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
Content

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

Consequences
1. enlarged coolant/material damage
2. dedicated constructive/operational/handling measures
3. long extensive licensing procedures demanding
   - data bases
   - ageing/fatigue aspects ➔ lifetime management
   - component qualification,
   - code & standards

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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 $\lambda, \lambda_w$
- thermal inertia $(\rho \cdot c_p)$
- temperature threshold
- thermal expansion
- kinematic viscosity $(\rho \cdot \nu)$

- $\nabla T$ ➔ material, fluid limits
- time ➔ operational grace time, removable power
- $\Delta T$ ➔ phase change (safety), removable power, design provisions (auxiliary heating, boiling detection)
- $\Delta \rho$ ➔ passive heat removal capability (safety), pumping power (Balance of Plant)
- $\Delta p$ ➔ pressure loss, wall shear stress (erosion, corrosion)
Coolant functions in fast (neutron) spectrum applications
thermo-physical considerations

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

<table>
<thead>
<tr>
<th></th>
<th>H$_2$O [300°C, 15MPa]</th>
<th>Li [500°C]</th>
<th>Na [500°C]</th>
<th>Hg [20°C]</th>
<th>Pb [500°C]</th>
<th>Pb$^{45}$Bi$^{55}$ [500°C]</th>
<th>Salt NaCl-KCl-MgCl$_2$ [600°C]</th>
<th>He [500°C, 6MPa]</th>
<th>CO$_2$ [500°C 2MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ [kg/m$^3$]</td>
<td>725</td>
<td>475</td>
<td>857</td>
<td>13534</td>
<td>10724</td>
<td>9660</td>
<td>1800</td>
<td>3.7</td>
<td>13.5</td>
</tr>
<tr>
<td>$c_p$ [J/(kgK)]</td>
<td>5475</td>
<td>4169</td>
<td>1262</td>
<td>140</td>
<td>145</td>
<td>145</td>
<td>1004</td>
<td>5190</td>
<td>1170</td>
</tr>
<tr>
<td>$(\rho \cdot c_p)$ [MJ/(m$^3$.K)]</td>
<td>3.97</td>
<td>1.98</td>
<td>1.081</td>
<td>1.895</td>
<td>1.555</td>
<td>1.401</td>
<td>1.807</td>
<td>0.19</td>
<td>0.158</td>
</tr>
<tr>
<td>$\lambda$ [W/(mK)]</td>
<td>0.561</td>
<td>49.7</td>
<td>66.3</td>
<td>8.3</td>
<td>15</td>
<td>11</td>
<td>0.39</td>
<td>0.303</td>
<td>0.056</td>
</tr>
<tr>
<td>$v$ [(m$^2$/s)·$10^{-7}$]</td>
<td>1.2</td>
<td>7.16</td>
<td>2.6</td>
<td>1.1</td>
<td>1.5</td>
<td>1.1</td>
<td>0.138</td>
<td>0.9</td>
<td>0.25</td>
</tr>
<tr>
<td>$T_{melt}$ [°C]</td>
<td>-0.4</td>
<td>180</td>
<td>98</td>
<td>-39</td>
<td>327</td>
<td>126</td>
<td>396</td>
<td>-</td>
<td>-58</td>
</tr>
<tr>
<td>$T_{boiling}$ [°C]</td>
<td>334</td>
<td>1317</td>
<td>883</td>
<td>356</td>
<td>1737</td>
<td>1533</td>
<td>2500</td>
<td>-</td>
<td>-78</td>
</tr>
</tbody>
</table>

- 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

- **Moderation** $\xi \Sigma_s$
  (logarithmic energy decrement per collision $\xi$, $\Sigma_s$ macroscopic scattering cross-section)
  - hardly moderation in $Pb$, $He$
  - moderate performance of $Na$
  - design challenges for $H_2O$

- **Nuclear cross-sections** ($\sigma_{\text{tot}}$)
  - 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
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.
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?)

Anticipated plant operation + material

Source term assessment

Input

PST = Process Source Term, MEI = Most Exposed Individual

PST = Process Source Term, MEI = Most Exposed Individual
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 @** $t_{\text{start}}$
- 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.
### 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**

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**Conventional PWR**

**loop type SFR**

**GFR**

**LFR**

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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 $\sigma_f/\sigma_a$ ratio and more $\nu_d$
  - breeding/transmutation options
- high $n$-leakage
- larger $n$-capture
  - higher fuel enrichment
- high volumetric power densities (>100MW/m$^3$)
  - power management
- coolant voiding
  - reactivity management
- high $n$-Energy challenging to
  - coolant (fuel, structure)
  - material (fuel, structure)
  - coolant material interaction

PWR

GFR

LFR

SFR
Coolant activation

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

<table>
<thead>
<tr>
<th>isotope</th>
<th>formation channel</th>
<th>$T_{1/2}$ [a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Na}$</td>
<td>$^{23}\text{Na}(n,2n)^{22}\text{Na}$</td>
<td>2.6</td>
</tr>
<tr>
<td>$^{24}\text{Na}$</td>
<td>$^{23}\text{Na}(n,g)^{24}\text{Na}$</td>
<td>$1.7\cdot10^{-3}$</td>
</tr>
<tr>
<td>$^{205}\text{Pb}$</td>
<td>$^{204}\text{Pb}(n,g)^{205}\text{Pb}$</td>
<td>$1.5\cdot10^{-7}$</td>
</tr>
<tr>
<td>$^{208}\text{Bi}$</td>
<td>$^{209}\text{Bi}(n,2n)^{208}\text{Bi}$</td>
<td>$3.7\cdot10^{5}$</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>$^{209}\text{Bi}(n,\gamma)^{210}\text{Bi}$</td>
<td>$3.6\cdot10^{6}$</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$^{210}\text{Bi} (\beta)\rightarrow^{210}\text{Po}$</td>
<td>0.38</td>
</tr>
</tbody>
</table>

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 $\Rightarrow$ 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 $\Rightarrow f=(T, t, c_O, u_0, dpa)$
  - oxygen sensor development
  - barrier development
  - process technology
  - material validation

#### Austenitic steel
- dissolution of alloying elements (Ni);
- rate up to 1 $\mu$m/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

\[ f = (T, \text{dpa}, E, \text{dose rate}, \sigma, \text{composition}, \text{He}) \]

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 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)

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Example-Fast reactors coolants confining structures and material degradation

- Most relevant for radiation damage He/dpa ratio
- Strongly depending on application
- Helium generated in material

![Graph showing He/dpa ratio for different reactor types.]

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

- Does this impact other quantities as well?

© Dai, 2009, workshop PSI

$T_{\text{test}} \cong T_{\text{irr}} = 450^\circ \text{C}$
Example-Fast reactors
coolant confining structures
and material degradation

YES

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

**EUROFER, <10 appm $He$**

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

**EUROFER, 10-500 appm $He$**

- $T_{irr} = 250-350^\circ C$
- Spallation
  - Y. Dai, PSI

Example-Fast reactors
coolant confining structures
and material degradation

Technical consequences for material development/qualification
- Safety margin enhancement ➔ larger operable $\Delta T$ for ironbased materials (300°-700°C (?))
- Enhanced irradiation stability and recovery strategies (annealing (??))

Currents Trends
- Stabilization of 9CrWTA$V$ steels by dispersed nanoparticles –ODS (mainly Japan)

Pre-requisites for material qualification for real deployment
- Coordinated common R&D activities by International Agencies (e.g. IAEA, IEA) + strategic
  ➔ accelerated development, cost reduction
- Coordinated “Small Specimen Test Technology” application towards near-term licensing
- Harmonization of test matrixes for reactor application ➔ effective use, cost sharing
- Availability of dedicated, intense neutron sources as indispensable element to generate
  reliable design & safety databases (esp. in view of life-time at high dpa)

Absence of those facilities
- Exceeding to achieve TRLs beyond 5 or even 6 unlikely.
- Design decision on in-pile coolant choice strongly hindered.
IAEA

Accidental safety analysis model improvement

**Approach**
- identification of modelling deficits
- by code-to-code comparision 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

- 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 PWR (loss of coolant accident (LOCA), reactivity-initiated accident (RIA))

- Passive DHR strategy

General ideas

- Heat transfer cascade via media separation
- 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

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

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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 boiling
  - Simple set-up, low power, no confinement penetration

Major drawbacks:
- Coolant activation
- Confinement of spallation products
- Complex operation
- Validation basis development risk

- 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
  - manageable manufacturing

- complex integration & safety demonstration

- challenging wheel design

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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