60 Years

IAEA Atoms for Peace and Development

Karlsruhe Institute of Technology

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

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- ☐ Coolant functions in fast (neutron) spectrum application
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  - Coolant poising/conditioning/handling
  - Coolant confing 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

Environment of fast spectrum applications

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

Coolant functions in fast (neutron) spectrum applications

thermo-physical considerations

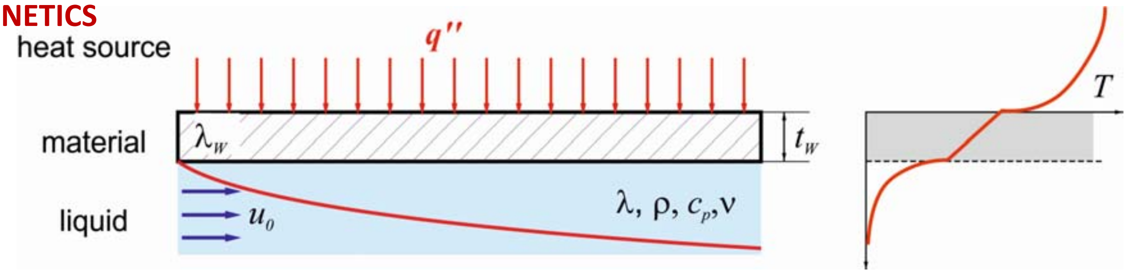
COOLING FUNCTION ➡ FUNDAMENTALS OF KINETICS & ENERGY TRANSFER

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 vicosity ($\rho \cdot \nu$)) ➡ Δp ➡ pressure loss, wall shear stress (erosion, corrosion)

Coolant functions in fast (neutron) spectrum applications

thermo-physical considerations

- ☐ **some typical soolants considered in fast spectrum applications** (thermo-physical data)

	H_2O [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$^3\cdot$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)$\cdot$ 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 !!**

Coolant functions in fast (neutron) spectrum applications

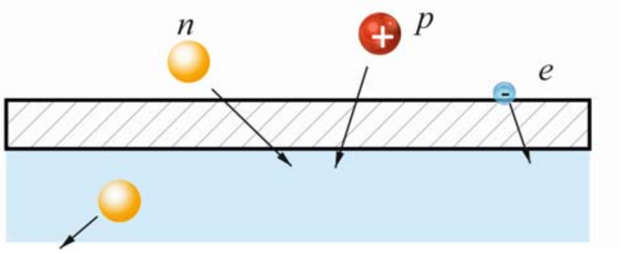
Neutron-physical considerations

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

➡ ……….

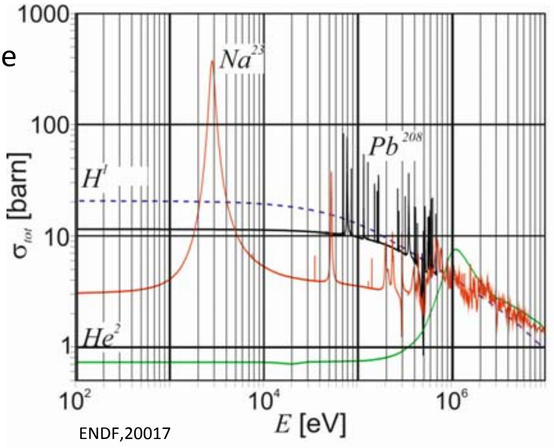
Coolant functions in fast (neutron) spectrum applications
Neutron-physical considerations

	$(\xi \cdot \Sigma_s)$ [cm^{-1}]
Zr	0.00046
Fe	0.0023
Na	0.0027
Pb	0.00013
H_2O	1.36
He	0.00024
C	0.06
O	0.0058

Neutronics

- **Moderation $\xi \cdot \Sigma_s$**
  (logarithmic energy decrement per collision ξ, $\Sigma_s$macroscopic scattering cross-section)
  $$\xi = 1 + \frac{(A-1)^2}{2A}\ln\left(\frac{A-1}{A+1}\right)$$
  - hardly moderation in *Pb* , *He*
  - moderate performance of *Na*
  - design challenges for H_2O
- **Nuclear cross-sections (σ_{tot})**
  - high hydrogen cross section throughout *E*-range
  - Large values for *Pb* and *Pb*-alloys in but no
  - broad band resoncances as *Na*
  - almost no interference using *He*

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



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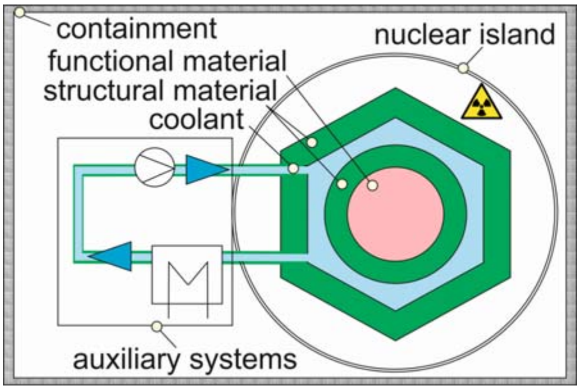
Coolant functions in fast (neutron) spectrum applications
Neutron-physical considerations

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 (∇T, ∇c, ∇p)
  - ➡ corrosion, stress-corrosion cracking, embrittlement enforced/assisted by irradiation.
- Nuclear and conventional island interlinked via coolant

➡ **coolant choice affecting nuclear system architecture.**



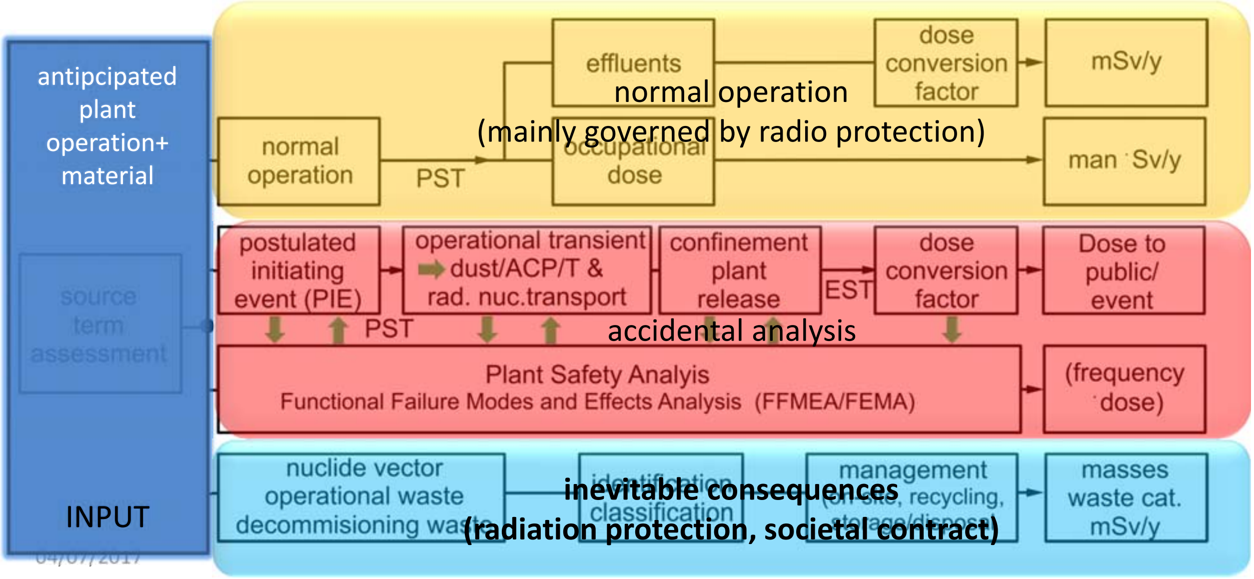
Coolant functions in fast (neutron) spectrum applications

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 Indivudual

Coolant functions in fast (neutron) spectrum applications

Consequences on licensing frame and time scales

Nuclear licensing requires

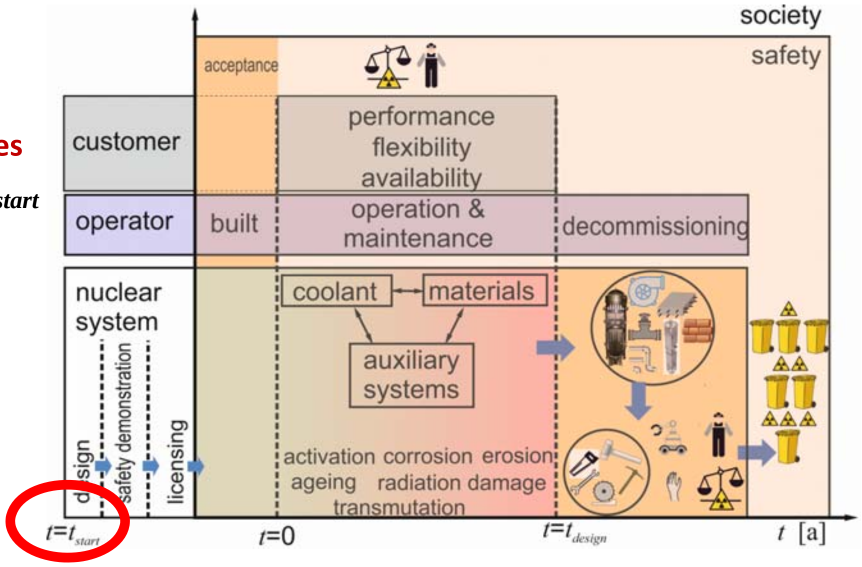
- ☐input at the **begin** of process
- ☐**tracking plant for decades**
- ☐taking responsibility for **centuries**

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 shortcommings



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

Example-Fast reactors

Impact of coolant choice on reactor design –power conversion options

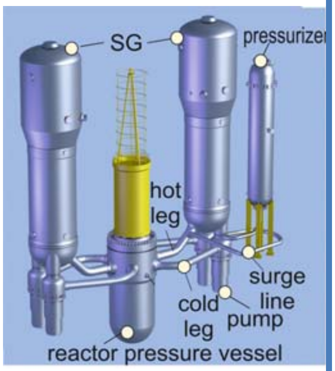
In Gen-IV 4 of 6 reactors fast reactors

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

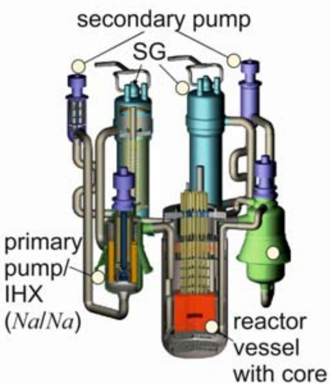
Selection criteria

- ☐ **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



loop type SFR



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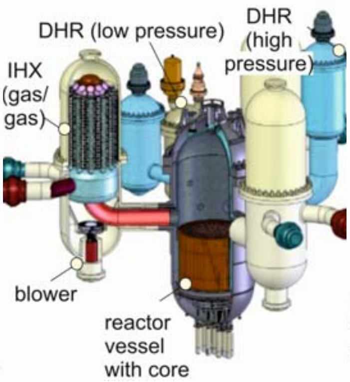
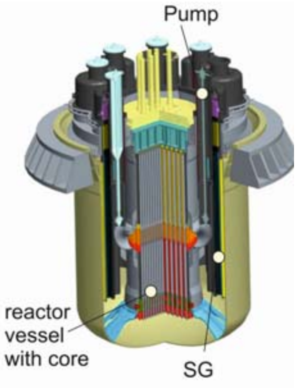


LFR



Example-Fast reactors

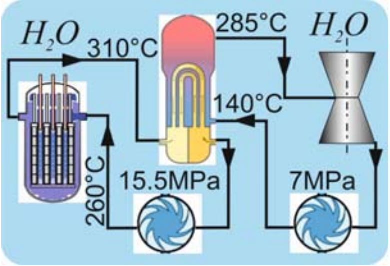
Impact of coolant choice on reactor design –power conversion options

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 ν_d
  - ➡ breeding/transmutation options
  - ➡ high *n*-leakage
- ☐ larger *n*-capture
  - ➡ higher fuel enrichment
- ☐ high volumetric power densities (>100MW/m³)
  - ➡ power management
- ☐ coolant voiding
  - ➡ reactivtiy management

- ☐ high *n*-Energy challenging to
  - ➡ **coolant** (fuel, structure)
  - ➡ **material** (fuel, structure)
  - ➡ **coolant material interaction**

PWR



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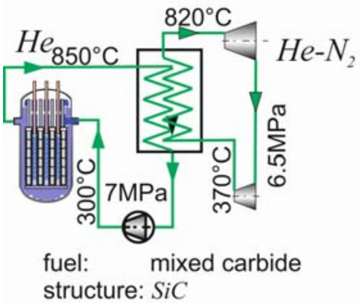
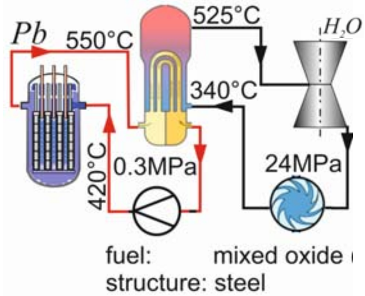
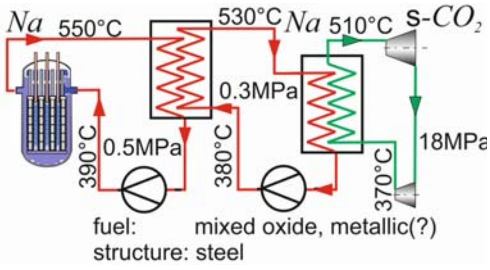


LFR



SFR

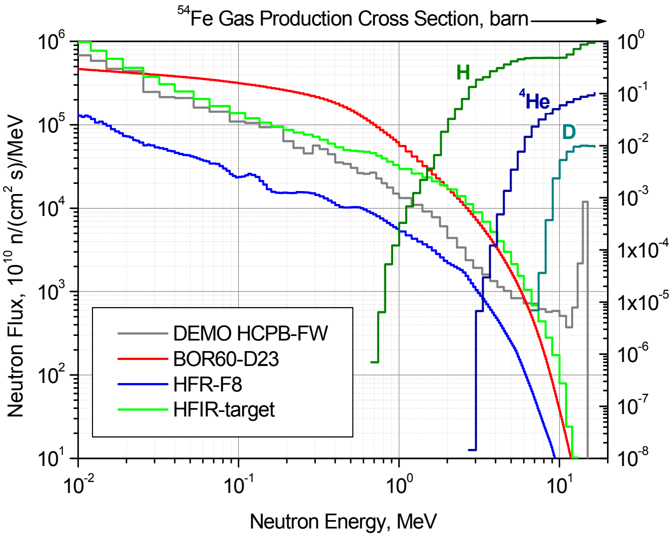


Example-Fast reactors
coolant poisoning/conditioning/handling

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

Coolant activation

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



Transmutation in structures

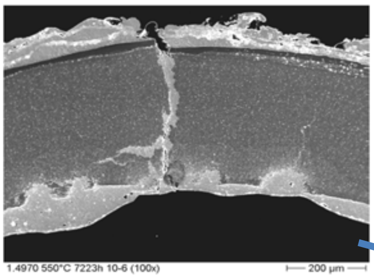
- ❑ n-energies exceeding E_{th}
  - ➡ gas production in structure (fuel)- such as H, D, T, He
- ➡ **2 effects**
  - ❑ **diffusion of gas into coolant**
    - ➡ necessitating diffusion barriers or
    - ➡ partial pressures on sec./ternary side
  - ❑ permanent gas formation in structure (**damage-*He***)

Example-Fast reactors
Coolant poisoning/conditioning/handling

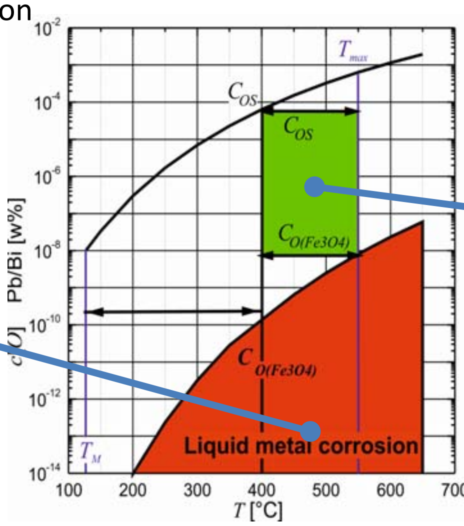
Operational consequences ➡ **permanent** coolant **conditioning** (physico-chemistry)

- ❑ 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 oxigen control to prevent steel corrosion, coolant oxidation ➡ f=(T, t,c_O, $u_{0,}$ dpa)
  - ➡ oxygen sensor development
  - ➡ barrier development
  - ➡ process technology
  - ➡ material validation

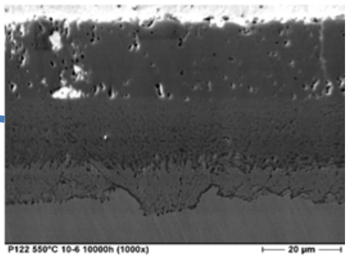
Austenitic steel



- ❑ dissolution of alloying elements (Ni);
- ❑ rate up to 1 µm/h



F/M steel



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

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

Example-Fast reactors
coolant confining structures
and material degradation

- **irradiation causes constraints to material performance.**

Physics

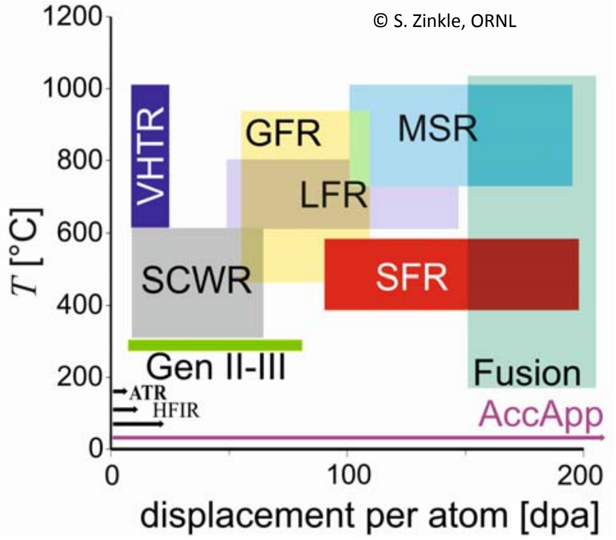
- radiation induced growth
- atom segregation in lattice (diffusion controlled)

➡ radiation induced growth

f =(T, dpa, E, dose rate, σ, 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):

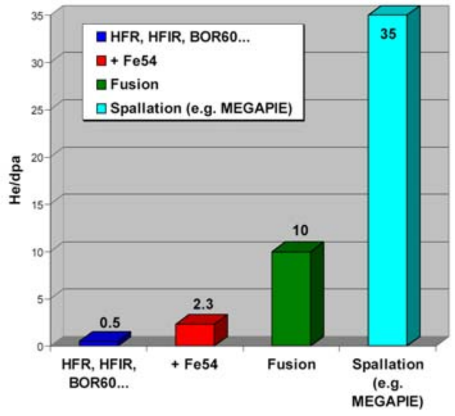
- radiation hardening & embrittlement (<0.4T_M, >0.1 dpa)
- phase instabilities from rad.-induced precipitation (0.3-0.6 T_M, >10 dpa)
- high temp. He embrittlement (>0.5 T_M, >10 dpa)
- vol. swelling from void formation (0.3-0.6 T_M, >10 dpa)
- irradiation creep (<0.45 T_M, >10 dpa)

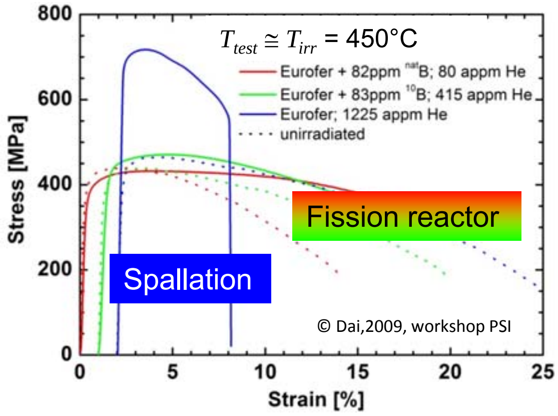
Example-Fast reactors
coolant confining structures
and material degradation

- **Most relevant for radiation damage He/dpa ratio**

➡ **strongly depending on application**

- Helium generated in material





© Dai,2009, workshop PSI

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

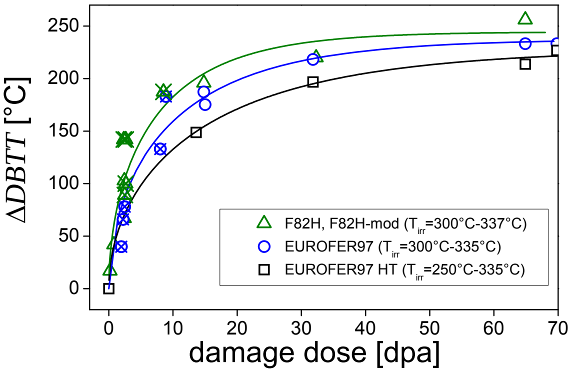
➡ **Does this impact other quantities as well?**

Example-Fast reactors
coolant confining structures and material degradation

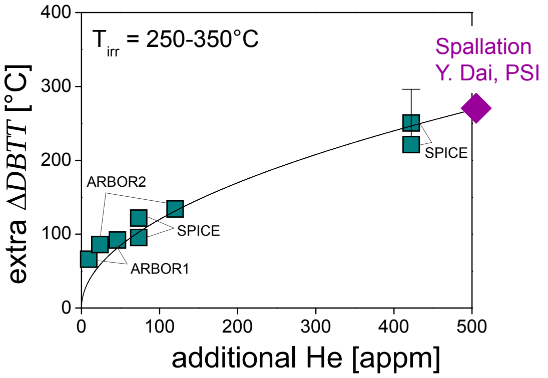
YES

- ❑ 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 ≥ 50dpa
- ❑ with *He* additional significant *DBTT* increase
- ➡ **significantly limiting the lower operation temperature**

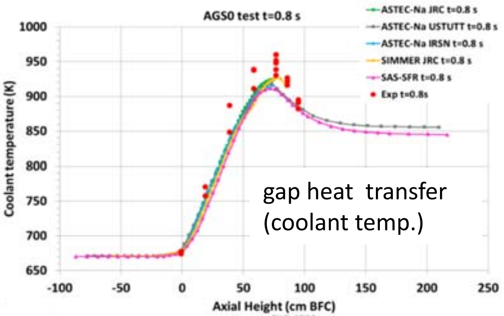
© Gaganidze et al., J. Nucl. Mater. 417 (2011)93-98

Example-Fast reactors
safety aspects

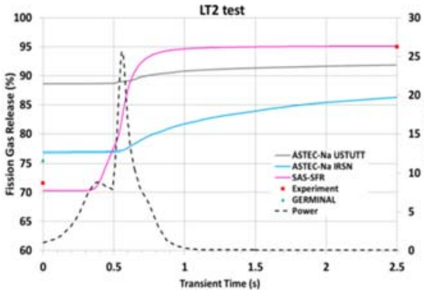
Accidental safety analysis
model improvement

Approach

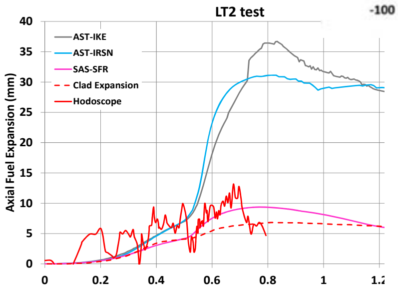
- ❑ identification of modelling deficits
- ❑ by code-to-code comparision complemented by experimental data



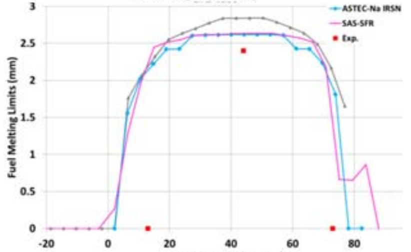
gap heat transfer
(coolant temp.)



fission gas release



axial fuel exp.



fuel melting

Some Results

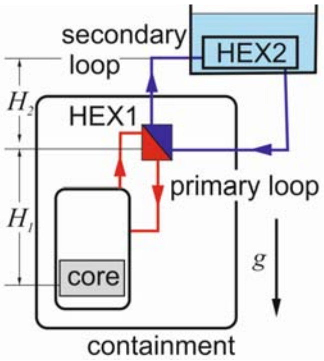
- ❑ gap heat transfer model validated
- ❑ fission gas model contains many parameters ➡ sensitivity analysis of some parameters
- ❑ axial fuel expansion overestimated ➡ visco-plasticity model now in ASTEC-Na V2.0
- ➡ **But major deficit lack of experimental data**

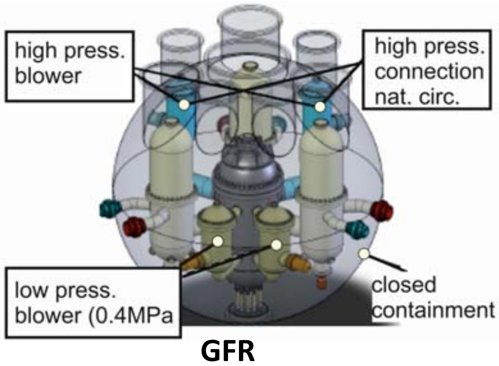
Example-Fast reactors

safety aspects

- ❑ **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 m terials, formation Po,
    seismic stability c ment, DHR.
- ❑ **Completely different to**
  (loss of coolant accident (ated accident (RIA))
- ❑ **Passive DHR strategy velopments**
  General ideas
  - ❑ Heat transfer cascade via m
  - ❑ buoyancy driven
  - ❑ accident tolerant design

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





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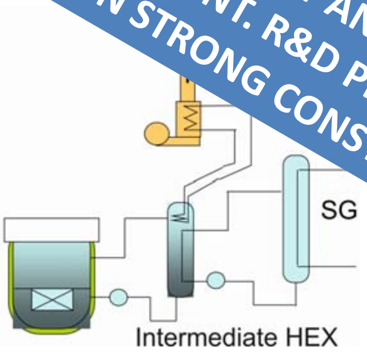

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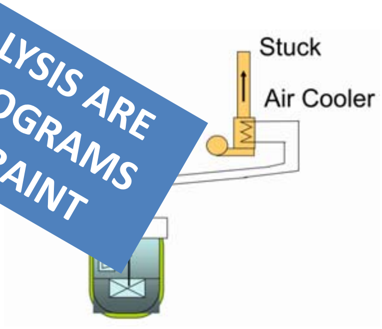


LFR

Example-Spallation neutron sources

design options

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)

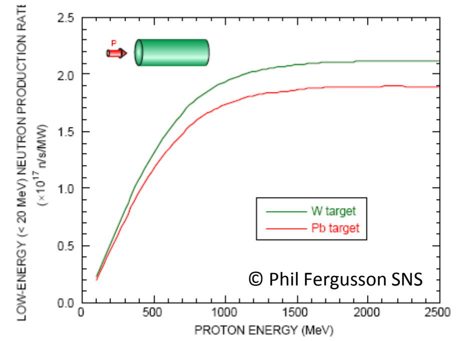
Consequences

- ➡ 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)



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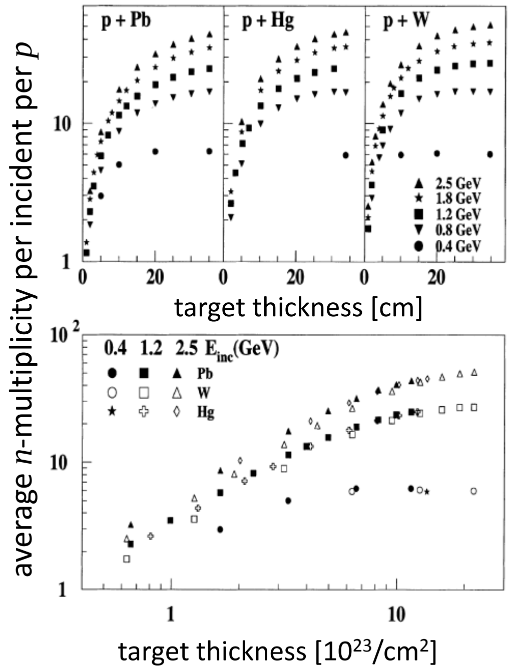


A. Letourneau et al., Nucl. Instr. and Meth. in Phys. Res. B 170 (2000) 299

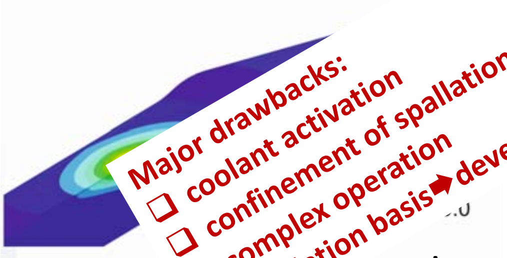
Example-Spallation neutron sources
design options

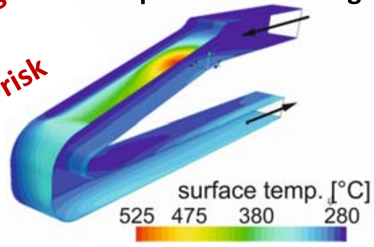
Target design options:

- ☐ 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 boili**
  - **e temperature & damage**

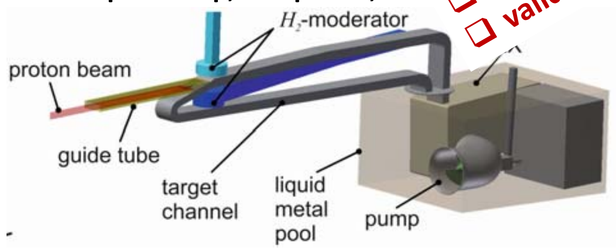




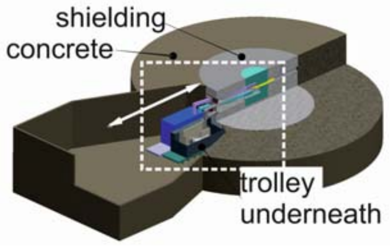
Major drawbacks:

- ☐ **coolant activation**
- ☐ **confinement of spallation products**
- ☐ **complex operation**
- ☐ **validation basis ➡ development risk**

- ✓ **simple set-up, low power, no**
- **enetration**



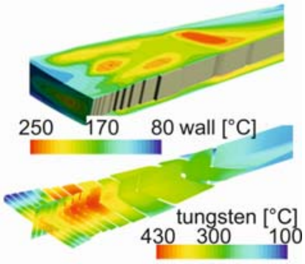
- ✓ **gravity drain (safety), marginal space**



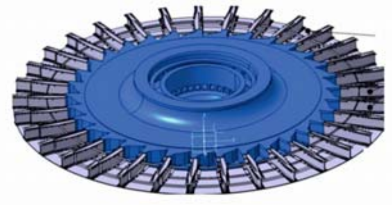
Example-Spallation neutron sources
design options

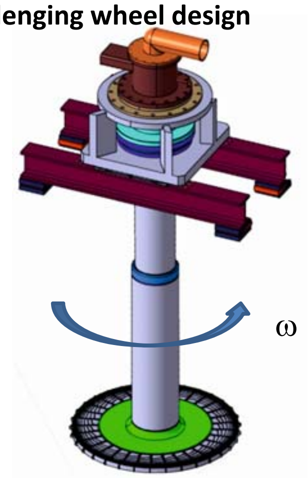
ESS- Target Selection exercise

- ☐ **Option 2:** rotating helium cooled tungsten target
  - ✓ **moderate wall & W temperatures**
  - ○ **challenging wheel design**

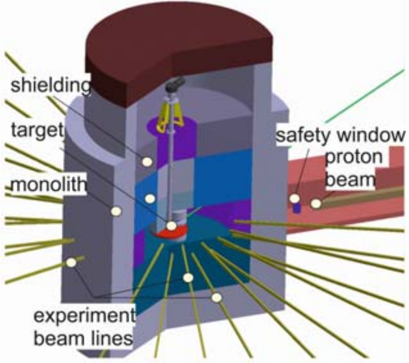


- ✓ **manageable manufacturing**





- 😐 **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

- descpription 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
- adressing 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 necessesary ?

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