

Impact of coolant choice on design and performance of a fast neutron system

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1st Workshop on Challenges for Coolant in Fast Spectrum Systems: Chemistry and Materials

- Environment of fast spectrum applications
- Coolant functions in fast (neutron) spectrum application
 - Thermo-physical aspects
 - Neutron-physical considerations
 - Consequences on licensing frame and time scales
- Example-Fast reactors
 - Impact of coolant choice on reactor design –power conversion options
 - Coolant poisoning/conditioning/handling
 - Coolant confining structures and material degradation
 - Safety analyses
- Example-Accelerator applications
 - Coolant choice consequence on integral facility design
- Objectives to be met by the workshop
- Vision/Measures for future cross fertilizing exploitation

Types of utilization

- fundamental sciences & technologies → Accelerator Applications
- nuclear energy conversion → Fission & Fusion

Boundary conditions

- I. volumetric high efficiency (particle yields, fuel utilization, thermal efficiency)
- II. improved safety (all three lines: accidental safety/operational safety/disposal)
- III. enhanced lifetime

Consequences

- I. enlarged coolant/material damage
- II. dedicated constructive/operational/handling measures
- III. long extensive licensing procedures demanding
 - data bases
 - ageing/fatigue aspects → lifetime management
 - component qualification,
 - code & standards

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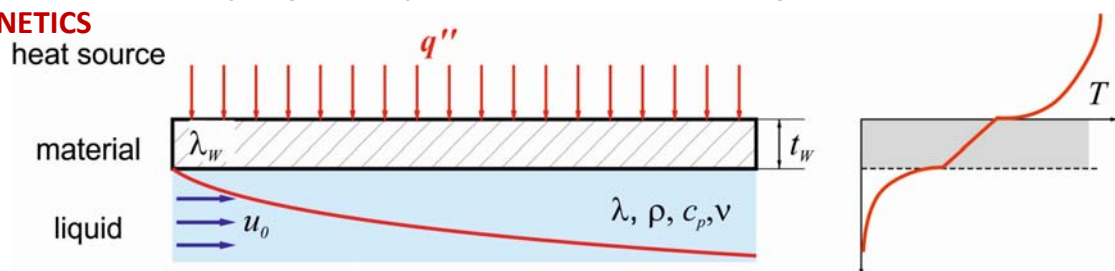
COOLING FUNCTION → FUNDAMENTALS OF KINETICS & ENERGY TRANSFER

Inputs

- heat source type (e.g. charged particles, neutrons, photons)
- coolant (thermophysical properties)
- coolant confining material (thermo-physical properties and thermo-mechanical properties)

Design to match functionality → geometry (wall thickness, flow-configuration,..)

RESULT = KINETICS



- | | | |
|--|-----------------|--|
| ▪ heat conductivity λ, λ_w | → ∇T | → material, fluid limits |
| ▪ thermal inertia ($\rho \cdot c_p$) | → time | → operational grace time, removable power |
| ▪ temperature threshold | → ΔT | → phase change (safety), removable power, design provisions (auxiliary heating, boiling detection) |
| ▪ thermal expansion | → $\Delta \rho$ | → passive heat removal capability (safety), pumping power (Balance of Plant) |
| ▪ kinematic viscosity ($\rho \cdot \nu$) | → Δp | → pressure loss, wall shear stress (erosion, corrosion) |

- some typical coolants considered in fast spectrum applications (thermo-physical data)

	H ₂ O [300°C, 15MPa]	Li [500°C]	Na [500°C]	Hg [20°C]	Pb [500°C]	Pb ⁴⁵ Bi ⁵⁵ [500°C]	Salt NaCl-KCl- MgCl ₂ [600°C]	He [500°C, 6MPa]	CO ₂ [500°C 2MPa]
ρ [kg/m ³]	725	475	857	13534	10724	9660	1800	3.7	13.5
c_p [J/(kgK)]	5475	4169	1262	140	145	145	1004	5190	1170
$(\rho \cdot c_p)$ [MJ/(m ³ ·K)]	3.97	1.98	1.081	1.895	1.555	1.401	1.807	0.19	0.158
λ [W/(mK)]	0.561	49.7	66.3	8.3	15	11	0.39	0.303	0.056
ν [(m ² /s) · 10 ⁻⁷]	1.2	7.16	2.6	1.1	1.5	1.1	0.138	0.9	0.25
T_{melt} [°C]	-0.4	180	98	-39	327	126	396	-	-58
$T_{boiling}$ [°C]	334	1317	883	356	1737	1533	2500	-	-78

not desirable

advantageous

- ➔ there is not optimal coolant from thermo-physical point of view !!

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COOLANT NEUTRONIC FUNCTION ➔ neutron (charged particle) interaction with matter

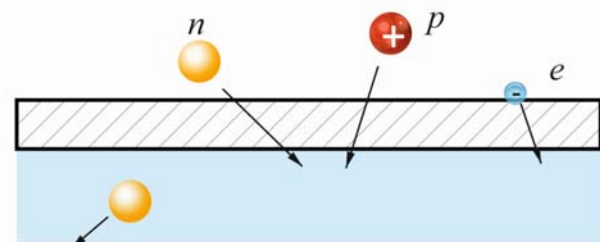
- high particle fluxes (e.g. charged particles, neutrons, photons)
- high incident particle energies
- dedicated material (fuel/target compositions ➔ secondary reactions)

Design to match functionality ➔ geometry (wall thickness, reduced leakage,..)

- ➔ high volumetric power densities

Constraints to coolant

- ➔ if possible transparent to incident particles
- ➔ no (or short lived) immobile activation products
- ➔ no temporal degradation by neutronic interaction (destruction of coolant chemistry, radiolytic decomposition)
- ➔ all safety & economic parameters
- ➔



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Coolant functions in fast (neutron) spectrum applications

Neutron-physical considerations



Neutronics

☐ Moderation $\xi \cdot \Sigma_s$

(logarithmic energy decrement per collision ξ , $\xi = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right)$
 Σ_s macroscopic scattering cross-section)

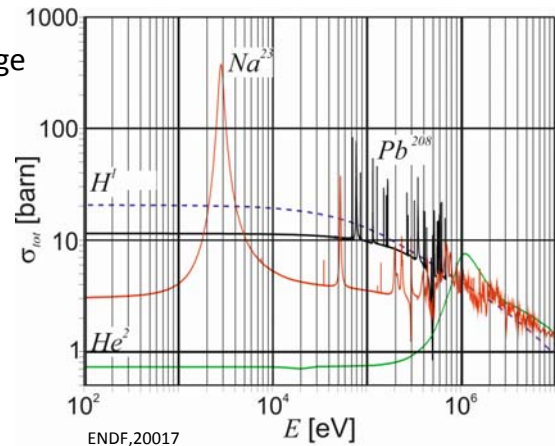
- hardly moderation in *Pb*, *He*
- moderate performance of *Na*
- design challenges for *H₂O*

☐ Nuclear cross-sections (σ_{tot})

- high hydrogen cross section throughout *E*-range
- Large values for *Pb* and *Pb*-alloys in but no
- broad band resonances as *Na*
- almost no interference using *He*

➔ except for *He* each other coolant poses neutron physics challenges

	$(\xi \cdot \Sigma_s)$ [cm ⁻¹]
<i>Zr</i>	0.00046
<i>Fe</i>	0.0023
<i>Na</i>	0.0027
<i>Pb</i>	0.00013
<i>H₂O</i>	1.36
<i>He</i>	0.00024
<i>C</i>	0.06
<i>O</i>	0.0058



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Coolant functions in fast (neutron) spectrum applications

Neutron-physical considerations



Coolant treatment requires consideration of coolant/functional materials.

☐ Structure material also affected by nuclei matter interaction

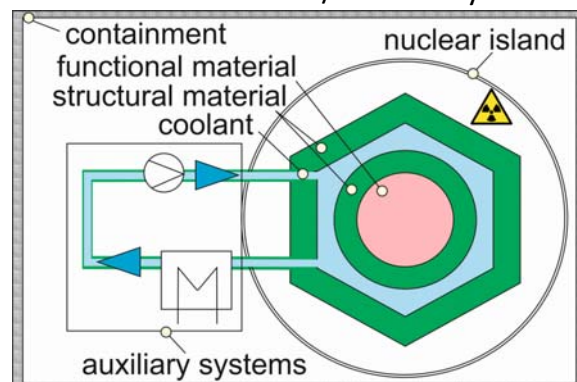
- nuclear reactions $f(E)$ and time,
- operational temperature,
- the design of the component
- ➔ swelling, formation of transmutation products within the material, hardening and a set of other phenomena (all dynamic).

☐ Additionally, at fluid-structure interface mass transport processes (bi-directional) due to scalar gradients ($\nabla T, \nabla c, \nabla p$)

➔ corrosion, stress-corrosion cracking, embrittlement enforced/assisted by irradiation.

☐ Nuclear and conventional island interlinked via coolant

➔ coolant choice affecting nuclear system architecture.



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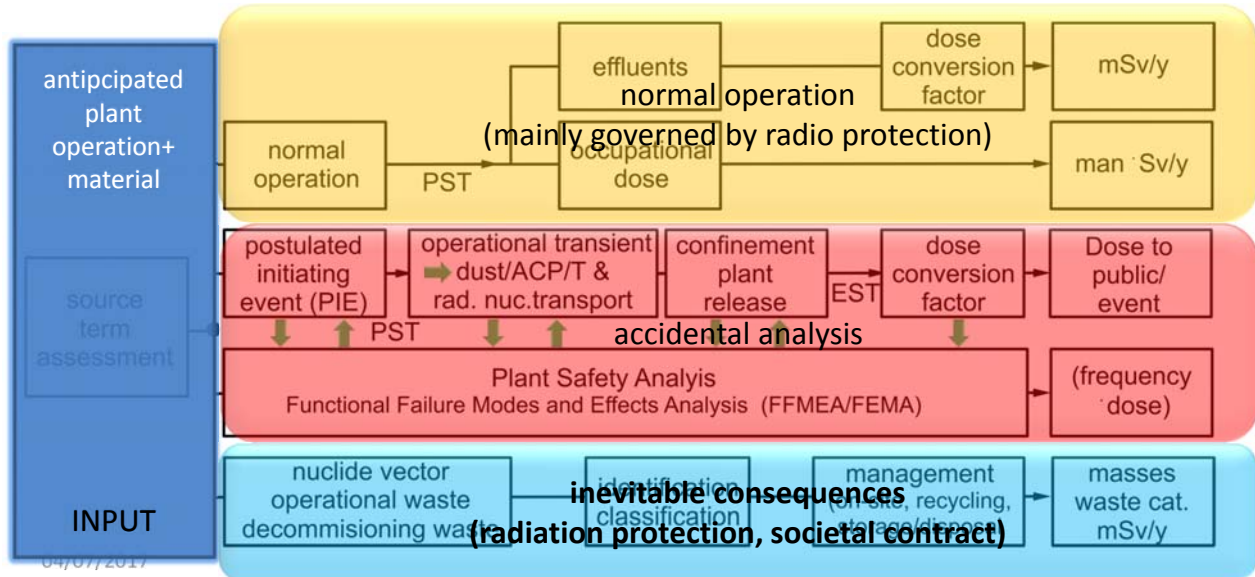
Coolant functions in fast (neutron) spectrum applications



Consequences on licensing frame and time scales

Systematic Safety Analysis (SSA) - Success criteria

- normal operation dose to worker on site < limit
- accidental analysis : worst dose to public (MEI) < limit
- consequences: mobility in long term storage < limit (what ?)
- ➔ **all to be met**



PST=Process Source Term, MEI=Most Exposed Individual



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Coolant functions in fast (neutron) spectrum applications



Consequences on licensing frame and time scales

Nuclear licensing requires

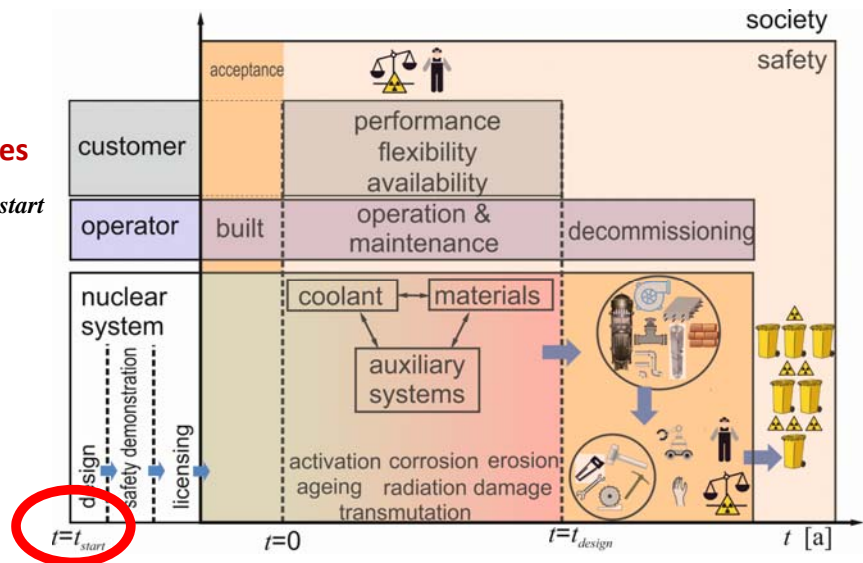
- input at the **begin** of process
- tracking plant for decades**
- taking responsibility for **centuries**

Mandatory pre-requisites @ t_{start}

- reliable, broad data base
- validated code/standards/procedures

Workshop objective

- synthesize knowledge on coolant behaviour in fast spectrum systems
- elucidate potential knowledge gaps
- Formulation of required efforts to overcome present shortcomings



➔ TOPICS

- Coolant characteristics under irradiation**
- Coolant confining structures**
- Interfaces and**
- Safety and operational aspects.**

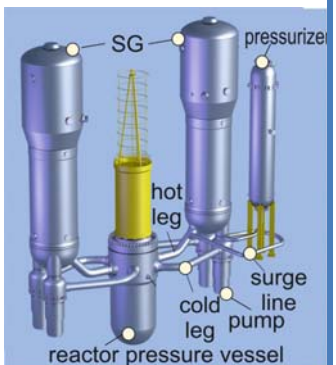
In Gen-IV 4 of 6 reactors fast reactors

- Sodium Fast Reactor (SFR)
- Gas cooled Fast Reactor (GFR)
- Lead cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

Selection criteria

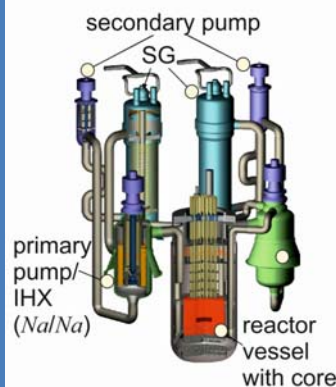
- Sustainability** (fuel utilization/ transmutation/ waste reduction)
- Economy** (long cycles, life >60y, compactness)
- Safety** (increased safety/operational reliability /low probability of core accidents/elimination for off-site emergency response)
- Proliferation resistance**

Conventional PWR

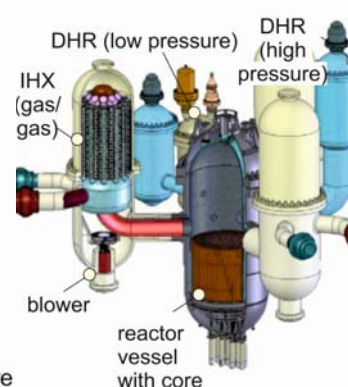


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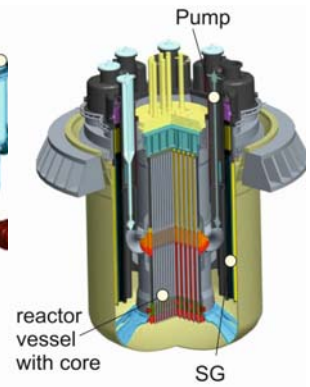
loop type SFR



GFR



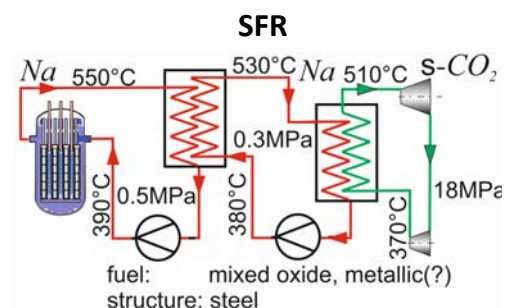
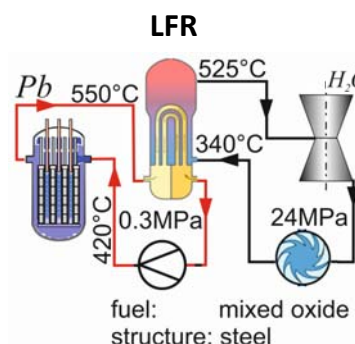
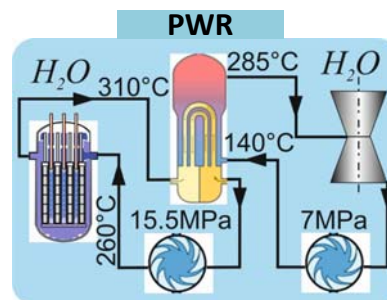
LFR



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Some FR characteristics

- high material allocation in core
 - ➔ max. utilization of neutrons
- small coolant channels (as e.g. fusion)
 - ➔ decay heat management
- higher σ_f/σ_a ration and more v_d
 - ➔ breeding/transmutation options
 - ➔ high n -leakage
- larger n -capture
 - ➔ higher fuel enrichment
- high volumetric power densities (>100MW/m³)
 - ➔ power management
- coolant voiding
 - ➔ reactivity management
- high n -Energy challenging to
 - ➔ **coolant** (fuel, structure)
 - ➔ **material** (fuel, structure)
 - ➔ **coolant material interaction**



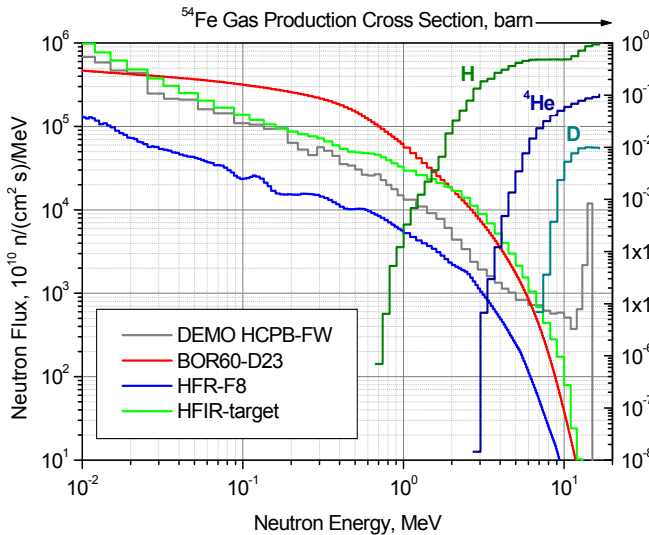
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Coolant activation

- nuclear reaction with $n \rightarrow$ radioisotope formation
- \rightarrow reuse of Na after 50-60years feasible
- \rightarrow PbBi will be classified waste (almost forever)

isotope	formation channel	$T_{1/2}$ [a]
^{22}Na	$^{23}\text{Na}(n,2n)^{22}\text{Na}$	2.6
^{24}Na	$^{23}\text{Na}(n,g)^{24}\text{Na}$	$1.7 \cdot 10^{-3}$
^{205}Pb	$^{204}\text{Pb}(n,g)^{205}\text{Pb}$	$1.5 \cdot 10^{-7}$
^{208}Bi	$^{209}\text{Bi}(n,2n)^{208}\text{Bi}$	$3.7 \cdot 10^5$
^{210}Bi	$^{209}\text{Bi}(n,\gamma)^{210}\text{Bi}$	$3.6 \cdot 10^6$
^{210}Po	$^{210}\text{Bi}(\beta) \rightarrow ^{210}\text{Po}$	0.38



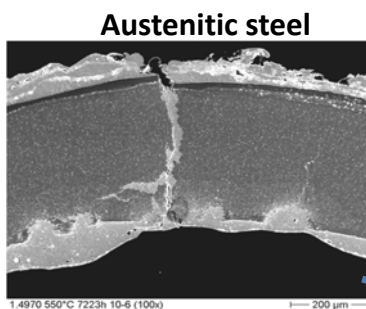
Transmutation in structures

- n -energies exceeding E_{th}
 - \rightarrow gas production in structure (fuel)- such as H, D, T, He
- \rightarrow 2 effects
 - diffusion of gas into coolant
 - \rightarrow necessitating diffusion barriers or
 - \rightarrow partial pressures on sec./ternary side
 - permanent gas formation in structure (**damage-He**)

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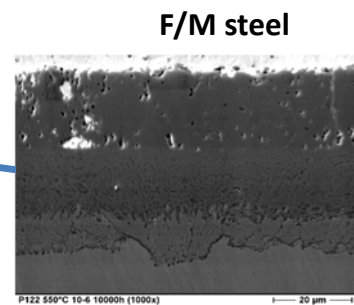
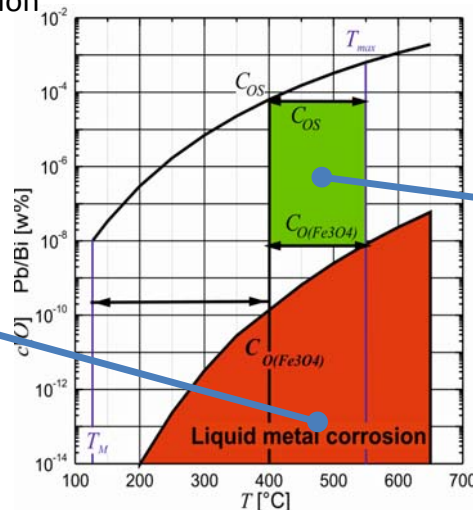
Operational consequences \rightarrow permanent coolant conditioning (physico-chemistry)

- Na : O, H -management via cold, traps, fire, explosion measures in bypass
- He : H (but esp. T) extraction by coolant purification techniques (getters)
- Pb : active oxygen control to prevent steel corrosion, coolant oxidation $\rightarrow f=(T, t, c_O, u_0, \text{dpa})$
 - \rightarrow oxygen sensor development
 - \rightarrow barrier development
 - \rightarrow process technology
 - \rightarrow material validation



- dissolution of alloying elements (Ni);
- rate up to $1 \mu\text{m/h}$

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- huge oxidation rate F/M-9Cr-steels
- oxide spallation by growth stress
- weak heat removal capability

Weisenburger et al., 2011, J. Nuc.Mat

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☐ irradiation causes constraints to material performance.

Physics

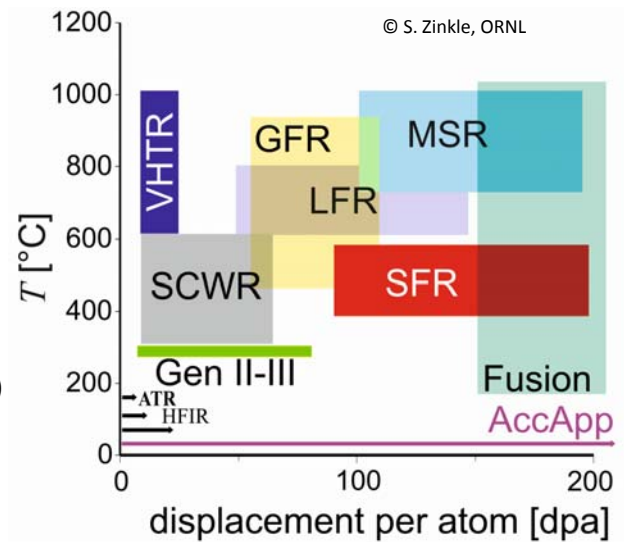
- ☐ radiation induced growth
- ☐ atom segregation in lattice (diffusion controlled)
- ➔ radiation induced growth
 - $f = f(T, \text{dpa}, E, \text{dose rate}, \sigma, \text{composition}, He)$
- ➔ radiation damage affects the mech. properties
 - ☐ hardening & localized deformation,
 - ☐ fracture behavior
 - ☐ embrittlement and
 - ☐ irradiation creep

Five evils for radiation damage

in metal based materials (G.Was, 2014):

- ☐ radiation hardening & embrittlement ($<0.4 T_M, >0.1 \text{ dpa}$)
- ☐ phase instabilities from rad.-induced precipitation ($0.3-0.6 T_M, >10 \text{ dpa}$)
- ☐ high temp. He embrittlement ($>0.5 T_M, >10 \text{ dpa}$)
- ☐ vol. swelling from void formation ($0.3-0.6 T_M, >10 \text{ dpa}$)
- ☐ irradiation creep ($<0.45 T_M, >10 \text{ dpa}$)

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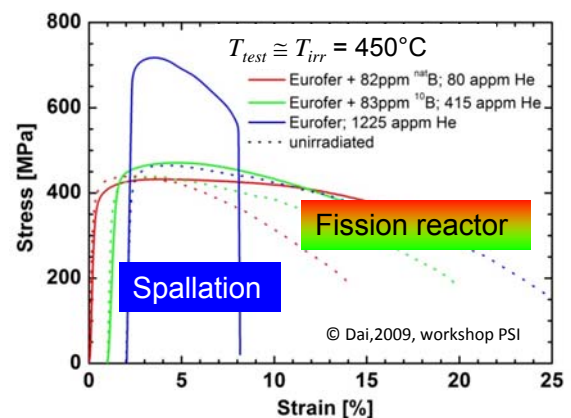
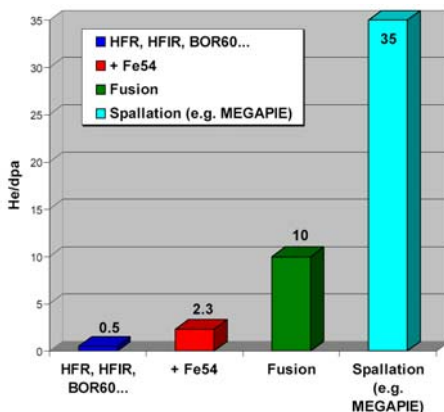


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☐ Most relevant for radiation damage He/dpa ratio

➔ strongly depending on application

☐ Helium generated in material



☐ Spallation irradiation yields higher strength $\Delta\sigma_{irr}$ than fission reactor irradiations due to He

➔ Does this impact other quantities as well?

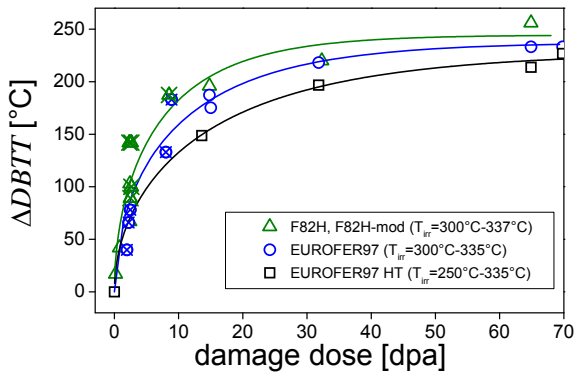
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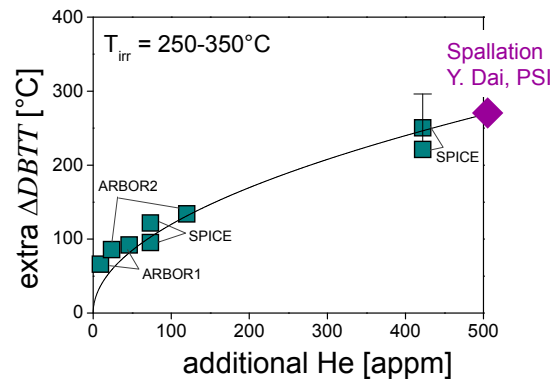
YES

- sensitivity of He to mech. Properties as fracture toughness (Charpy tests)

EUROFER, <10 appm He



EUROFER, 10-500 appm He



- without He saturation of Ductile Brittle Transition Temperature ($DBTT$) for ≥ 50 dpa
- with He additional significant $DBTT$ increase
- ➔ significantly limiting the lower operation temperature

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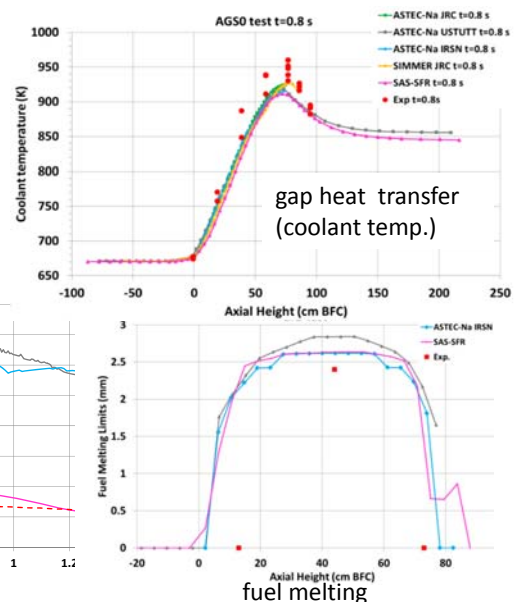
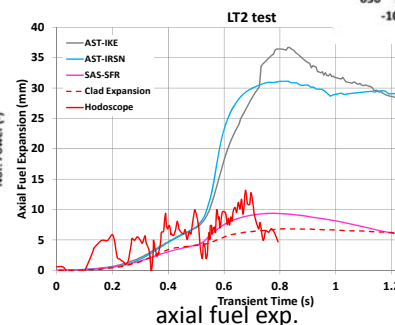
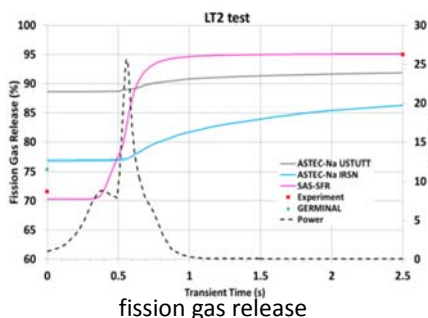
© Gaganidze et al., J. Nucl. Mater. 417 (2011)93-98

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Accidental safety analysis
model improvement

Approach

- identification of modelling deficits
- by code-to-code comparison complemented by experimental data



Some Results

- gap heat transfer model validated
- fission gas model contains many parameters ➔ sensitivity analysis of some parameters
- axial fuel expansion overestimated ➔ visco-plasticity model now in ASTEC-Na V2.0
- ➔ **But major deficit lack of experimental data**

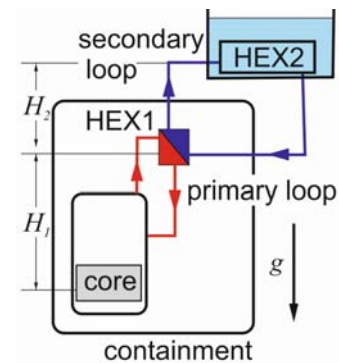


Example-Fast reactors safety aspects

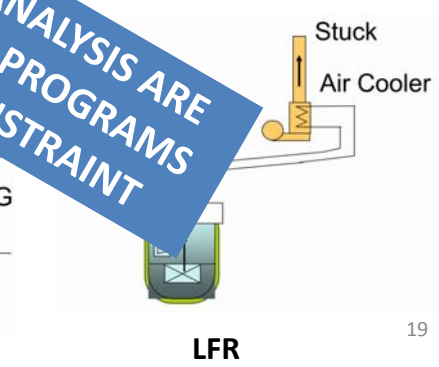
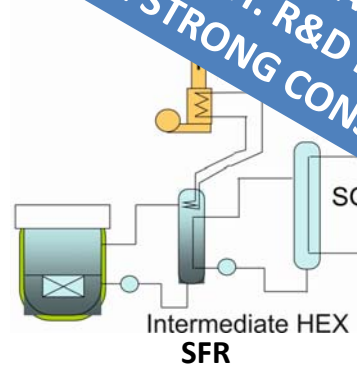
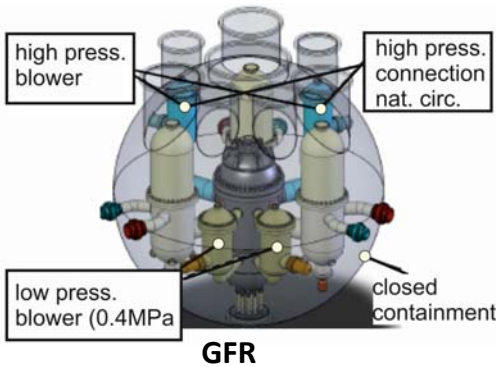


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- each FR type exhibits safety limiting scenarios (worst case)
 - GFR: decay heat removal (DHR) in depressurized conditions.
 - SFR: sodium fires, positive void effect (for unprotected loss of flow/ loss of heat sink), DHR.
 - LFR: degradation core materials, formation Po, seismic stability of containment, DHR.
- Completely different to ... (loss of coolant accident ... initiated accident (RIA))
- Passive DHR strategy ... developments
 - Heat transfer cascade via me ...
 - buoyancy driven
 - accident tolerant design



ALL ENVELOPING SAFETY ANALYSIS ARE PART OF IAEA AND INT. R&D PROGRAMS
 → VALIDATION STRONG CONSTRAINT



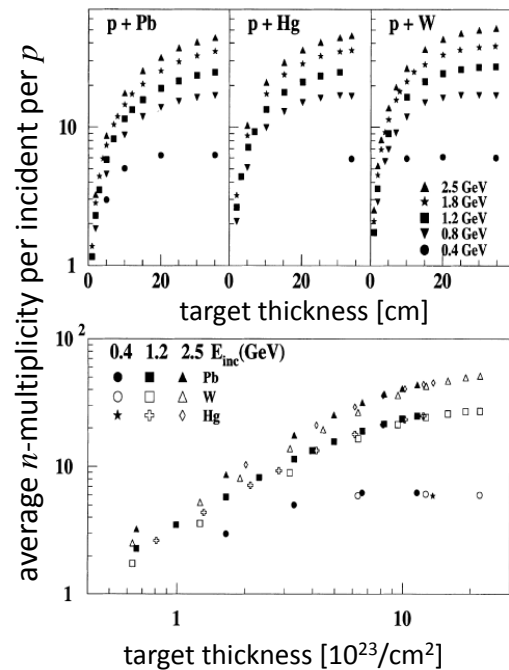
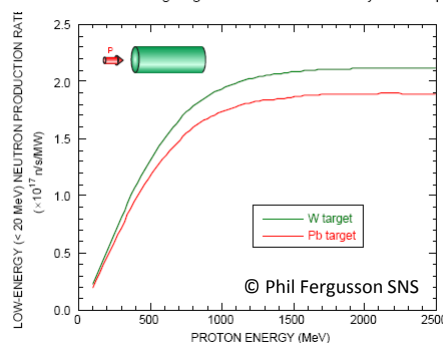
Example-Spallation neutron sources design options



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- Target:** generation of high quantities of neutrons
Means: interaction of matter in a thick target - target material selection
- high current, high energy accelerator
 - internuclear cascade dominant
 - higher amount of neutron production
 - number of n/p depend on target material
 - high Z -materials (Pb, Hg, W)
- Consequences**
- heat deposition in target
 - activation of target (&and coolant)
- How many neutrons can we get ?**
- saturation of generated n/p @ 2.5GeV

(50-cm-diam × 200-cm-long targets bombarded on axis by ~1-GeV protons)



A. Letourneau et al., Nucl. Instr. and Meth. in Phys. Res. B 170 (2000) 299

Target design options:

- homogeneous – coolant spallation source & target (*Hg, Pb, PbBi*)
- heterogeneous – inert coolant + solid target (*He/W*)

ESS- Target Selection exercise

- Option 1:** liquid PbBi gravity (pump support)

✓ despite high power no boil!

✓ simple set-up, low power, no penetration

Labels: proton beam, guide tube, target channel, liquid metal pool, pump, H₂-moderator

Major drawbacks:

- coolant activation
- confinement of spallation products
- complex operation
- validation basis → development risk

Temperature & damage

surface temp. [°C]
525 475 380 280

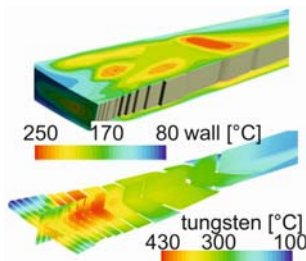
✓ gravity drain (safety), marginal space

Labels: shielding concrete, trolley underneath

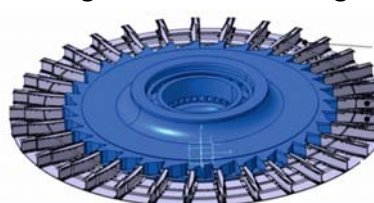
ESS- Target Selection exercise

- Option 2:** rotating helium cooled tungsten target

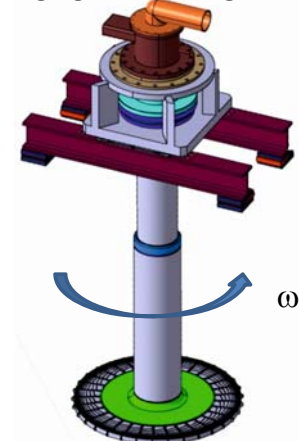
✓ moderate wall & W temperatures



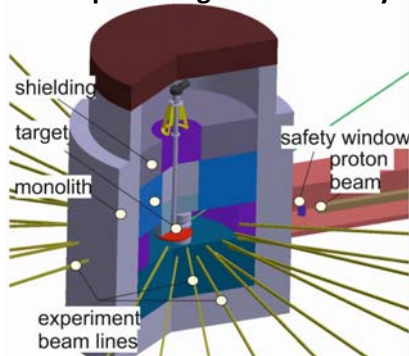
✓ manageable manufacturing



○ challenging wheel design



☹ complex integration & safety demonstration



Major decision criteria:

- Small & separated development risks
- spallation products easy to confine
- nuclear waste foot print
- timely realization**

Summary & Workshop objectives

SUMMARY

- neutronics, thermo-physics and thermo-chemistry of both coolant(s) and its confining structures are strongly interconnected
 - validated data, approved modelling means are of key importance to establish code/standards/procedures and to allow for an
 - integral enveloping safety assessment
-

Hard Objectives

- description of state-of the art knowledge in your individual expert field
- formulation of fundamental physics based limitations, constraints
- identification of knowledge gaps and means/suggestions/proposals to overcome present deficits (experimental, instruments, modeling, data) → R&D needs
- addressing interfaces to adjacent fields and methods for overarching topics such as safety/design

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Workshop objectives & Perspective

Soft Workshop objectives

- interdisciplinary information exchange
- cross-fertilization of different communities
- identification of collaborations (use of infrastructures, common R&D projects, development of codes)

Vision on continuation

- regular meeting of experts as side meeting to community conferences (Fast reactor conference, ISFNT and accelerator applications)
 - Formation of sub-groups necessary ?
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