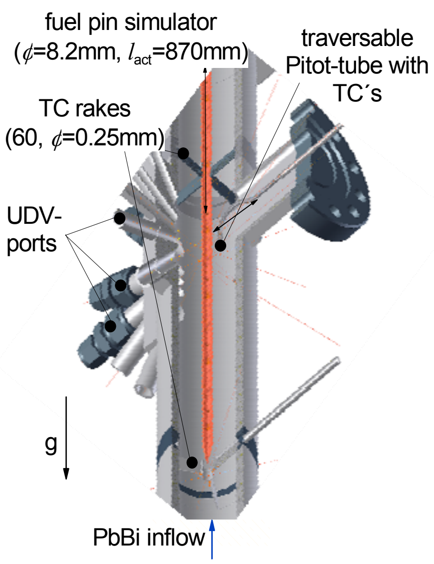
$$n = 0.752 + \frac{0.01657}{b} - \frac{0.000883}{b^2};\quad b = \frac{d_r}{D}$$

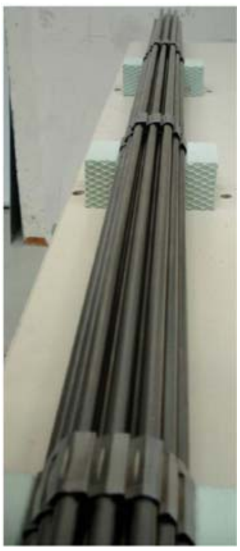
Experimental investigation of the turbulent heavy liquid metal heat transfer in the thermal entry region of a vertical annulus with constant heat flux in the inner surface
L. Marocco, A. Loges, Th. Wetzel , R. Stieglitz, International Journal of Heat and Mass Transfer

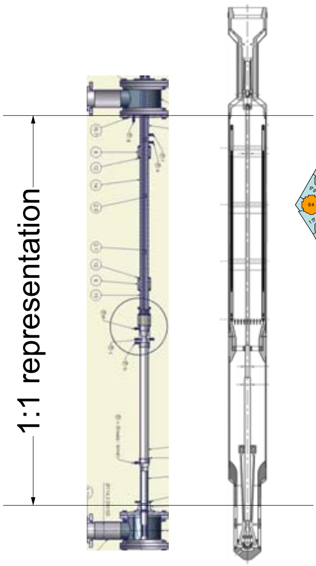
Energy transfer: “real world” -reactor qualification

- **Strategy**

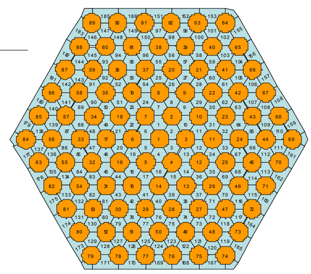
Single pin → **Bundle** → **Assembly simulator**



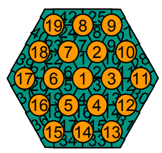




Reactor SA

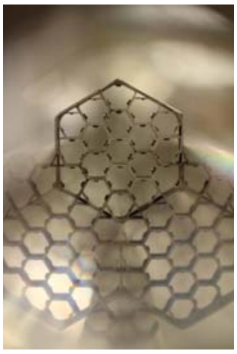
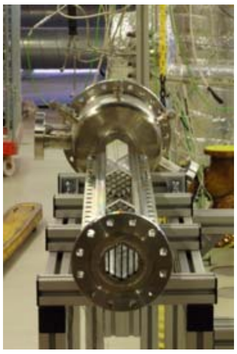
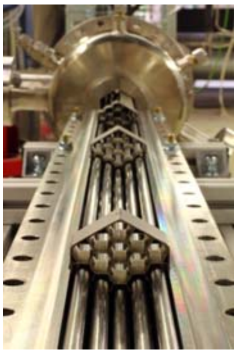
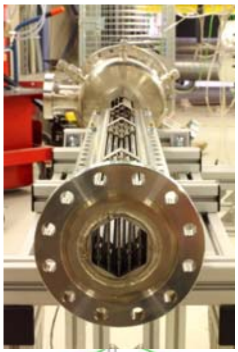


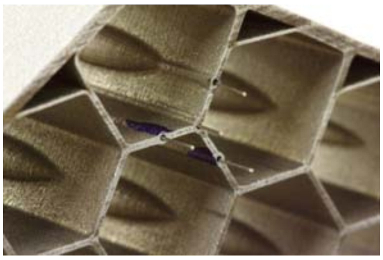
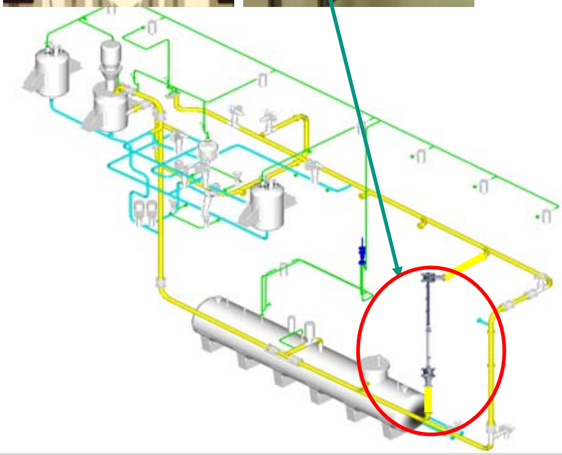
simulator SA



- Complementary CFD simulation → system analysis codes

Turbulent Heat Transfer : assembly simulator

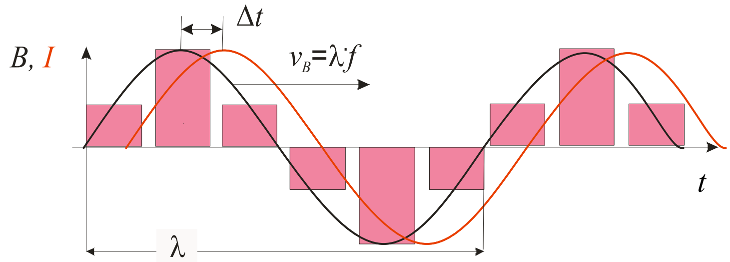



Engineering in liquid metals

Engineering: LM-Pumps

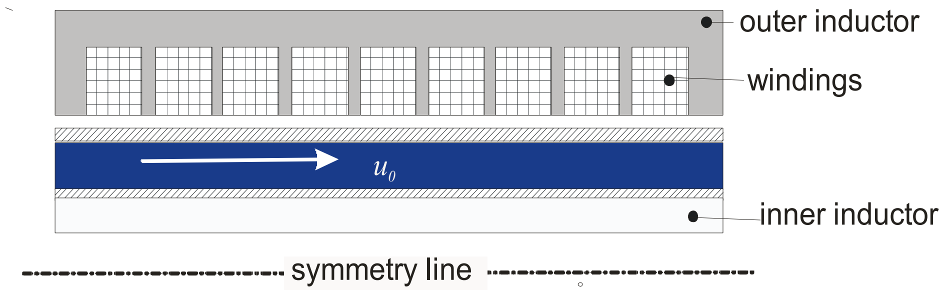
Liquid metal operated loops utilize often MHD-pumps, why ?

- Low maintenance costs (absence of sealings, bearings, moving parts),
- Low degratation rate of structure material,
- Simple replacement of inductor,
- Fine regulation of flow rate and pump characteristics (p'/p, V'/V<<1).
- Computations: Electrodynamics + MHD (Stieglitz, FZKA-6826)



slip definition s:

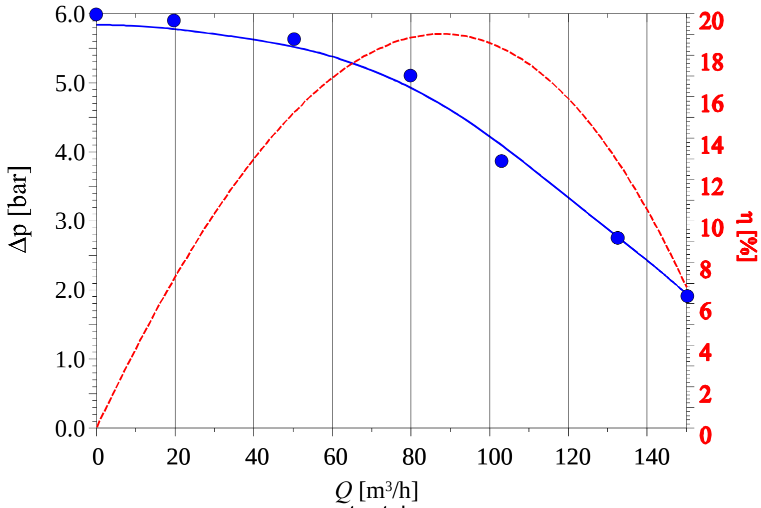
$$s = \frac{(v_B - u_0)}{v_B}$$

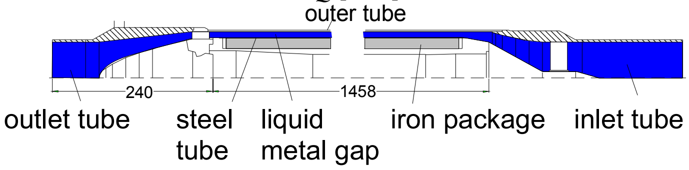


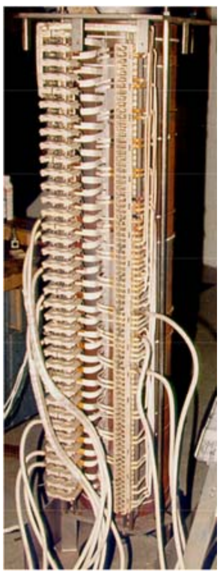
Engineering: LM-Pumps

Sodium operated Annular Linear Induction Pump (ALIP)

- Q at Δp 150m³/h …0.2MPa
- 115°<T<500°C

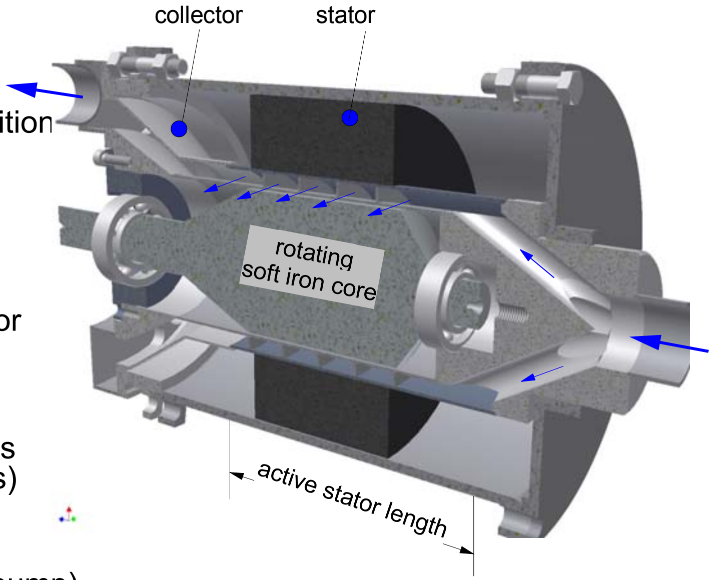






Engineering -Pumps

Development of new pump types at KIT
(ACHIP -Alternating Current Helical Induction Pump)



Motivation

- High price of EM-pumps, no competition
- Inspection, sealings
- complex set-up and loop integration

Ansatz

- Use of stator of asynchroneous motor (e.g. old pump, crane motor,….)
- design of liquid metal duct in stator
- Compensation of eddy current losses by rotating soft iron core (in bearings)

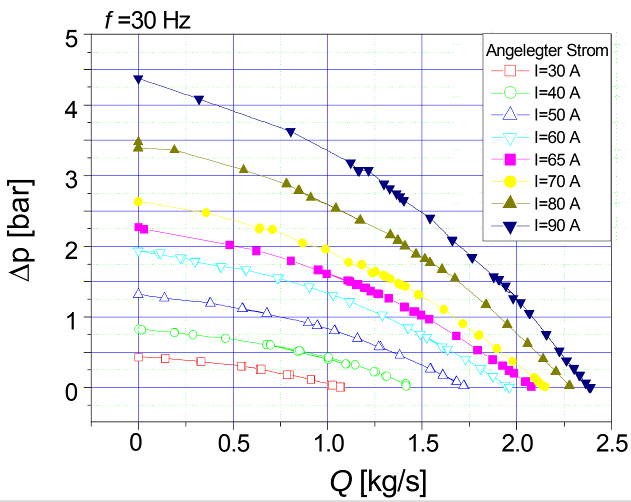
Advantages

- Low construction price (1/10 to EM pump)
- No sealings, conventional parts, pumpin in both directions possible
- High reliability low pressureoscillations ($\Delta V/V$, $\Delta p/p$<<10%)

Engineering -Pumps

Functional and performance tests of ACHIP

- Successful operation
- First shot : acceptable efficiency η_{max}=14% no optimization
- Next optimization
  - instead soft iron permanent magnets,
  - Use of 4 pole instead of 2 pole stator
- Resonable agreement between model and FOAK demonstrator



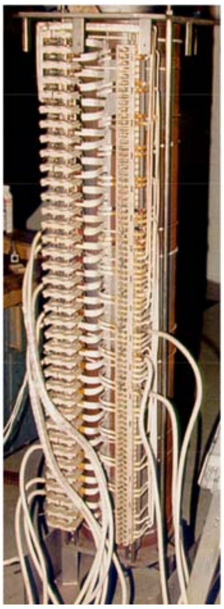
NaK pump in MEKKA @KIT

Liquid metal components

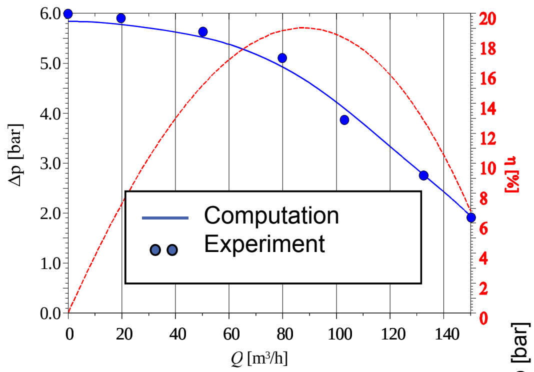
- Design, Computation and Construction of MHD pumps

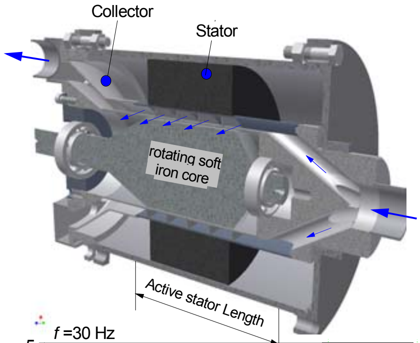
Annular Linear Induction Pump (ALIP)

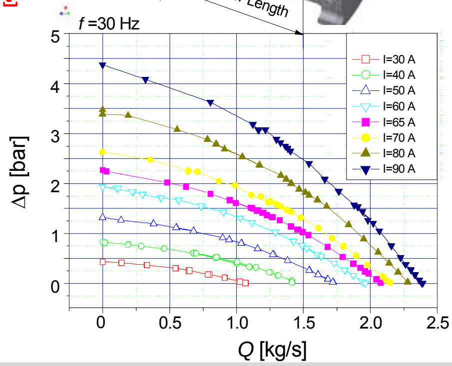
ACHIP –(Alternating Current Helical Induction Pump)



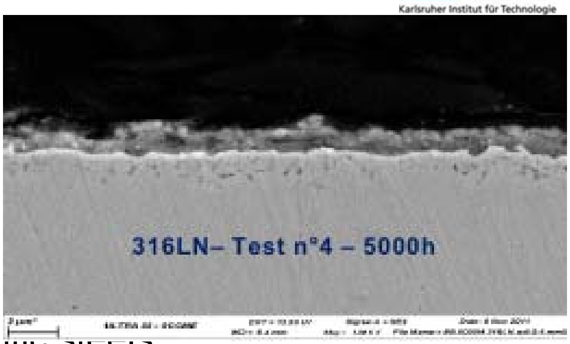
Sodium -ALIP







Engineering – Materials -SFR

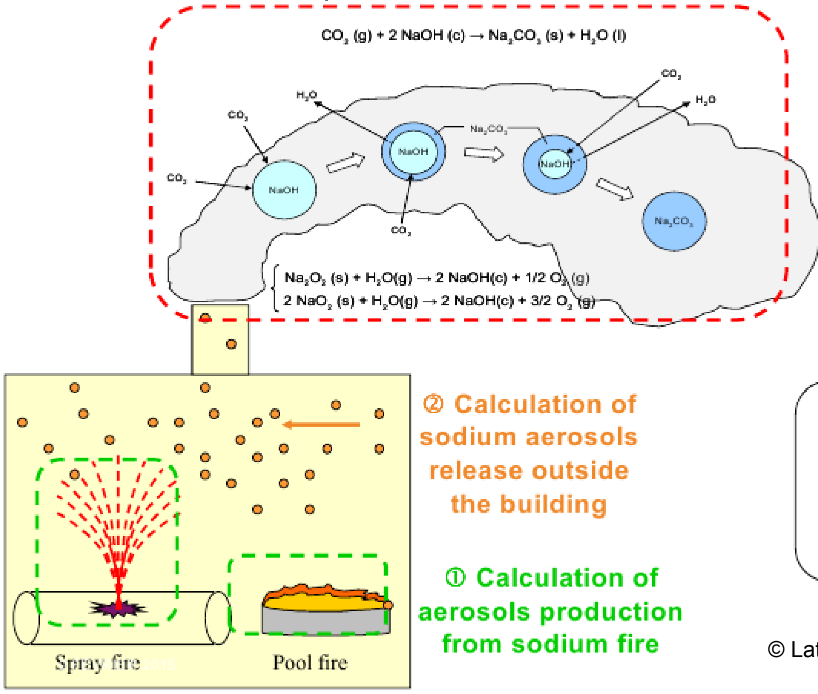


- Sodium can cause corrosion depending mainly on oxygen content
  - Kinetics for stainless steels available up to 5000 h at 550°C for [O]<10 µg/g
- Ferritic steels more sensitive to oxidation and carburizationthan austenitic steels
- 9Cr steels exhibit a similar behavior
- ➡ Vast database and operational experience available
- ➡ Joining techniques qualified
- ➡ No dissolution attack

More details: Courouau et al., 2013,Corrosion by oxidation and carburization in liquid sodium at 550°C of austenitic steels for sodium fast reactors, Paris FR13

Engineering – Materials SFR

- Sodium-Fire ➡ coupled for CDA scenarios with source term



③ Calculation of atmospheric dispersion and chemical conversion: carbonation of NaOH aerosols

② Calculation of sodium aerosols release outside the building

① Calculation of aerosols production from sodium fire

Comparison of aerosol products concentrations with toxicity exposure limits (Contain-LMR)

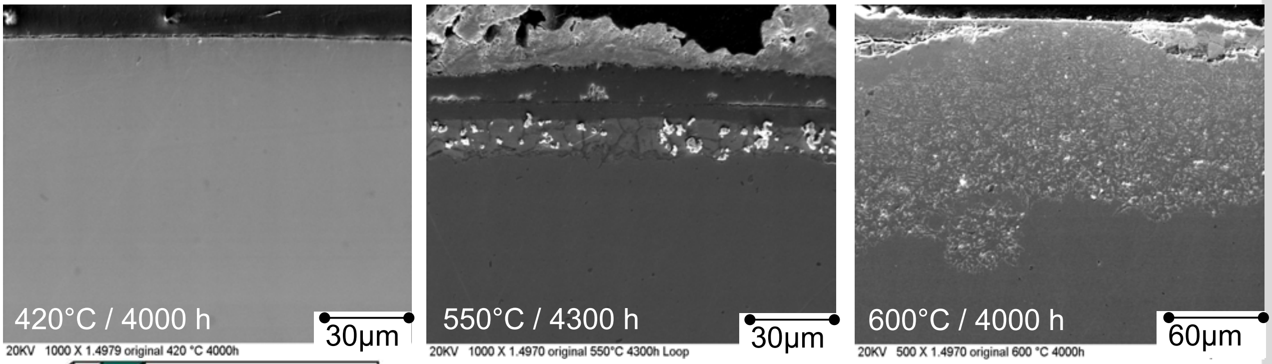
© Latge, 2015, ESNII, Workshop

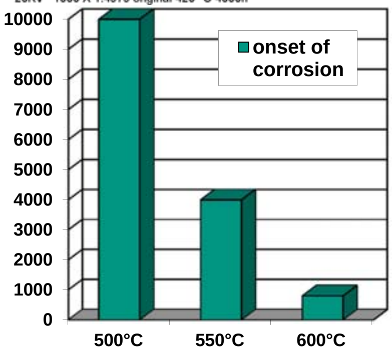
- Old experiments available (FAUNA, CABRI,..) basis for code development

Gordeev, Hering, Schikorr, Stieglitz ,2012, **Validation of CONTAIN-LMR code for accident analysis of sodium-cooled fast reactor containments**, ***ICAPP 2012*** **Chicago, pp. 2088-2095. Paper ID 12155 or ICAPP 2013**

Engineering -Materials

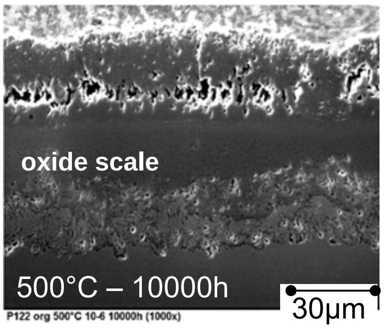
Material selection: depends strongly on liquid
Example : Heavy liquid metal (here $Pb^{45}Bi^{55}$)

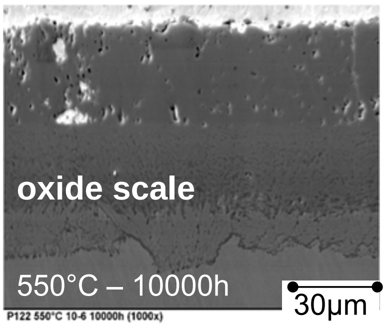


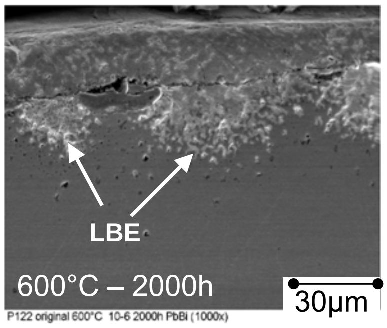


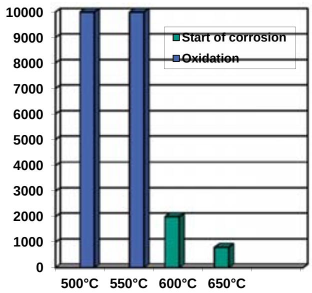
Material
Austenitic steel (316L-type)
Influence of temperature on material compatibility
at optimal oxygen concentration 10^{-6} wt%
Result
Austenitic steels operable without protection for temperatures below 500 °C

Engineering -Materials









Material:
F/M steel (HCM12a -type)
Influence of temperature on material compatibility
at optimal oxygen concentration 10^{-6} wt%
Result
Martensitic steels operable below ≤ 550 °C.
huge oxidation rate: up to 50 -100µm/10.000 h
and frequent spallation of oxide scale.
➡ contamination of liquid metal
➡ reduced heat removal capability $(\lambda_{M_3O_4} = 1W/mK)$

SAFETY AND SYSTEM DYNAMICS - LFR (ORIENTED)

- ADS involves additional considerations
- SFR scenarios consist of tenth of aspects- most of them couteracting requiring an own lecture.*

* More nformation
D. Verwaerde, R. Stieglitz, Final-Report-EU-Project, CP-ESFR-WP3-Safey, 2013 or
Kruessmann, Ponomarev,Pfrang, Struwe, Champigny, Carluec, Schmitt, Verwaerde, 2015, Assessment of SFR reactor safety issues: Part II: Analysis results ofULOF transients imposed on a variety of different innovative coredesigns with SAS-SFR, NED, 2015, 285, p.263-283

GEN-IV–Guidelines

Generation IV Roadmap goals

- **safety and reliability**,
- economics,
- sustainability, and
- proliferation resistance and physical protection.

➡ TRANSLATION of GEN-IV Criteria

- Excellent behaviour in operational safety and reliability;
- Low likelihood and degree of core damage;
- Elimination of need for off-site emergency responses in case of severe accident.

➡ Technical solution

- seek simplified designs,

➡ Two design axis

- reduce/eliminate the potential for entering into severe plant conditions- **prevention** of core damage accidents (CDA),
- minimize the respective consequences (radiological releases)- **mitigation**.

Safety approach FR

- core design with improved natural behavior during sequences without active protection

Types of events to be considered

- Reactivity insertion
  - **Liquid metal draining (generalized boiling, gas ingress ...)**
  - Inadvertent control rod withdrawal
  - Core compaction (earthquake ...)
- Loss of core cooling
  - Loss of primary/secondary flow (pump failures, loss of electricity sources ...)
  - Flow blockage in some assemblies

LFR Safety approach- Incidents/Accidents

- Grouping of relevant Incidents and Accidents

Incident/Accident	Description
Reactivity & power distribution anomalies	▪ Inadvertent control rod assembly withdrawal ▪ Control rod assembly ejection/drop ▪ Changes in core geometry (earthquake) ▪ Failures/malfunctions of DHR System ▪ Fuel assembly loaded in an incorrect position/ composition ▪ SG tube rupture ▪ Fuel rod failure
increase of heat removal from primary system,	▪ Inadvertent actuation of DHR systems ▪ Reduction in feedwater temperature ▪ Increase in feedwater flow ▪ Excessive increase in sec. steam flow ▪ Inadvertent opening of SG safety valve
decrease of heat removal by secondary system,	▪ SG feedwater system line break, ▪ Loss of normal feed ▪ Turbine trip ▪ Inadvertent closure of main steam isolation valves ▪ Loss of load ▪ Loss of AC power ▪ FW pump failure or malfunction ▪ SG Flow blockage ▪ FW line break

LFR Safety approach-Incidents/Accidents

- **Grouping of relevant Incidents and Accidents**

Incident/Accident	Description
decrease in primary coolant system flow rate,	▪ Fuel Assembly Partial Blockage ▪ Fuel Assembly Mechanical Lock Failure ▪ Mechanical/ electrical failure of primary pump (Partial loss of flow-PLOF) ▪ Loss of electrical supplies to primary pumps (Complete loss of Flow-LOF) ▪ Pump Shaft Break/Seizure
decrease in primary coolant inventory	▪ Loss of coolant accident (LOCA) resulting from Main vessel leakage or break
challenges to reactor building.	▪ Steam line break ▪ Cover Gas line break ▪ Leakage from Vessel Top Closure ▪ Fuel Handling Accident

➡ ***Regrouping of Events into DBC 2 , DBC 3, …….***

LFR- Design background

- LFR = class of LMFBRs (Liquid Metal-cooled Fast Reactors) ➡ similar intrinsic characteristics as SFRs
  - fast neutron spectrum,
  - positive void coefficients for larger core designs
- LFR rely on a different base-technology (lead vs. sodium) ➡ different response to transient initiators due to:
  - boiling point of Pb-coolant : > 1700 °C for LFR
  - boiling point of Na-coolant : ~ 900 °C for SFR
- Coolant boiling ➡ positive reactivity insertion in large LMFBRs (advantage to SFRs).
- In LFRs positive reactivity insertions starts ~ 1300 °C (due to melting and subsequent removal of cladding material from the core region.
- No credible transient initiator so far identified leading to core temperatures >1100 °C (aside of total SA flow blockage) ➡ LFR are thus not expected to experience any serious <u>energetic</u> core degradation events.
- No large-scale exothermic chemical interactions between Pb (or LBE) and water
- No currently known large-scale hydrogen production sources using Pb (or LBE) as coolant
- LFR Core meltdown has already been experienced in Russia. Reason: gradual flow degradation / blockage due to coolant loop slugging (Pb-oxide accumulation and deposition in flow channels).

LFR- Challenges

Operational issues:

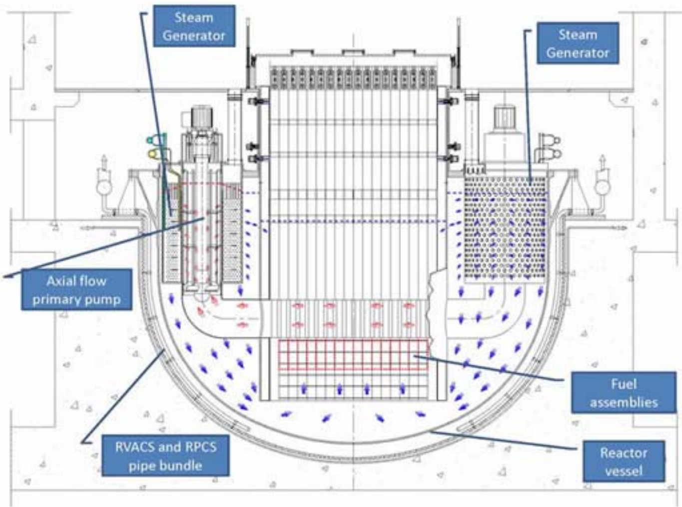
- Melting point of Pb at ~ 327 °C requires that LFR is maintained at all times during its operational life at temperatures in excess of at leat 330 °C.
  - **<u>Overcooling</u>** transient (secondary side) can lead to freezing at the outlet of the heat exchanger (SG) on the primary side leading to a partial loss of flow
- Lead technology:
  - **<u>Corrosion/erosion</u>** of structural materials (➡coolant quality control, coating of primary loop structural materials – cladding, HX tubes)
  - **<u>Slugging</u>** of primary coolant loop (lead-oxide accumulation)

Challenges :

- Overcooling: (By <u>diversity</u> and <u>redundancy</u> assure that SG secondary inlet temperatures does not fall below 330 °C (➡ assured high pressure on secondary side - water >> note: currently remaining weak link in LFR fullfilling „totally passive“ design criteria)
- seismic risk due to large mass of lead;
- in-service inspection of core support structures/replacing of internal components
- refueling at high temperature in lead; spent fuel management by remote handling;
- managing of the SG tube rupture inside the primary system;
- prevention of flow blockage and mitigation of core consequences;
- development of techniques and instrumentations for coating (i.e. aluminization...) of steam generators and reactor vessel

LFR- Safety study (ELSY Project)

ELSY DESIGN



- Verify for all design basis accident conditions ability of the protection system to bring and maintain the reactor in safe conditions:
  - The coolant, core materials and vessel structure safety limits are not exceeded
  - Decay heat removal in the short and long term

SAFETY LIMITS (Therm. power = 1500 MW, T-lead = 400 – 480 °C)

- Lead properties: boiling point = 1740 °C, freezing point = 327.5 °C
- Clad temperature <550 °C (DBC1) up 700 - 800 °C (DBC4 – no systematic clad failure)
- Large margin to fuel melting (DBC2) – Only local fuel melting (DBC4)
- Vessel wall temperature < 450 °C – 550 °C (DBC1 – DBC4)

LFR -DBC Transient Analysis in ELSY

List of representative DBC transients in (ELSY) safety analysis:

- All primary pump trip (PLOF) → Natural circulation in the primary system
- Transient overpower (PTOP) → Control rod withdrawal
- Transient overpower (PTOP at CZP) (T = 380 °C)
- All SG feedwater trip (PLOH) → Decay heat removal by DHR-2 system (ICs on secondary side)
- All SG feedwater trip + primary pump trip (PLOF+PLOH) (Station blackout)
- PLOF+PLOH without DHR
- Vessel leakage (lead level –1 m) → partial uncovery of steam generators
- Overcooling of primary side → Loss of feedwater pre-heating → Risk for lead freezing
- Large break in secondary circuits → Depress. of SS → Activation of DHR-1 on primary side
- Steam generator tube rupture

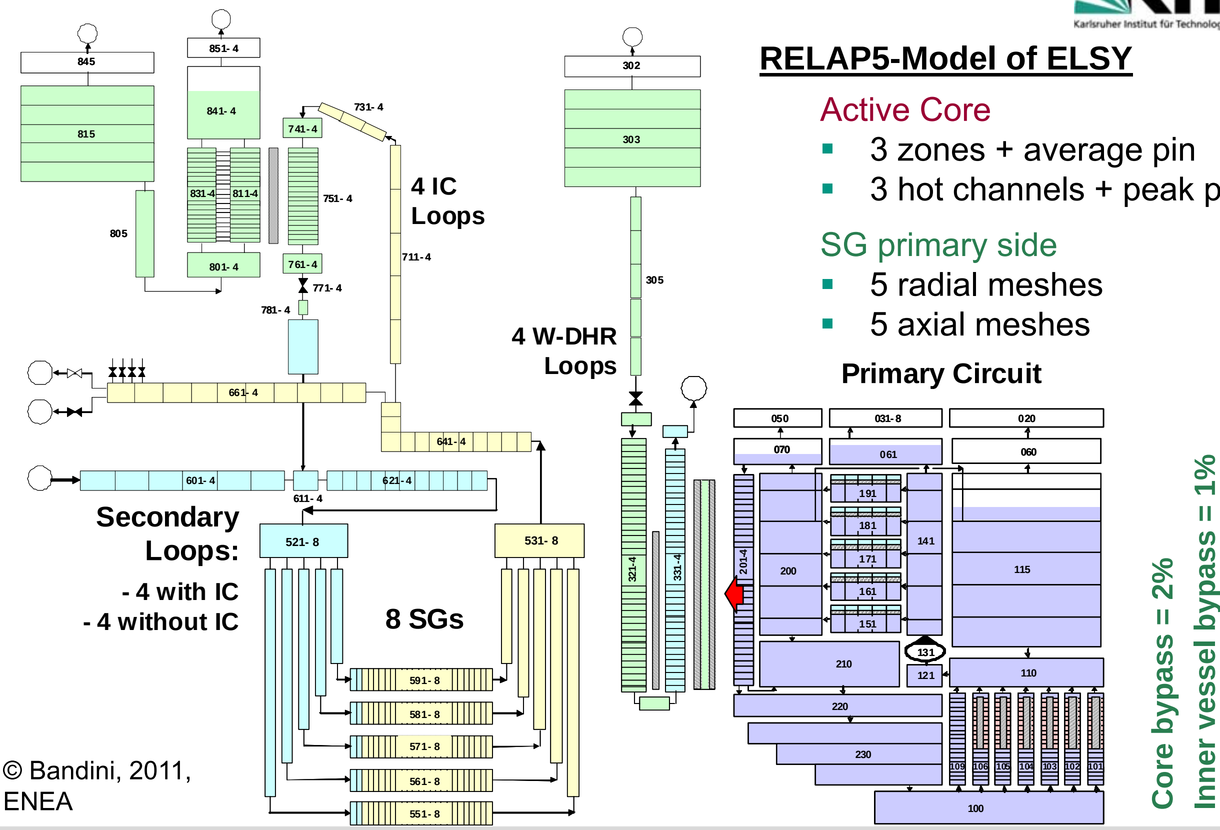
Decay heat removal system

- Two independent and redundant (3 out of 4) systems are available:
  - DHR-1: 4 W-DHR loops working in natural circulation on primary side
  - DHR-2: 4 IC loops working in natural circulation on secondary side

Reactivity feedbacks

- Doppler (negative)
- Radial core exp. (Diagrid, negative)
- Axial fuel exp. (negative)
- Coolant exp. (positive in the active core, negative outside the active core)
- Axial clad exp. (positive)
- Control rod drive exp. (positive)

LFR – Reactor Transients Modeling



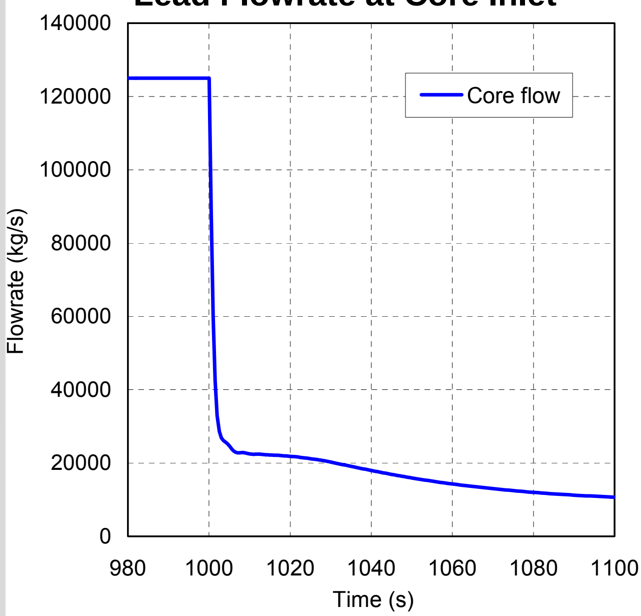
RELAP5-Model of ELSY

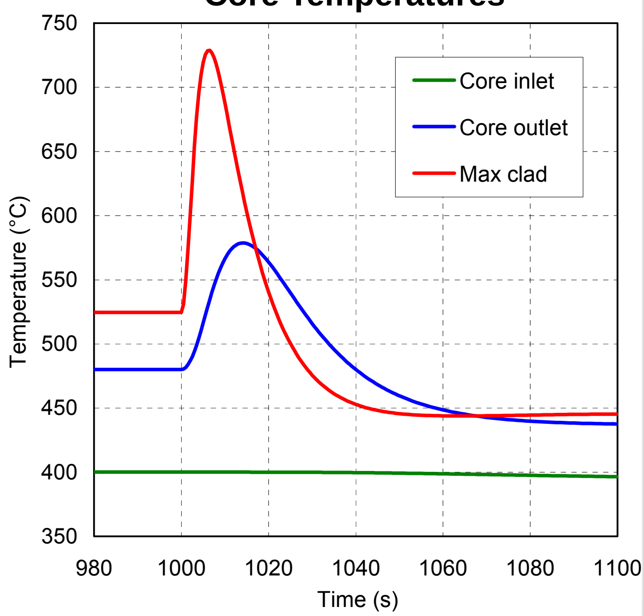
Active Core
- 3 zones + average pin
- 3 hot channels + peak pin

SG primary side
- 5 radial meshes
- 5 axial meshes

© Bandini, 2011, ENEA

LFR PLOF: All Primary Pump Trip

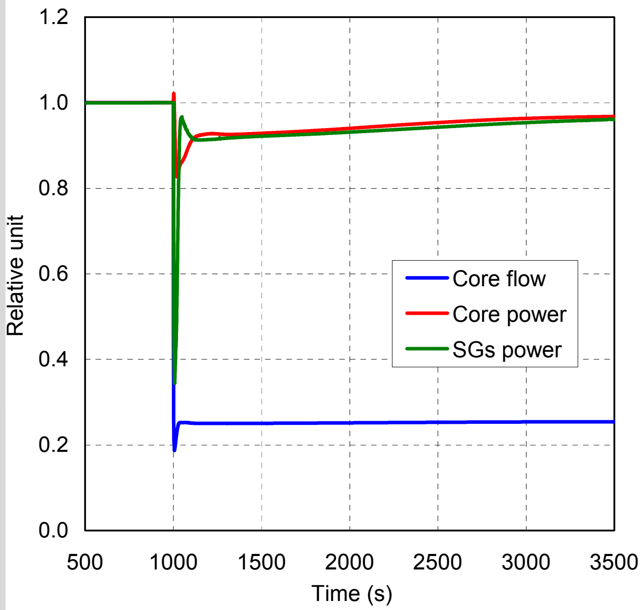




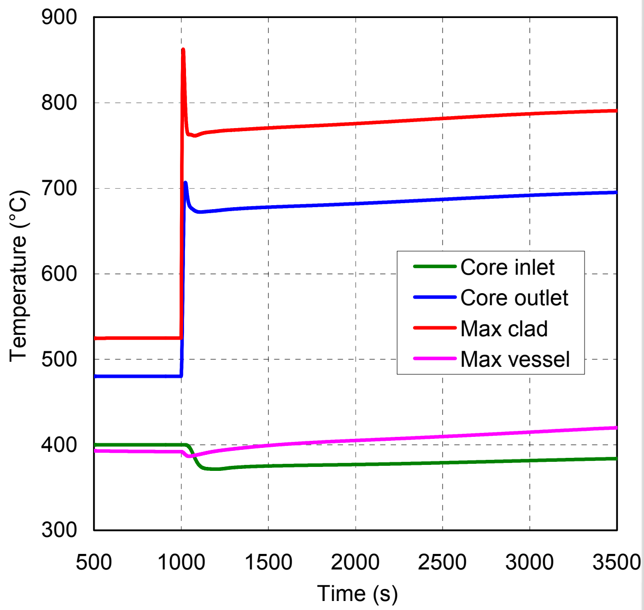
- Primary flowrate reduces to about 20% of nominal value in few seconds after primary pump trip at t=1000 s (low pump inertia)
- Reactor scram at t=1003 s on low primary pump speed signal
- Clad peak temperature rises up to 729 °C in 7 s

LFR-ULOF: All Primary Pump Trip (1)

Core Flow rate, Core and SG Powers



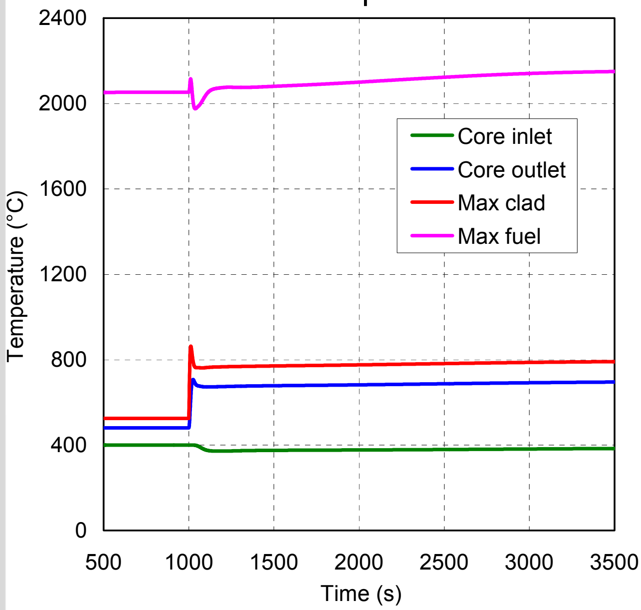
Core and Vessel Temperatures



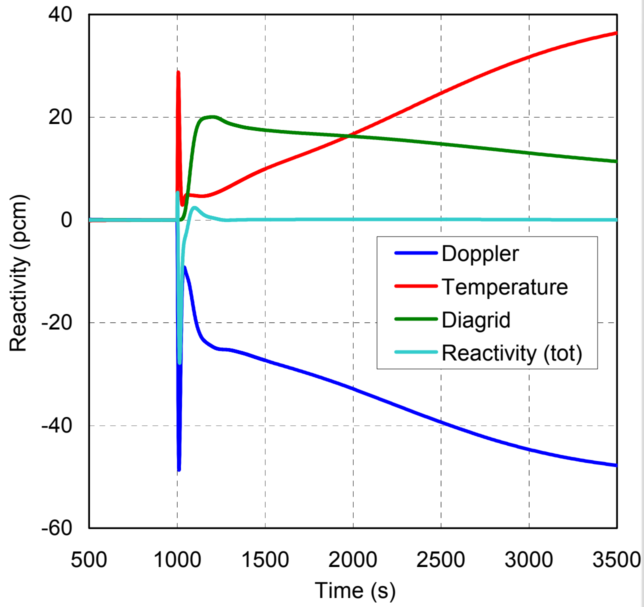
- Natural circulation in the primary system stabilizes at 25% of nominal value
- Core neutronic power slightly reduces around 95% during the transient phase
- After an initial peak up to 863 °C lasting few tens of seconds the maximum clad temperature stabilizes below 800 °C

LFR ULOF: All Primary Pump Trip (2)

Core Temperatures

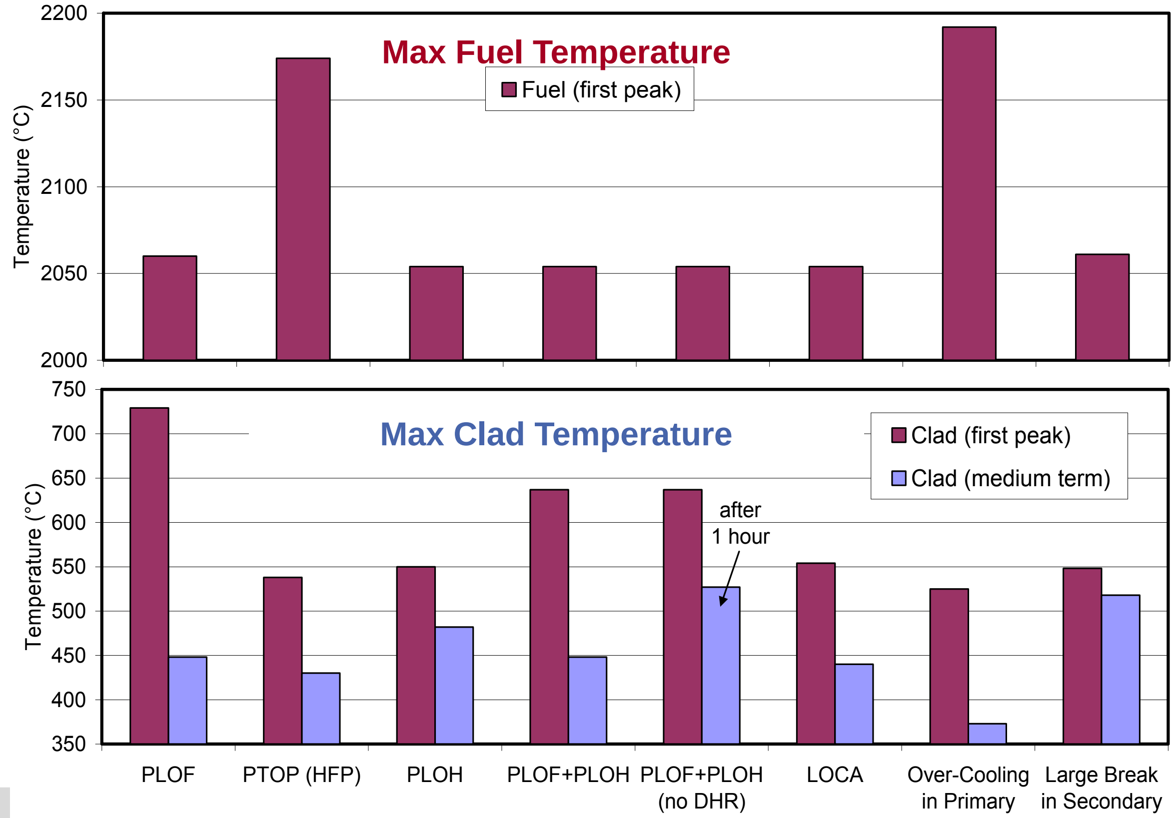


Reactivity and Feedbacks

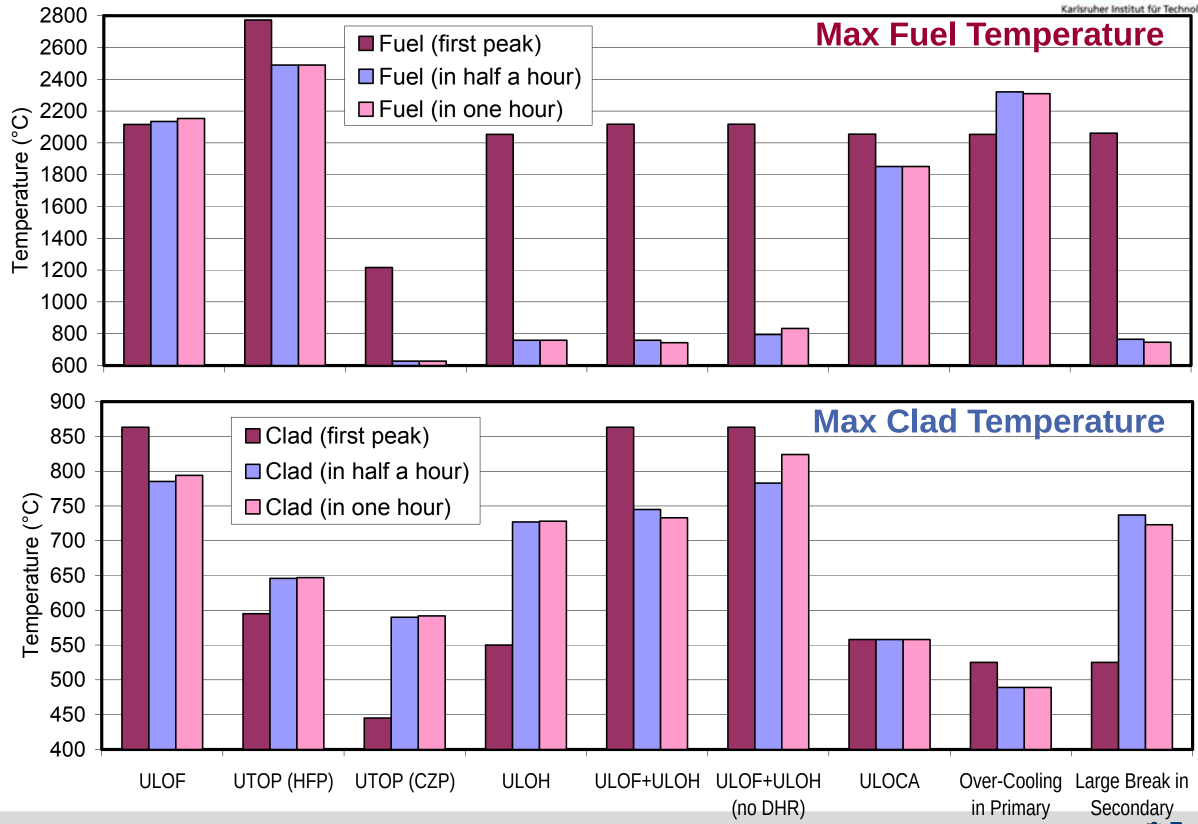


- increase of maximum fuel temperature is not very significant (about 100 °C)
- positive diagrid and temperature feedbacks counterbalanced by Doppler effect
- grace time greater than half a hour is assured before fuel rod clad failure might occur in the hottest FA (confirmed by the analysis with the SIM-LFR code)

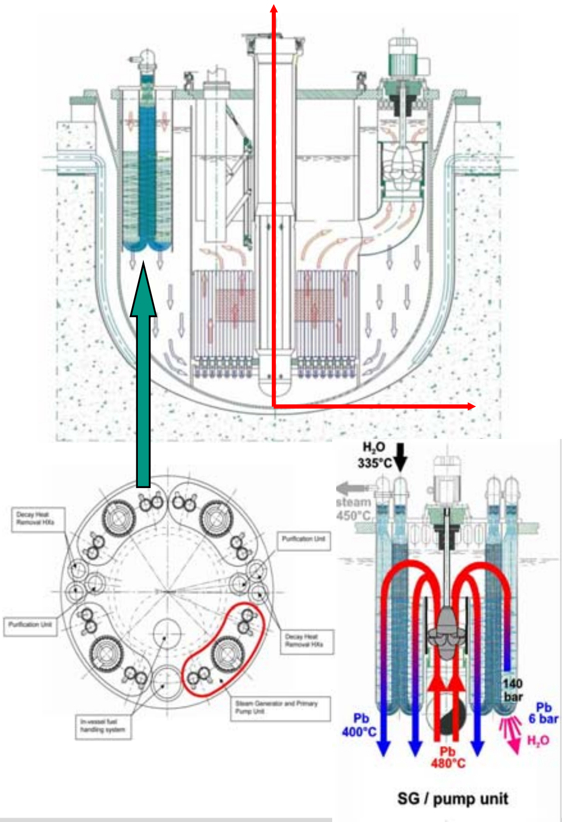
LFR - Max. Core Temperatures (Protected Accidents)



LFR - Max. Core Temperatures (Unprotected Accidents)



LFR – DEC Safety Analyses : SGTR accident



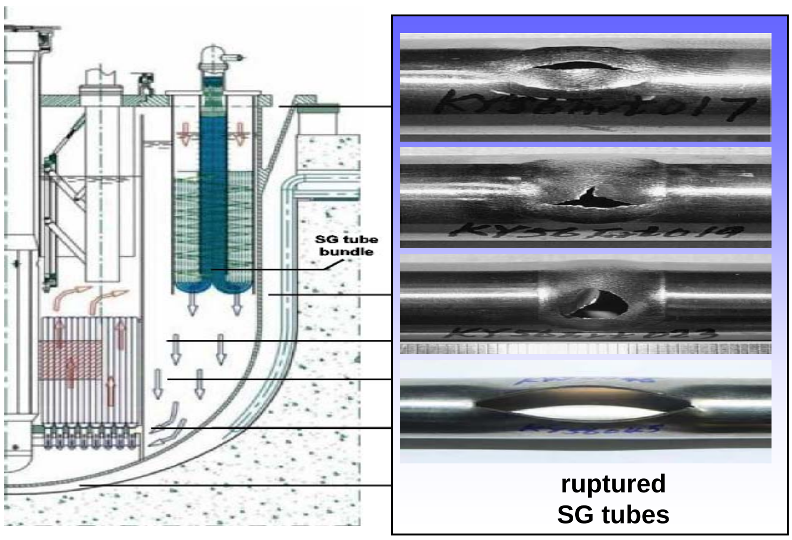
EFIT Design :

- Two-loop design (147 bar, 335°C)
- No intermediate loop
- 4 pumps / 8 internal heat exchangers
- Pumps located in hot leg
- Core with MA load
- High positive void worth

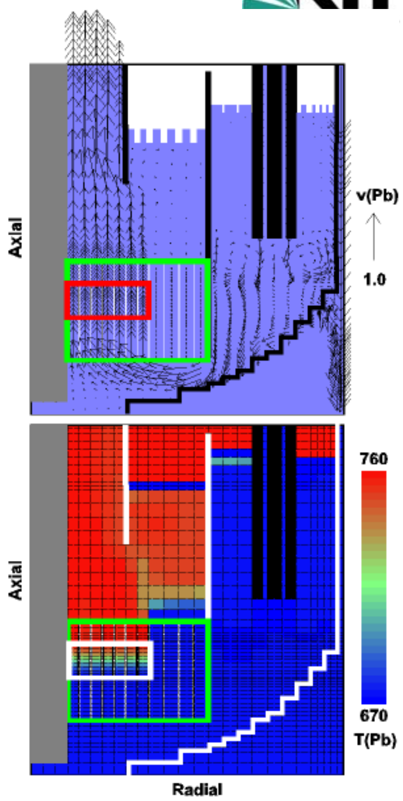
Concerns :

- Steam ingress into core
- Pb-Water interaction with (CCI)
- Pressure build-up and voiding
- Sloshing, plenum pressurization, …
- Detection

LFR – DEC Safety Analyses : SGTR accident



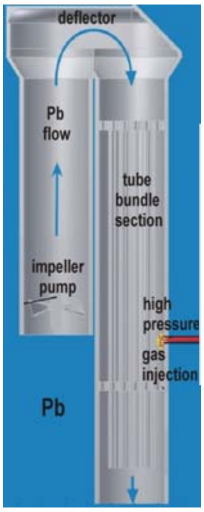
ruptured
SG tubes



- Analyses performed with SIMMER-III code
- SIMMER-III validation for multiphase flows in HLM

LFR – DEC Safety Analyses : SGTR accident

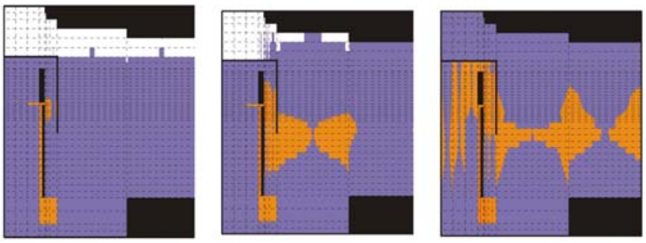
- FZK Experiment on SGTR

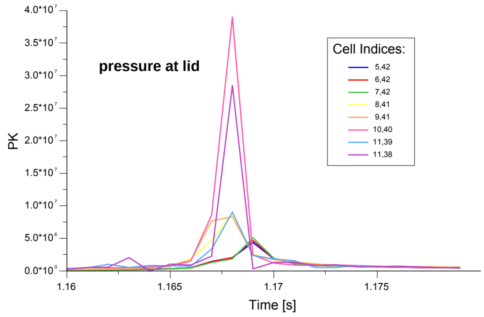


EFIT as Basis :

- Scale factor to EFIT: ~1:4
- 19 pin bundle (solid pins)
- EFIT SG design
- Pb: 480 °C, 1 atm, 0.8 m/s
- H_2O vapor: 400 °C, 240 bar,

SIMMER-III Simulation





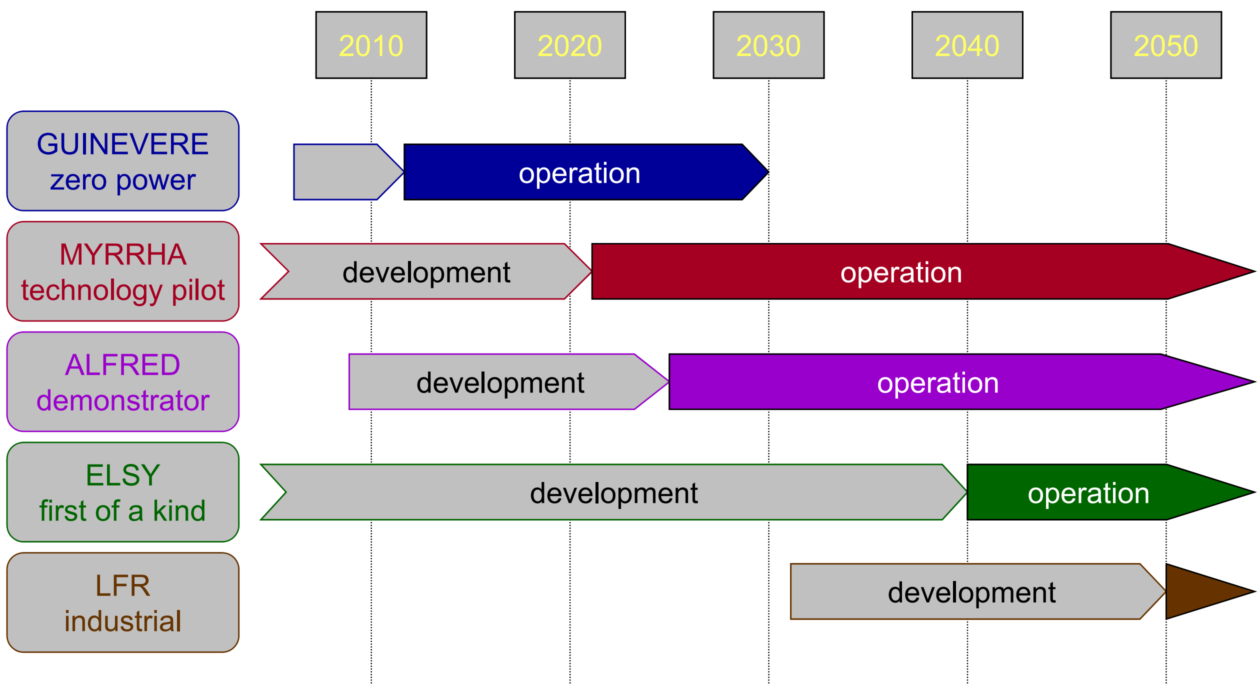
Summary

- Liquid metal and esepcially heavy liquid metals pose specific technological & scientific challenges towards realization of a reactor in terms:
  - Instrumentation,
  - thermalhydraulics in heat transfer and free surface flows,
  - ISI&R (in-service insepction & repair)
  - Material development.
- Considerable progress has been made in many fields thanks to European programs and establishment of a Pb-Technology society
- Nevertheless technological issues poses still challenges such as
  - Deficits in commercial CFD codes to predict MHD flows, heat transfer problems and free surface flows in low Prandtl number fluids even in the steady case with a reliable accuracy
  - (in-situ, non-invasive) in core flow monitoring
- LFR safety profited from the progress made so that developed LFR design exhibit a principle and safe feasibility. However, still
- generic experiments in many fields aimed are to be performed to
  - develop advanced physical models for heat transfer & free surface problems
  - generate a broad data base & local correlations for design purposes

to allow for PSA and reliable safety assessment

SUPPLEMENTARY

LFR Roadmap



Momentum Transfer (Turbulent flow) MICROSCALE

Modelling of turbulent momentum transport by CFD means

- Reynolds-Averaged Navier-Stokes (RANS) equations → closure problem in convective term

$$\frac{\partial}{\partial x_i}\left(\overline{u_i}\cdot\overline{u_j}+\overline{u_i^{'}\cdot u_j^{'}}\right)$$

- Standard model assumption: gradient hypothesis

$$\overline{u_i^{'}\cdot u_j^{'}}=-\varepsilon_m^{ij}\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right)$$

Simplification

$$\overline{u_i^{'}\cdot u_j^{'}}=-\varepsilon_m\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right)$$

isotropic exchange coefficient

Momentum Transfer (Turbulent flow) MICROSCALE

Classification of momentum transport models

Order	isotropic turbulent transport	anisotropic turbulent transport	No. of transport equations
1st	Gradient models, eddy diffusivity models		
	l mixing length models	l_i mixing length models	0
	k-l, k-ε, k-ω, SST, etc.		1,2, ...
	non-linear k-ε, V2-f and branches		2
		ASM models with k-ε	2
2nd	transport equations for all second order closure moments		
		equations for complete shear stress tensor	6+2

(green) available in CFD-codes

Momentum Transfer (Turbulent flow) MICROSCALE

Modelling by CFD means

- Decision of anisotropic modelling demands qualified user
- Anisotropic measures are relevant if
  - Wall conditions are $f(y,z)$ (y,z .... lateral coordinates)
  - Geometry yields $\tau_{Wall} = f(y,z)$ as e.g. bundle flows (τ_{Wall} ...wall shear stress)
  - Resolution of viscous sublayer is required (nozzles- relaminarization of BL, orifices-detached flow) →(low Re-models)
  - ⇨ Experimentally demonstrated in numerous experiments [*1]
  - ⇨ Num. solutions for bundles (anisotr.mixing length models[*2], phenomen. models[*3], non-lin k-ε[*4])
- Super-imposed temporal perturbations (e.g. oscillations-bundle flows with small P/D, pump oscillations, etc.) cause travelling patterns or fluid structure interaction. Solution method ?
  - First clarification of frequency f_ω and time scales by analytic means if
    - $f_\omega \approx f_{SGS,edge}$ → LES-Simulation
    - $f_\omega < f_{turbulence}$ → URANS
- Ultimate solution Direct Numerical Simulation (DNS) (containing all time and length scales without any reduced physical models)

[*1] Quarmby, Quirk 1972,1974 [*2] Meyder, NED, 1975 [*3] Ramm&Johannsen, JHMT, 1975 [*4] Baglietto&Ninokata, NURETH-10,2003

Momentum Transfer (Turbulent flow) MICROSCALE

Other problems in u-field calculations ?

- Low or High Re model selection: Required pre-requisite
  - Less sensitivty and more freedom (partly realized by combined models)
  - Detailed analytic pre-analysis necessary by user to evaluate, BL-modification, flow instabilities
- Improved near wall treatment at high Reynolds numbers : Required pre-requisite
  - Wall conditions for separated flows
  - Wall conditions for buoyant flows (thermal wall function $T^+=f(Pr_p x)$, spatial resolution $y^+ \cdot Pr$<<10)
- Time-dependent large scale fluctuations only achievable by LES : Required pre-requisite
  - Sub-Grid Scale (SGS) models
  - Inlet- and wall conditions
  - Code performance (stability, relaxation models, convergence, numerical scheme)

⇨ Development is an ongoing process in all fluid dynamic fields

Heat Transfer (Turbulent flow) MICROSCALE

Turbulent heat flux modeling

Available turbulent diffusion models for $\overline{T'^2}$

$$\overline{u_i T'^2} = -C_{ST'} \frac{k^2}{\varepsilon} \frac{\partial \overline{T'^2}}{\partial x_i}$$

Scalar GDH

$$\overline{u_i T'^2} = -C_{DT'} \frac{k}{\varepsilon} \overline{u_i u_j} \frac{\partial \overline{T'^2}}{x_i}$$

Tensorial GDH

still no influence of the molec. ***Pr***

New development accounting for the temperature diffusion

$$\overline{u_i T'^2} = -C_{T'} \left[\frac{2}{Re \cdot Pr} \sqrt{\frac{k}{\varepsilon} \frac{\overline{T'^2}}{\varepsilon_{T'}}} \Delta_x \overline{u_i T'^2} + \frac{k}{\varepsilon} \overline{u_i u_j} \frac{\partial \overline{T'^2}}{x_i} \right]$$

Helmholtz-type

GDH≈Gradient diffusion hypothesis

LFR - Fundamental Safety Objectives

- **General nuclear safety objective:**
  Protection of individuals, society and the environment by establishing & maintaining an effective defence against radiological hazard;
- **Radiation protection objective**:
  Assurance in normal operation that radiation exposure in plant and due to any release of radioactive material from plant is **A**s **L**ow **A**s **R**easonably **A**chievable (**ALARA**)…. and are below prescribed limits and to ensure mitigation of the extent of radiation exposure due to accidents;
- **Technical safety objective:**
  Prevention of accidents to ensure that for all accidents taken into account in plant are of very low probability, radiological consequences, if any, would be minor; and to ensure that the likelihood of severe accidents with serious radiological consequences is extremely small.

LFR -Safety Objectives

	Public[1]	Operational staff
Normal operating conditions	ICRP 60 recommends 1 mSv/year LFR target 0.1 mSv/y as EUR (Rev C)	ICRP 60 individ. dose <20 mSv/year during 5 years with a maximum value of 50 mSv during 1 year. LFR = EUR target: individual dose <5 mSv/year, 0.5 man-Sv/unit for annual collective dose averaged over the plant life
DBC 2	Releases from DBC 2 conditions shall not cause annual release criteria to be exceeded ➡ each DBC 2 operating condition shall individually meet the annual release criteria	
DBC 3	1 mSv/event [2]	
DBC 4	5 mSv/event [3]	
DEC design extension conditions	objective is minimization of requirements for emergency planning & offsite countermeasures [4]	

[1] This shall be assessed for the most exposed individual: At 100 m from the most significant sources with an occupancy factor of 1/30, or at 300 m with an occupancy factor of 1.

[2] 1 mSv is EFR value and consistent with EUR value.

[3] 5 mSv is 1/10 of EFR value and consistent with EUR value.

[4] These requirements should be defined for GEN IV reactors, and compared to EUR ones.

Slide after

J. Carretero

LFR -Basic Safety Design Concept: Defense in Depth (DiD)

- Five levels are defined in defence-in-depth strategy.
- DiD concept applied to safety-related activities and measures, (incl. design, organisational and behavioural factors).
- DiD adequacy established by number of barriers and number and quality of systems in each level of defence.
- Objective is inherent exclusion of possibility of core damage accidents and elimination of need for technical justification of off-site emergency response.

Levels of Defence in Depth	Objective	Essential Means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions (incl. prevention of accident progression & mitigation of consequences of severe accidents	Complementary features and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Offsite emergency response

Slide courtesy of J. Carretero

LFR - Design Basis & Extension Conditions (DBC, DEC)

DBC divided into categories:

- **DBC1:** normal operating conditions; power operation, normal transients (start-up, shutdown, load following…), commissioning)
- **DBC2:** incidents or Anticipated Operational Occurrences (AOO)
- **DBC3, DBC4:** accidents.

Initiating event categories

Categories of initiating events	Initiating event occurrence frequency range (per reactor year)
DBC1	Normal operating conditions
DBC2 Incident	Ef >10^{-2}
DBC3 Accident	10^{-2} > Ef > 10^{-4}
DBC4 Accident	10^{-4} > Ef > 10^{-6}

DEC = Complex sequences and limiting events

- Complex sequences= unlikely sequences going beyond those considered in deterministic design basis (in terms of failure of equipment, or operator errors) and potentially to lead to significant releases but do not involve core melt.
- Severe accidents= Severe accidents are certain unlikely events beyond DBC 4 involving significant core damage potentially leading to significant environmental releases (Fukushima).

➡ Fundamental safety approach=Avoiding wherever possible any severe and generalized damage to the core.

LFR -Qualitative Criteria for Fuel & Cladding

Category	Fuel limits	Cladding limits
Normal operation	No degradation	No clad failure
DBC2	No degradation	No clad failure, except due to random effects or for experimental pins
DBC3	No melting *	No systematic clad failure (i.e. large number)
DBC4	Any predicted localised melting* to be demonstrated acceptable	No systematic clad failure
Complex sequences and limiting events	No severe core damage: (e.g. no criticality risk, decay heat removal capability, no large number of pin failures (leakage))	
Severe accidents	Coolability of the damaged core within the primary system enclosure (e.g. no criticality risk, decay heat removal capability)	

* melting here means degradation leading to clad failure

LFR -Probabilistic Safety Assessment (PSA)

Consideration of three PSA –Levels

Level 1: Assessment of plant failure ➡ "core damage frequency";

Level 2: Assessment of containment response ➡ containment release frequency/ release fractions;

Level 3: Assessment of off-site consequences ➡ estimation of public risk.

Statement:

PSA limitations to innovative concepts characterized by

- large uncertainties,
- lack of reliable data
- incomplete & precise knowledge about provisions
- sparse understanding of degradation and failure machanisms

Additional tools complementing PSA:

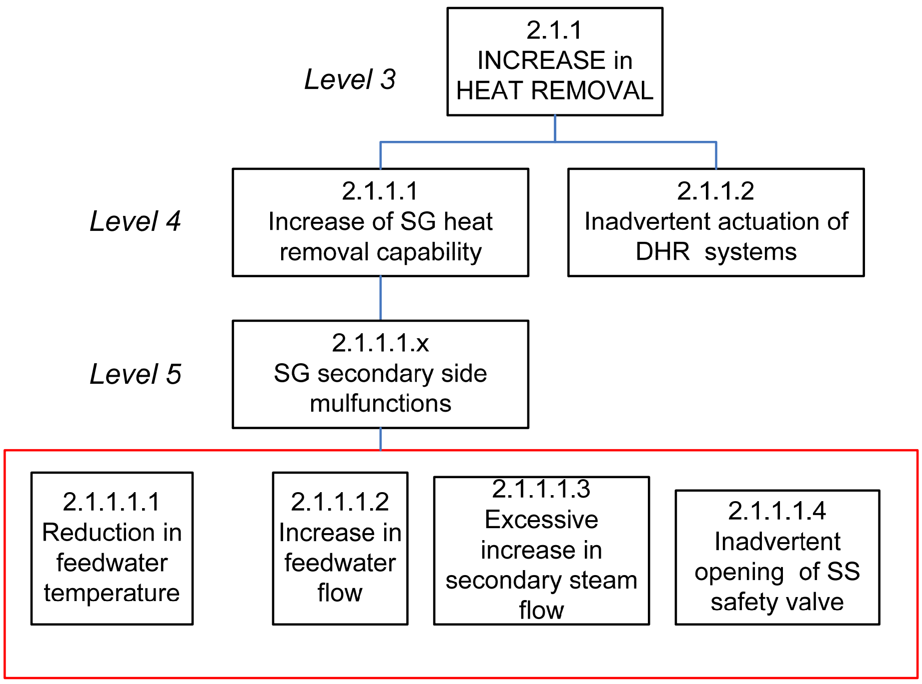
- Objective Provision Tree (**OPT**) = practical tool applied to design and to assess the structure of the safety architecture coherently with the DiD philosophy.
- Line of Protection (**LOP**) integrates all sort of provisions and characterizes their reliability and the conditions of their mutual independence.
- A Master Logic Diagram (**MLD**) then applied to LFR plant, in order to give a list of events for the re-evaluation of consequences of representative transient initiators.

➡ All relevant transient initiators are analyzed in form of MLDs (example follows):

LFR – PSA /MLD

MLD for the case:

- Increase in Heat Removal from Reactor Coolant System



From Schikorr, Bandini, Bubelis – IAEA/GRS Workshop 22.November 2011, Garching

LFR - Hazards assessement

- Safety demonstration includes consideration of harzards

Internal hazards	External hazards
▪ Fires. ▪ Failures of pressure retaining components; ▪ Flooding (water, steam). ▪ Failure of supports and other structural components. ▪ Explosions. ▪ Missiles from disruptive failure of rotating machinery (turbine failure). ▪ Dropped or impacting loads. ▪ Release of gases toxic or noxious substances. ▪ Electromagnetic interference from equipment on site.	**Natural** ▪ Earthquake. ▪ External flooding. ▪ Extremes of temperature/ winds. ▪ Rain, snow, ice formation. ▪ Drought/Lightning/Groundwater/Fire. **Man made** ▪ Aircraft crash. ▪ Hazards from adjacent installations, transport activities: ▪ Missiles. ▪ Toxic/corrosive/burnable gas. ▪ Explosion etc. ▪ Electromagnetic interference. ▪ Sabotage.

LFR Safety approach- Regrouping

- Separation of Incidents and Accidents

Category	Description
Incident **DBC 2**	▪ Inadvertent control rod assembly withdrawal ▪ Control rod assembly drop ▪ Inadvertent actuation of DHR systems ▪ Reduction in feedwater temperature ▪ Increase in feedwater flow ▪ Excessive increase in secondary steam flow ▪ Inadvertent opening of SG SS safety valve ▪ Loss of normal feed ▪ Turbine trip ▪ Inadvertent closure of main steam isolation valves ▪ Loss of load ▪ Loss of AC power ▪ Mechanical or an electrical failure of a primary pump (Partial loss of flow)
Accident **DBC 3**	▪ Control rod assembly ejection ▪ Fuel assembly loaded in an incorrect position ▪ Fuel assembly loaded with incorrect composition ▪ Loss of electrical supplies to primary pumps (Complete loss of Flow) ▪ Steam generator tube rupture

List from D4: M. Frogheri

LFR Safety approach- Regrouping

- Separation of Incidents and Accidents

Category	Description
Accident **DBC 4**	▪ Pump Shaft Break ▪ Pump Shaft Seizure ▪ SG feedwater system line break, ▪ Fuel Assembly Partial Blockage ▪ SG flow Partial Blockage ▪ Steam line break ▪ Cover Gas line break ▪ Feed line break ▪ Fuel Handling Accident
Accident **DEC**	▪ Changes in core geometry due to earthquake (Large core compaction) ▪ Simultaneous main and safety vessels rupture ▪ Main vessel break

➡ **Result :** **"Risk-informed" plant design**

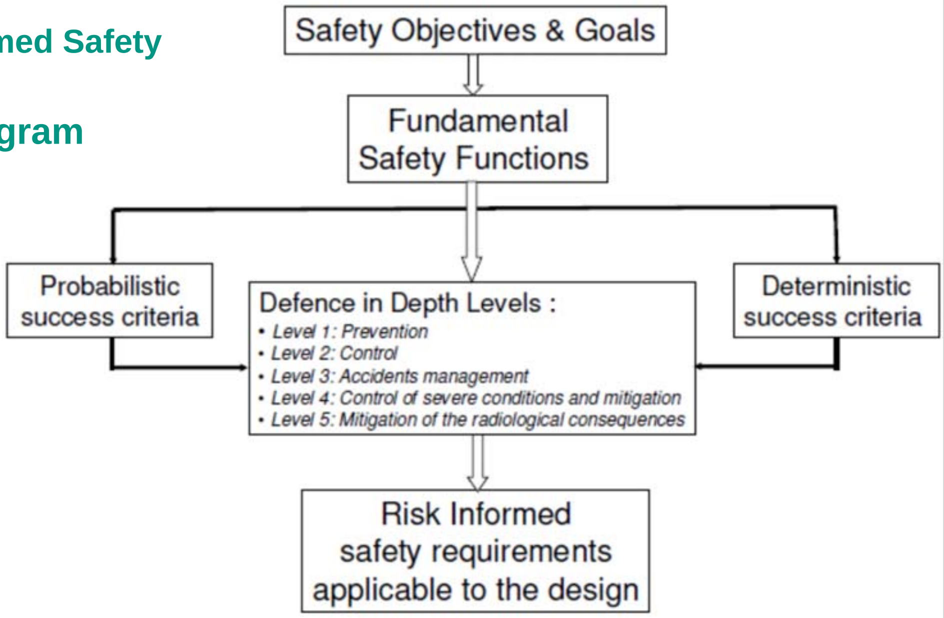
List from D4: M. Frogheri

LFR Safety approach- "Risk-informed" plant design

DiD and **Risk-Informed Safety**

➡

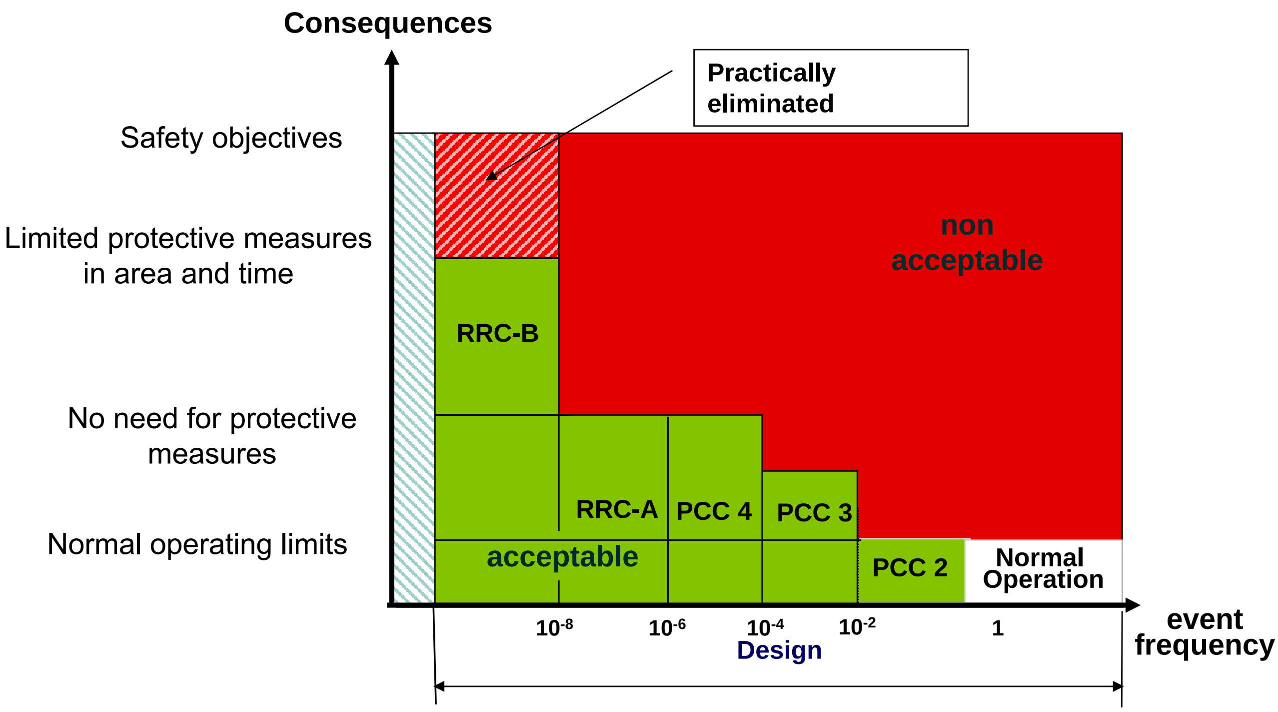
Master Logic Diagram



Objective: Generation of safety requirements by integrating both deterministic and probabilistic success criteria.

LFR - Events considered in the design

Giovanni B. BRUNA



PCC: Plant Condition Category
RRC: Risk Reduction Category

RRC-A: multiple failures situations, without core melt
RRC-B: core melt situations

LFR –DBC/DEC Transient Analysis in ELSY

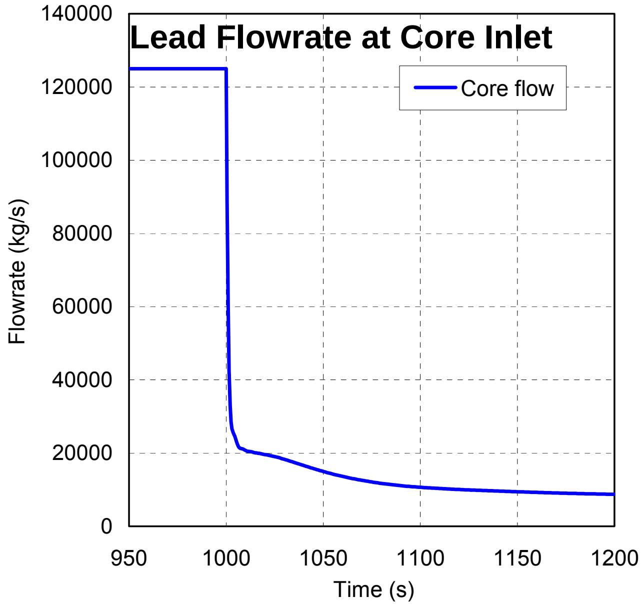
- Main Events and Reactor Scram Thresholds in Protected Accidents

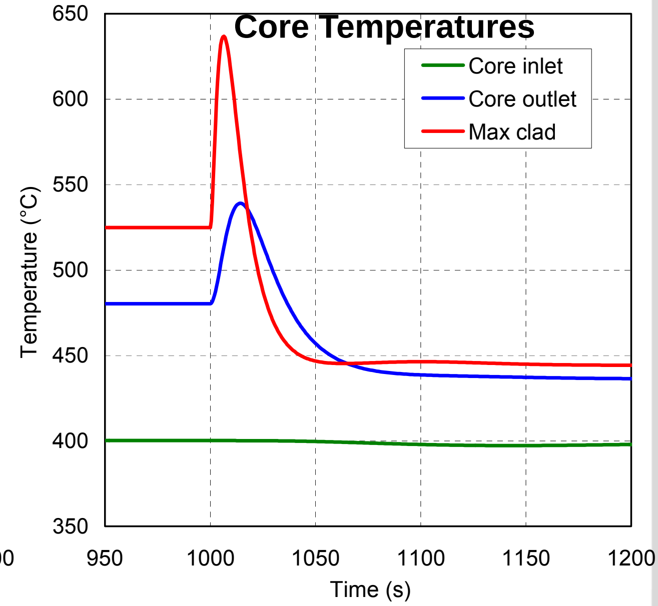
TRANSIENT	Initiating Event (t = 1000 s)	Reactor scram and threshold	Primary pump trip	SG feed-water trip	MSIV closure	DHR startup
PLOF	All primary pumps trip	1003 s Low pump speed	1000 s	1003 s	1003 s	DHR-2 at 1003 s
PTOP at HFP (C. rod withdrawal)	+200 pcm in 10 s at HFP	1005 s Power > 120%	no	1005 s	1005 s	DHR-2 at 1005 s
PTOP at CZP	+350 pcm in 10 s at CZP (380 °C)	1010 s, High power or low period	no	-	-	no
PLOH	All SG feedwater trip	1035 s T-core out > 500 °C	no	1000 s	1003 s	DHR-2 at 1003 s
PLOF + PLOH (Station Blackout)	All SG feedwater + primary pump trip	1000 s Station Blackout	1000 s	1000 s	1000 s	DHR-2 at 1000 s
PLOF + PLOH without DHR	All SG feedwater + primary pump trip	1000 s Station Blackout	1000 s	1000 s	1000 s	no
LOCA (Vessel leakage)	Vessel level -1 m in 10 s	1040 s T-core out > 500 °C	no	1040 s	1040 s	DHR-2 at 1040 s
Over-Cooling of Primary Side	Loss of pre-heaters (Tin -40 °C in 70 s)	1070 s T-core in < 360 °C	no	1070 s	1070 s	DHR-2 at 1070 s
Large Break in Secondary	Depressurization of secondary side	1060 s T-core out > 500 °C	no	1003 s	1003 s	DHR-1 at 1060 s

➡ All DBC Transients have been analyzed also in case of Unprotected Transients (DEC -that is without reactor scram)

LFR - PLOF+LOH: Station Blackout (1)

Karlsruher Institut für Technologie

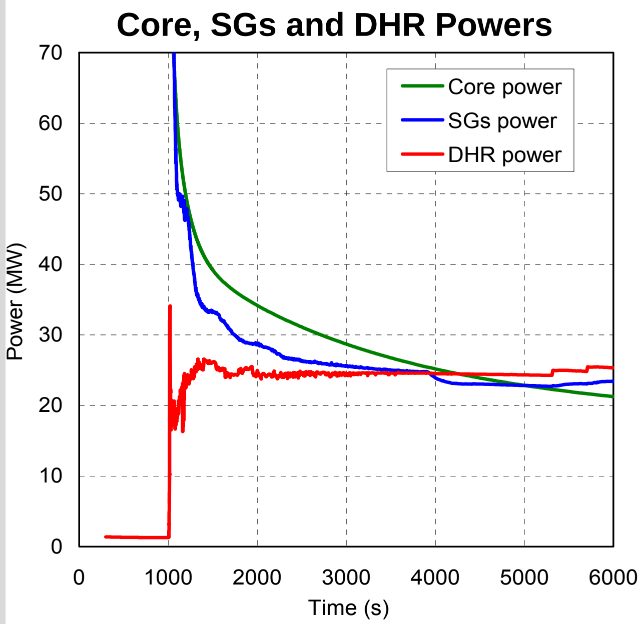


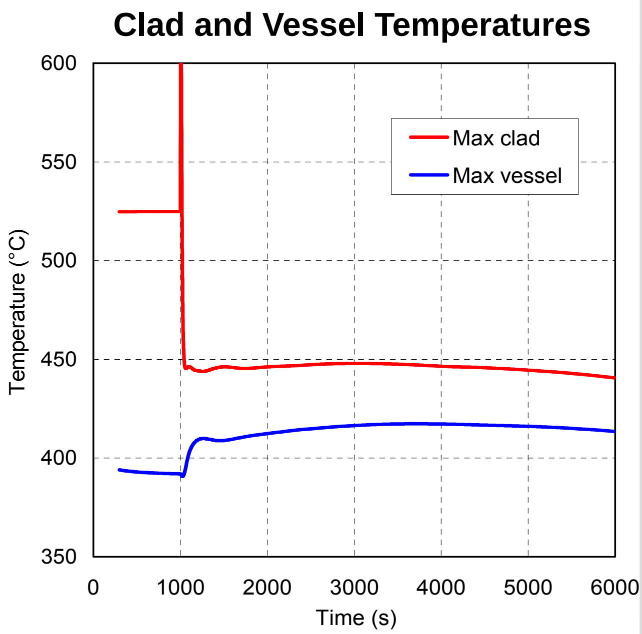


- Natural circulation in the primary circuit stabilizes at about 6% of nominal value after primary pump and SG feedwater trip @ t=1000s
- Clad peak temperature rises up to 637 °C at t = 1007 s (Reactor scram @ t=1000s)

LFR- PLOF+LOH: Station Blackout (2)

Karlsruher Institut für Technologie

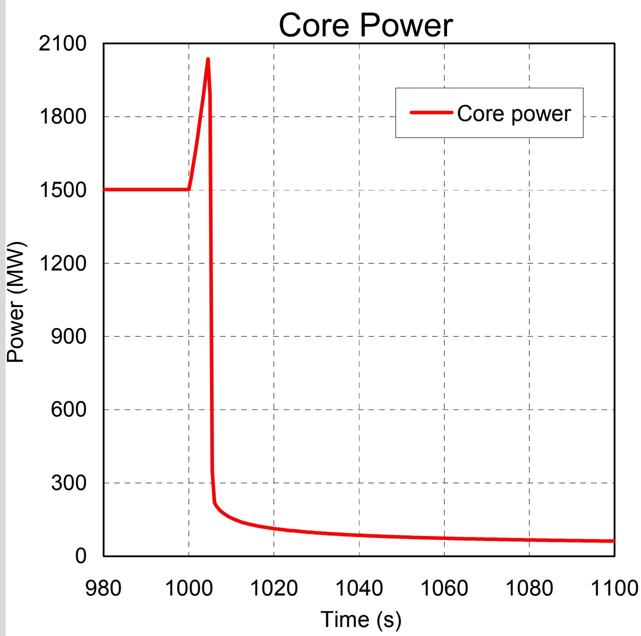


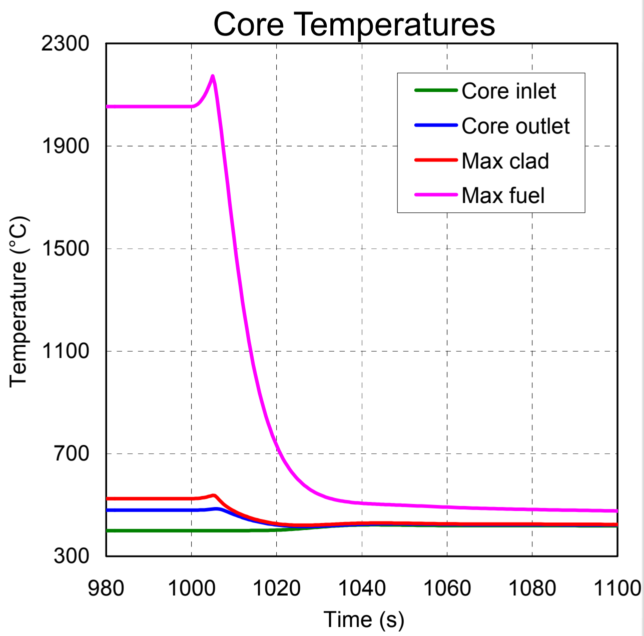


- SGs power in excess to DHR power by steam release through relief valves
- DHR power (3 IC loops+RVACS*) exceeds the decay power within one hour transient
- Maximum vessel wall temperature of 417 °C at t = 4000 s

*RVACS=Reactor Vessel Auxiliary Cooling System

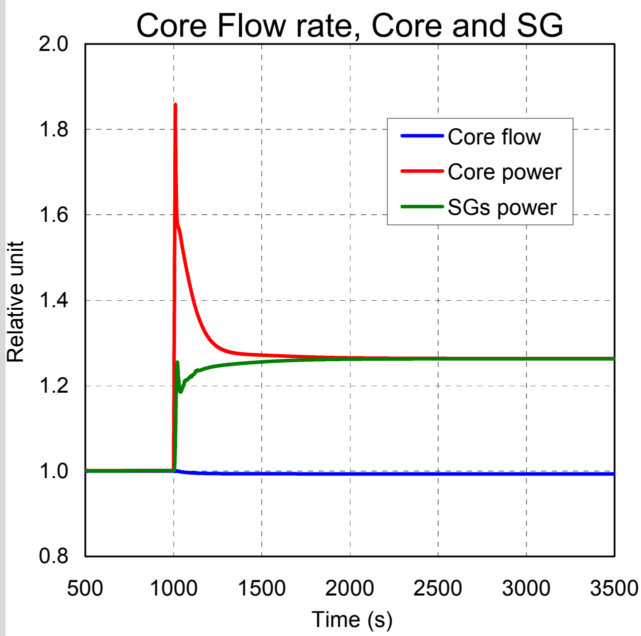
LFR PTOP: Control Rod Withdrawl

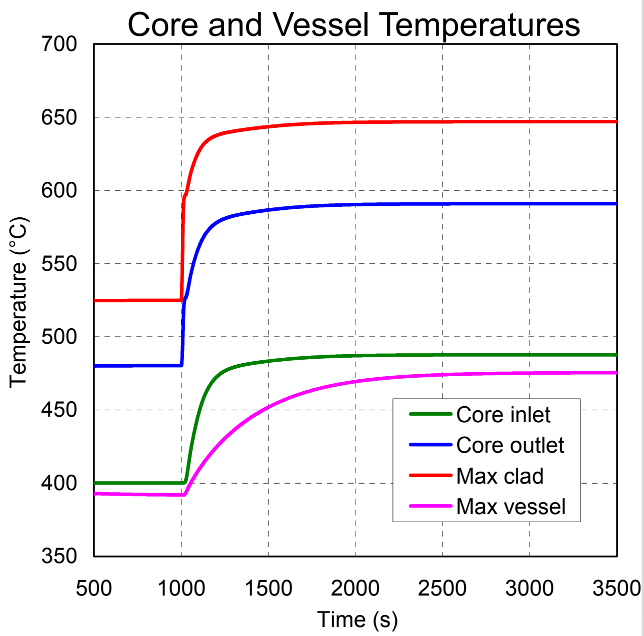




- +200pcm in 10 s → Reactor scram at t=1005s on high neutronic power signal (> 120%)
- Core power rises up to 2040 MW in 5 s (136% of nominal value)
- Max T-fuel rises up 2173 °C at t=1005 s (+120 °C) - Max T-clad = 540 °C

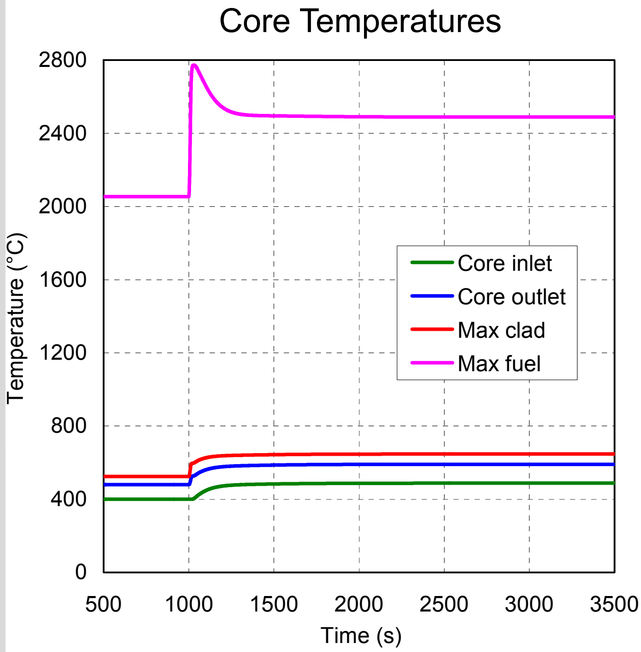
LFR- UTOP: Control Rod Withdrawl (1)

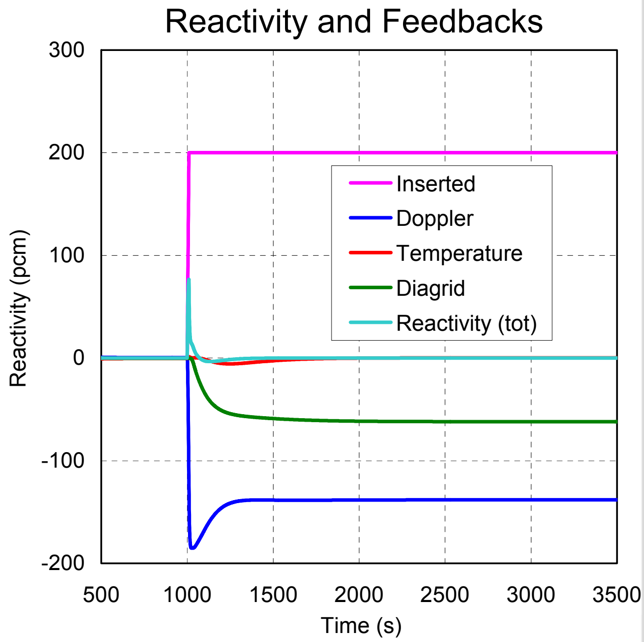




- Initial core power rise up to 186% of nominal value, then core power is balanced by the SG power removal at 126% of nominal value (no control on secondary side)
- Maximum clad & vessel wall temperatures rises and stabilizes at 647°C and 475°C

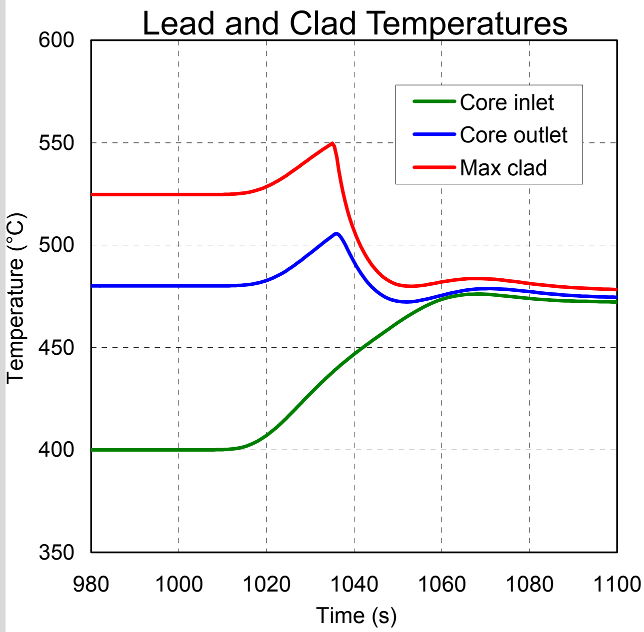
LFR -UTOP: Control Rod Withdrawl (2)

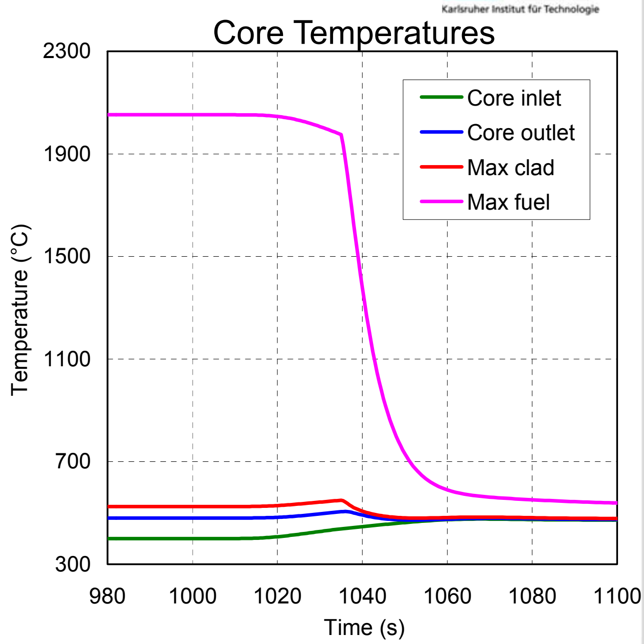




- Max. fuel temperature rises quickly up to 2772°C (ΔT =718 °C), then stabilizes down to 2490°C → No significant fuel melting, but local melting in centerline of fuel pellets of hottest FA cannot be excluded
- Reactivity inserted is counterbalanced by negative Doppler and Diagrid feedbacks

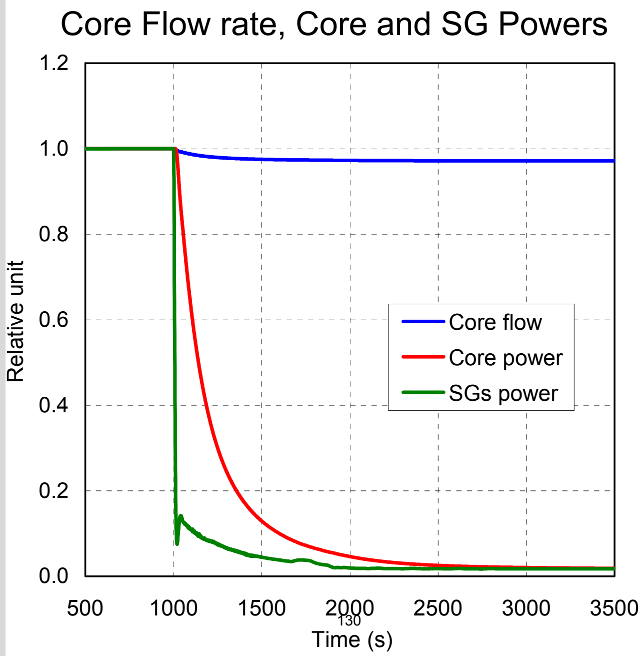
LFR- PLOH: All SGs Feedwater Trip

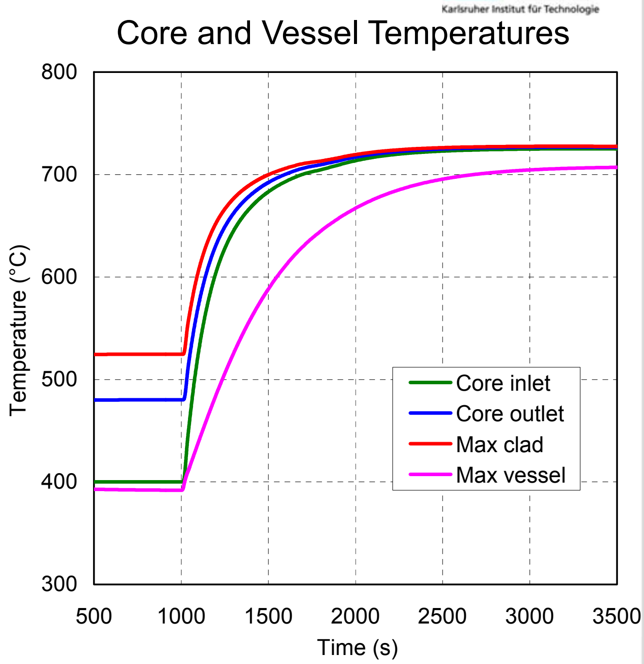




- Reactor scram at t = 1035 s on core outlet temperature > 500 °C
- Clad peak temperature rises up to 550 °C which is within the normal operation limit
- Core power and then fuel temperature reduce before reactor scram due to negative Diagrid feedback

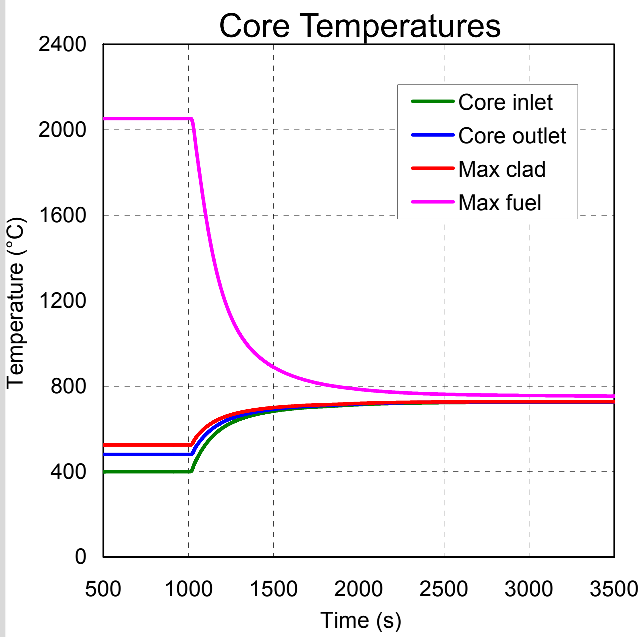
LFR- ULOH: All SGs Feedwater Trip (1)

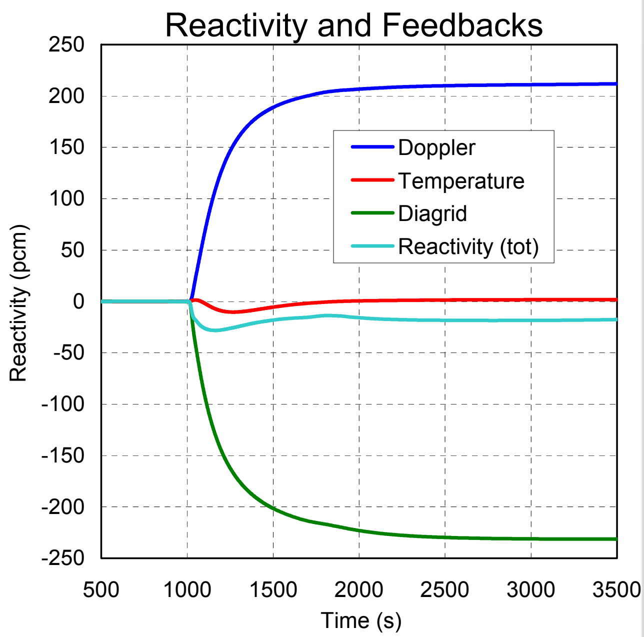




- Core power progressively reduces to decay level after ~ half a hour from transient initiation due to temperature reactivity feedbacks
- Max. clad temp. rises up to 727 °C – Critical point is vessel wall temperature exceeding DBC4 limit of 550 °C after about 6 minutes

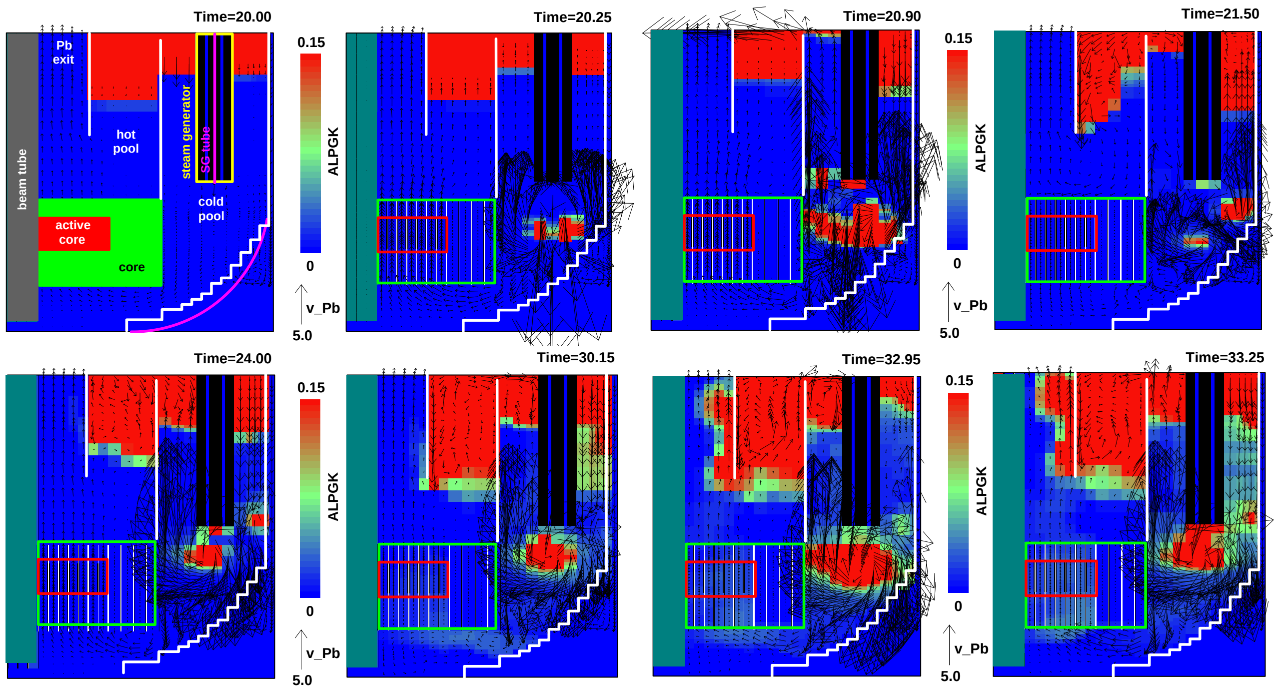
LFR -ULOH: All SGs Feedwater Trip (2)





- Negative Diagrid feedback mainly counterbalanced by positive Doppler feedback associated with large fuel temperature drop

LFR – DEC Safety Analyses : SGTR accident



Volume fraction plots for vapor (gas) for SGTR accident simulation