Generation IV Coolants Quality Control

Summary / Objectives:

The quality of coolant in Fast Neutron Reactors must be controlled due to the potential impact of impurities on the structural material, on the dosimetry and subsequently on the operation. Liquid metals (sodium, lead-bismuth eutectic, pure lead) and gas (He) need to be purified in order to avoid deleterious effects and satisfy several safety requirements. Several purification systems and dedicated instrumentation have been developed for this purpose, taking into account the specific properties of each coolant.

Meet the Presenter:

Dr. Christian Latgé graduated in Chemical Engineering (1979) and earned his PhD from the Institut National Polytechnique in Toulouse (France). His PhD in CEA Cadarache was dedicated to Na chemistry and purification systems. He participated in the start-up and then operation of Superphenix and operational feedback analysis (Phenix, Superphenix and foreign reactors), in the field of chemistry, radiochemistry and technology. He was also involved in design activities in EFR & SMFR. As Head of Service, he coordinated activities dedicated to process studies for decontamination and nuclear waste conditioning in Cadarache. He carried out studies dedicated to tritium systems and hydrogen risk mitigation for the ITER project. As Director of the International Project Megapie, Dr. Latgé led a team dedicated to the development of a Lead-Bismuth Eutectic Spallation target for nuclear waste transmutation. He served as the Head of Sodium School in Cadarache and now teaches at CEA-INSTN and several French Universities. He has been involved in several Educational Sessions organized by the IAEA on Fast Reactors, in Argentina, Mexico and Trieste ITCP and is the CEA representative on the GEN-IV International Forum Education & Training Task Force. He is currently involved in SFR and recently in ASTRID project as expert and he is involved in several international collaborations (Russia, India, Japan, Latvia, EU, IAEA, NEA-OECD….) related to the development of Fast Neutron Reactors.

In the XFR, X means the kind of coolant. SFR is sodium cooled fast reactor and LFR is lead cooled fast reactor. The coolant must be able to extract heat from the reactor efficiently. It is also required to transfer heat efficiently to the energy conversion system. They are also required to ensure the safety structural and operational conditions.

Coolant Functions for the Primary Circuit of XFR

- The coolant(s) must accomplish the following key tasks
  - Extract heat from the core: high specific heat and thermal conductivity ensure good extraction
  - Transfer heat to an energy conversion system (steam generator or exchanger + turbine) or to a system which directly uses the heat: heavy oil extraction (oil shales), thermochemical production of hydrogen, desalination of sea water
  - Assure safety by providing the system with a degree of thermal inertia
- In a Fast Neutron Reactor, the coolant must NOT
  - Significantly slow neutrons
  - Activate under flux, producing compounds which create unacceptable dosimetry
  - Change the behavior of structural materials
  - Induce unacceptable safety conditions
  - Induce insurmountable operating problems
  - Lead to wastes which can't be processed during operation or dismanting

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Impurities in the coolant may adversely affect the operation of SFR and LFR. It can cause corrosion, reduction of heat transfer coefficient and formation of an obstruction in a narrow space.

Why is it necessary to control quality and to purify the coolant?

- Primary coolant of XFR:
  - [O] is a key parameter of corrosion
    - For SFR→ contamination→dosimetry → necessity to decontaminate (handling, repair, ISI,..): [O]<3ppm
    - For HLM-FR (or ADS)→ necessity to master dosimetry and to eliminate corrosion particles (filtering)
  - [O] well mastered can help to maintain oxide layer stable (protection against hard corrosion in heavy liquid metals HLM). It also allows enhancement of tribology.
  - [O] can induce precipitation of coolant oxide : issue for HLM: PbO particles due to very low dissolution rate; in case of very large O ingress, it can modify the composition of binary alloys ie Pb-Bi... (it is not a problem for Na),
- For Intermediate circuits of SFR (Na) :
  - [H] has to be maintained as low as achievable in order to detect as soon as possible a water ingress in Na (Na-H_2O reaction generates H_2): [H] <0.1 ppm
  - In steady-state operation, aqueous corrosion in SGU produces Fe_3O_4 and H: H diffuses towards intermediate Na.
  - Moreover, Na purification allows to minimize tritium release. (Nota: Tritium release is a common issue for all nuclear systems, including HLM cooled FRs
- For all the circuits :
  - Control plugging hazards in narrow gaps, tubing, openings, seizing of the rotating parts, reduction of heat transfer coefficient in IHX (Intermediate Heat Exchanger)...

→ to limit the plugging hazard, necessity to maintain [O] < [O]* and [H] < [H]* at the coldest point of the circuits, for all operating conditions ; value recommended in SFRs: Tsat < Tcp - 30°C

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The concentration of impurities such as oxygen and hydrogen that can be dissolved depends on the temperature of the coolant sodium in the case of SFR.

O & H Solubilities in Liquid Na

Wittingham solubility law

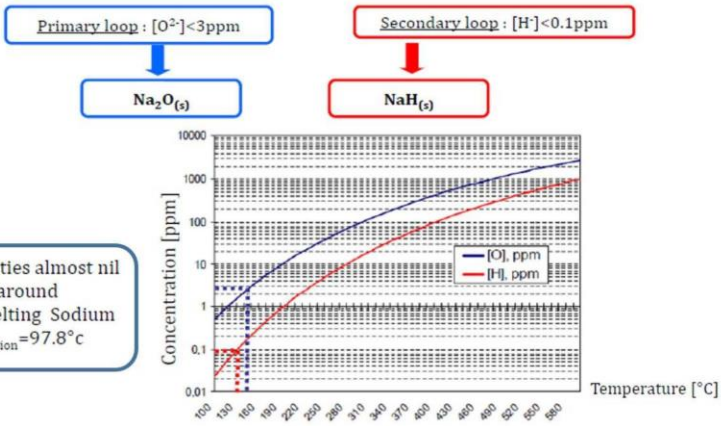
$$\log_{10}[H(ppm)] = 6.467 - \frac{3023}{T(K)}$$

Noden solubility law

$$\log_{10}[O(ppm)] = 6.250 - \frac{2444.5}{T(K)}$$

Na can be purified by cooling, leading to crystallization of O and H as Na_2O and NaH in a "cold trap"

Solubilities almost nil around the melting Sodium T_{fusion}=97.8°c



➔ O control: no necessity to keep a minimum value to protect structures (coating)
No risk of Na_2O precipitation in Na bulk)
➔ Ternary oxydes ($Na_xM_yO_z$ limited amount, thermodynamic stability depends on T, [O])

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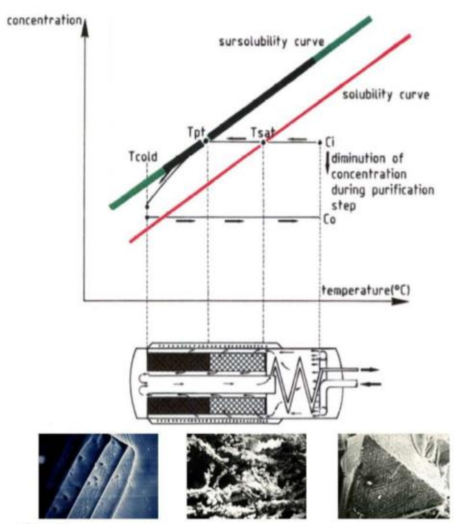
The principle of purification in a cold trap is explained. Sodium can be purified by cooling, leading to crystallization of O and H as Na_2O and NaH in a “cold trap”. The cooled sodium is then heated up again for operation.

Cold Trap Principle



C. Latgé
« Sodium quality control; French developments from Rapsodie to EFR ».
Conférence FR09 Kyoto Décembre 2009

Crystallization kinetics, given for one impurity O or H,]:
in [kgNa_2O/s] or [kgNaH/s]

$$r_{jX}(T,t) = k_{oX}\exp(-\frac{E_X}{RT})\,A_{jX}(t)\left[\frac{(C-C^*)}{1.10^{-6}\,\rho_{Na}}\right]^{n_x} = Ko_X\,A_{jX}(t)[\Delta C]^{n_x}$$

In this equation:
Index X refers to Nucleation (N) or growth (G)
Index j refers to the location on wire mesh packing (p) or cold walls (w).
k0 is the rate constant (kg/(s.ppmnx.m²)),
E is the activation energy (J/mol),
R is the Boltzmann constant (J/(mol.K)).
A is the crystallization surface of reference (m²)
(wire or walls for nucleation, nuclei and crystals for growth).
nX is the order of the crystallization process.
C*(kg/m³) is the saturation concentration (from solubility law.)
ρNa is the sodium density in (kg/m³)
(C-C*) is the supersaturation at temperature T(K).

Phenomena	Nucleation (N)		Growth (G)	
Impurity	Na_2O	NaH	Na_2O	NaH
E (kg/mol)	-60	-450	-45	-43.6
n	5	10	1	2

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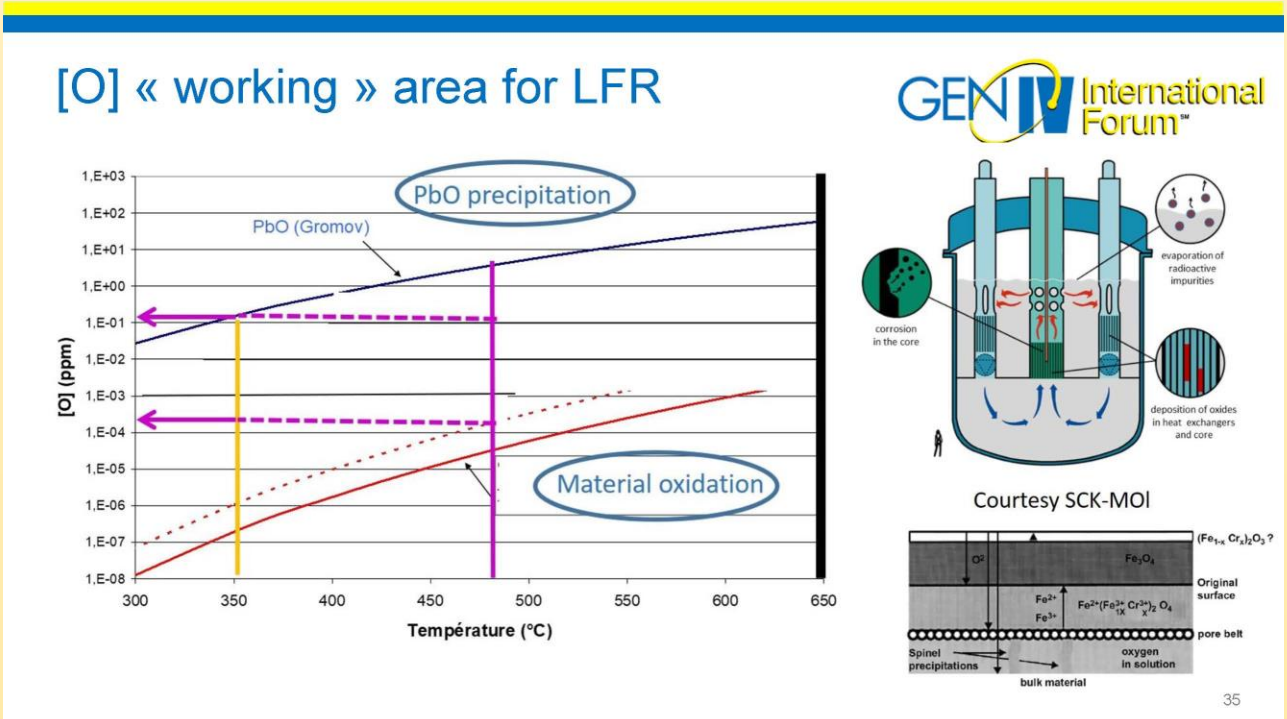
In the case of LFR, if the working area of the coolant is not properly maintained, it will cause corrosion and oxide deposition, which will damage the reactor.



The method of removing impurities in cold traps and filters is being carefully investigated because it is different from the case of sodium. Examples of recent research results are given, and these results can be used to design efficient purification devices.