Sodium coolant: chemistry & quality control, In service on-line monitoring

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Why is it necessary to purify Na?

Two main impurities : O and H, even if other impurities (radionuclides) can be considered with other specific purification systems.

Primary Na :

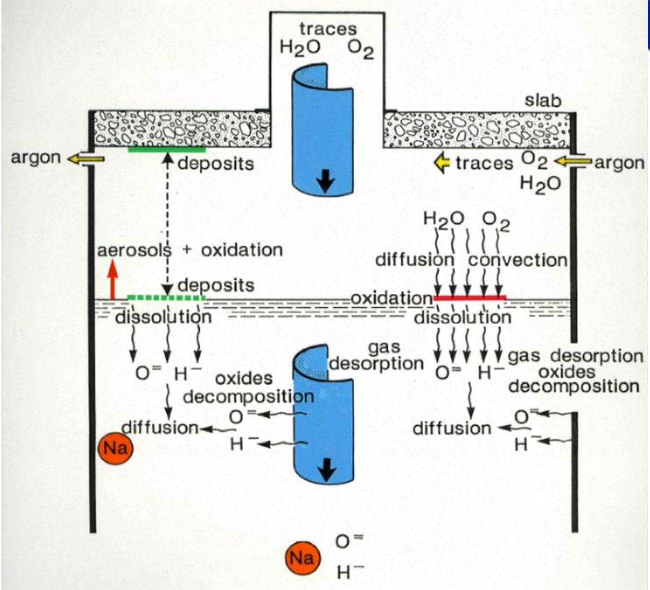
- [O] is a key parameter of corrosion → contamination: production of ACP's
  - Consequences on dosimetry → necessity to decontaminate (handling, repair, ISI,..)
- Cs dissolved in Na due to fuel clad rupture (+ noble gases)
- Tritium from ternary fissions Pu, B_4C

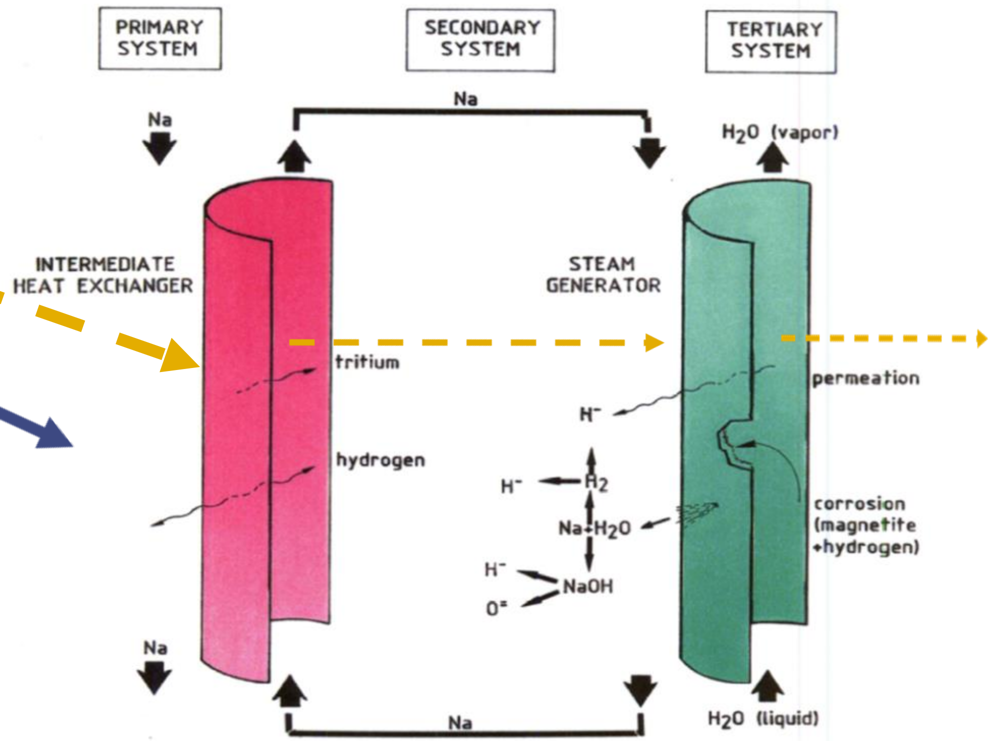
Intermediate Na :

- [H] has to be maintained as low as achievable in order to detect as soon as possible a water ingresss in Na.
- Moreover, Na purification allows to minimize tritium release.

For all the circuits :

- Control the risks of plugging, seizing of the rotating parts, reduction of thermal transfer coefficient…





Main environmental effects

Main parameters:

-neutron flux

-temperature T, T gradients, T cycling, T instabilities & drifts

-Na chemistry (O, N, C, H, H_2O...)

-life duration (requirement: up to 60 years)

-local Na velocities and pressures …

Involved phenomena:

➔ **On structural materials:**

-generalized corrosion and mass transfer deposition

-embrittlement

-desquamation

-Activation....

➔ **On coolant:**

-activation of coolant (^{22}Na, ^{24}Na)

-Na contamination : activated corrosion products, fission products (cesium, tritium…), fuel (open pin rupture)

-introduction of particles ($NaCrO_2$) in Na,….

➔**On cover gas:**

- contamination

Activated corrosion products in Na

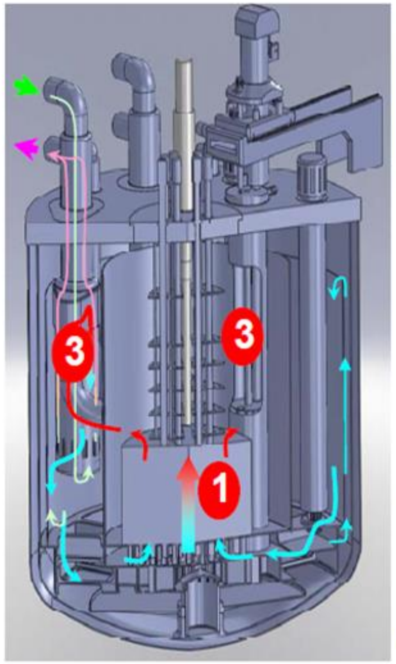
Mass transfer (Fe, Ni, Cr, …)

Is due to solubility difference between hot parts and cold parts of species in the sodium

→ Steel solution in hot regions (bulk corrosion)

→ Precipitation in cold regions (bulk deposition)

Radioactive corrosion product transfer (^{54}Mn, ^{60}Co, ^{58}Co, …)



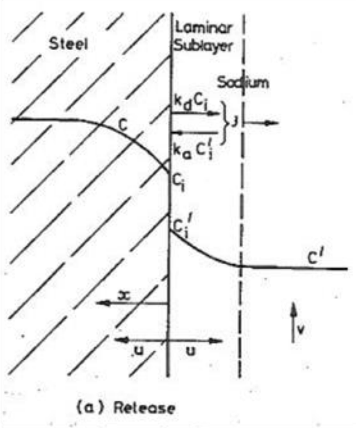
1) Release from the activated cladding

- Bulk corrosion of cladding steel
- Preferential release of highly soluble elements

2) Transfer in the flowing sodium
(parameters : T, velocity, [O])

3) Contamination of out-of-flux surfaces (IHX, primary pumps, …)

- Diffusion in the steel
- Precipitation on cold surfaces



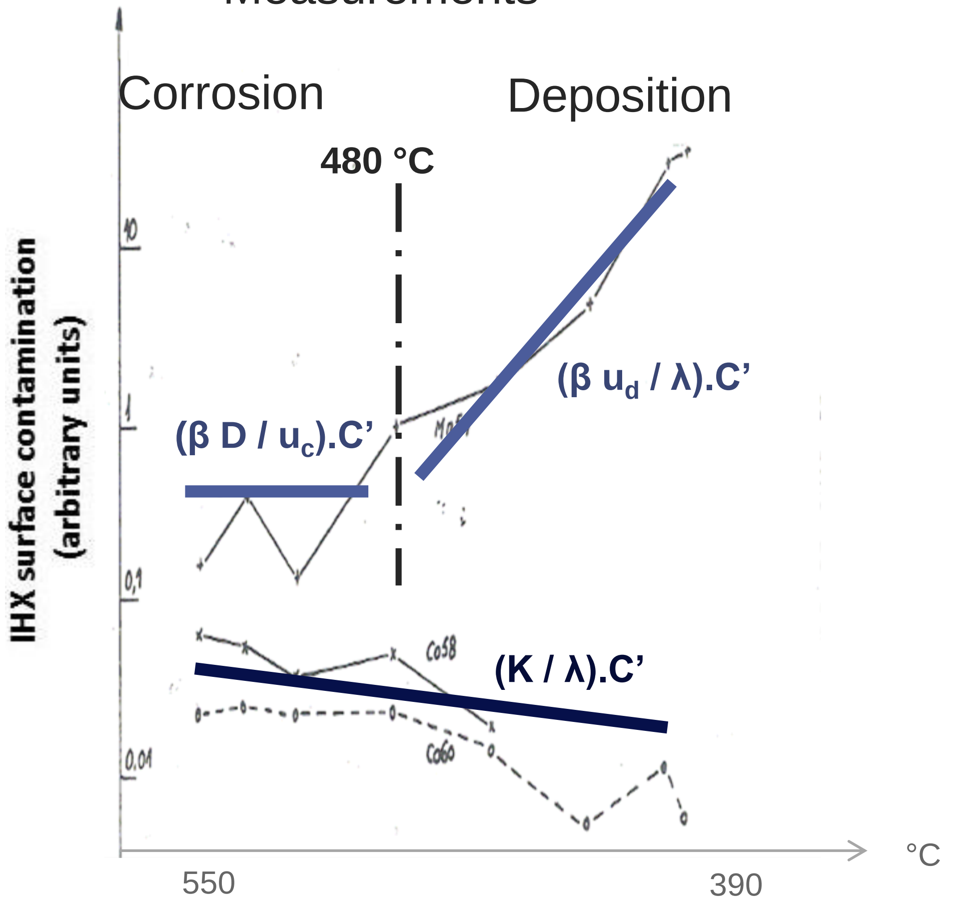
Industrial issues of contamination

- Personnel exposure to radiation
- Plant design
- Waste management
- Decomissionning

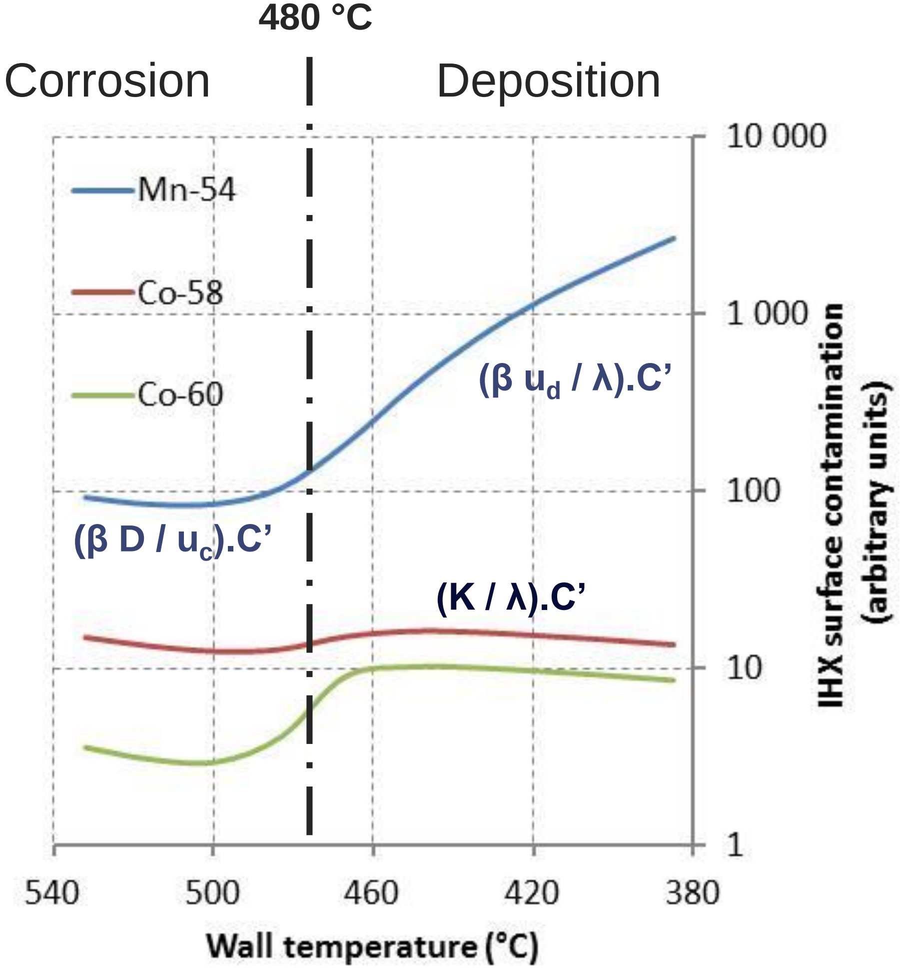
L. Brissonneau, "New considerations on the kinetics of mass transfer in sodium fast reactors: an attempt to consider irradiation effects and low temperature corrosion", Journal of Nuclear Materials 423 (2012) 67-78

Contamination profiles on PHENIX IHX (1st OSCAR-Na validation)

Measurements



OSCAR-Na calculation



Global contamination as well as contamination profiles on PHENIX IHX are correctly simulated

J.-B. Génin et all *"OSCAR-Na V1.3: a new code for simulating corrosion product contamination in SFR reactors"* Conf. IAEA FR13, Paris March 2013

Hydrogen & tritium transfer from SGU

Kutim code - Distribution of hydrogen and tritium in the different media of the reactor :

governs tritium activities in liquid and gaseous releases, as well as tritium activities build-up in units such as the purification units.

Main objectives of the code :

Assess tritium releases to the environment (gaseous and aqueous)

- at the design stage

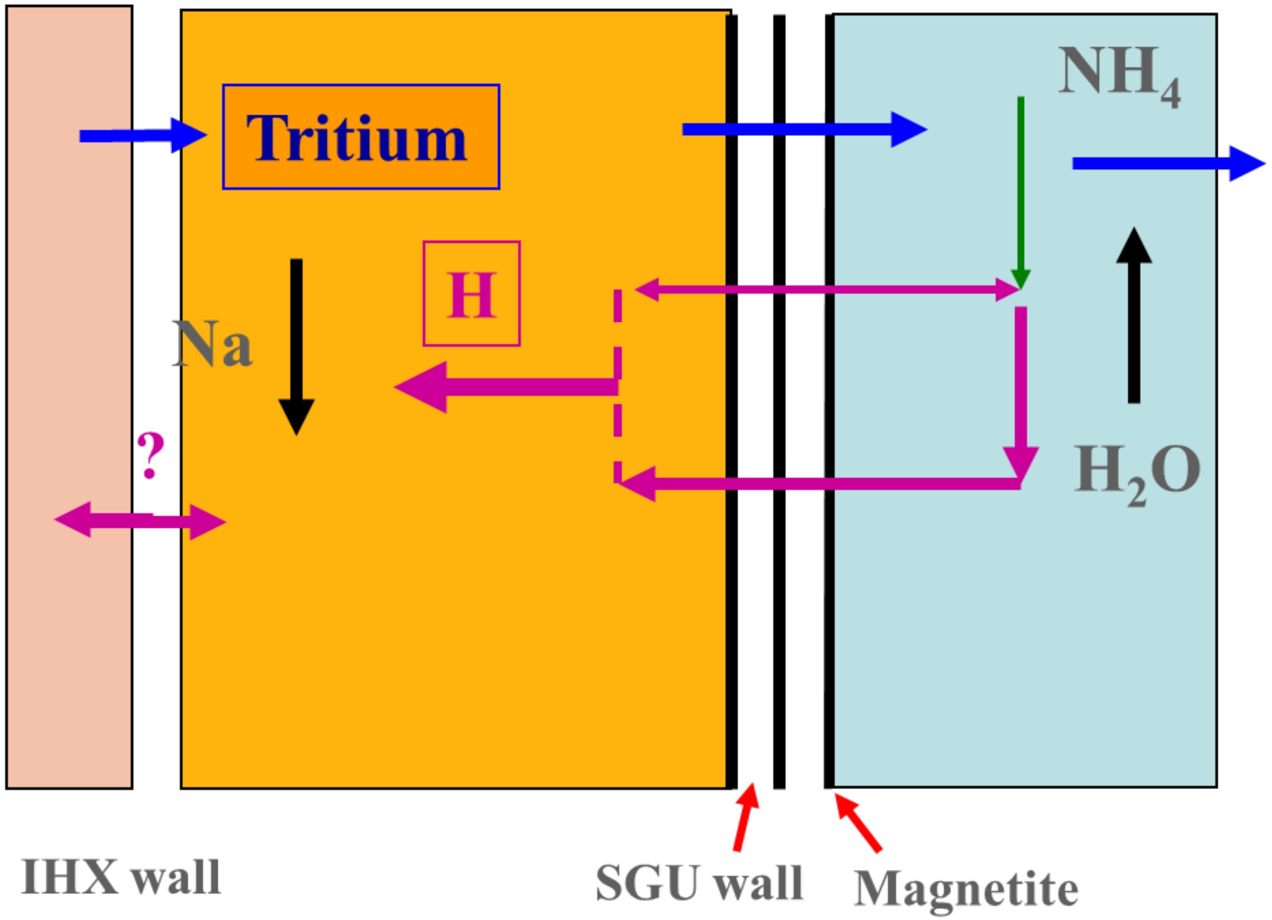
- at the operating stage

guarantee that they are below the authorised thresholds

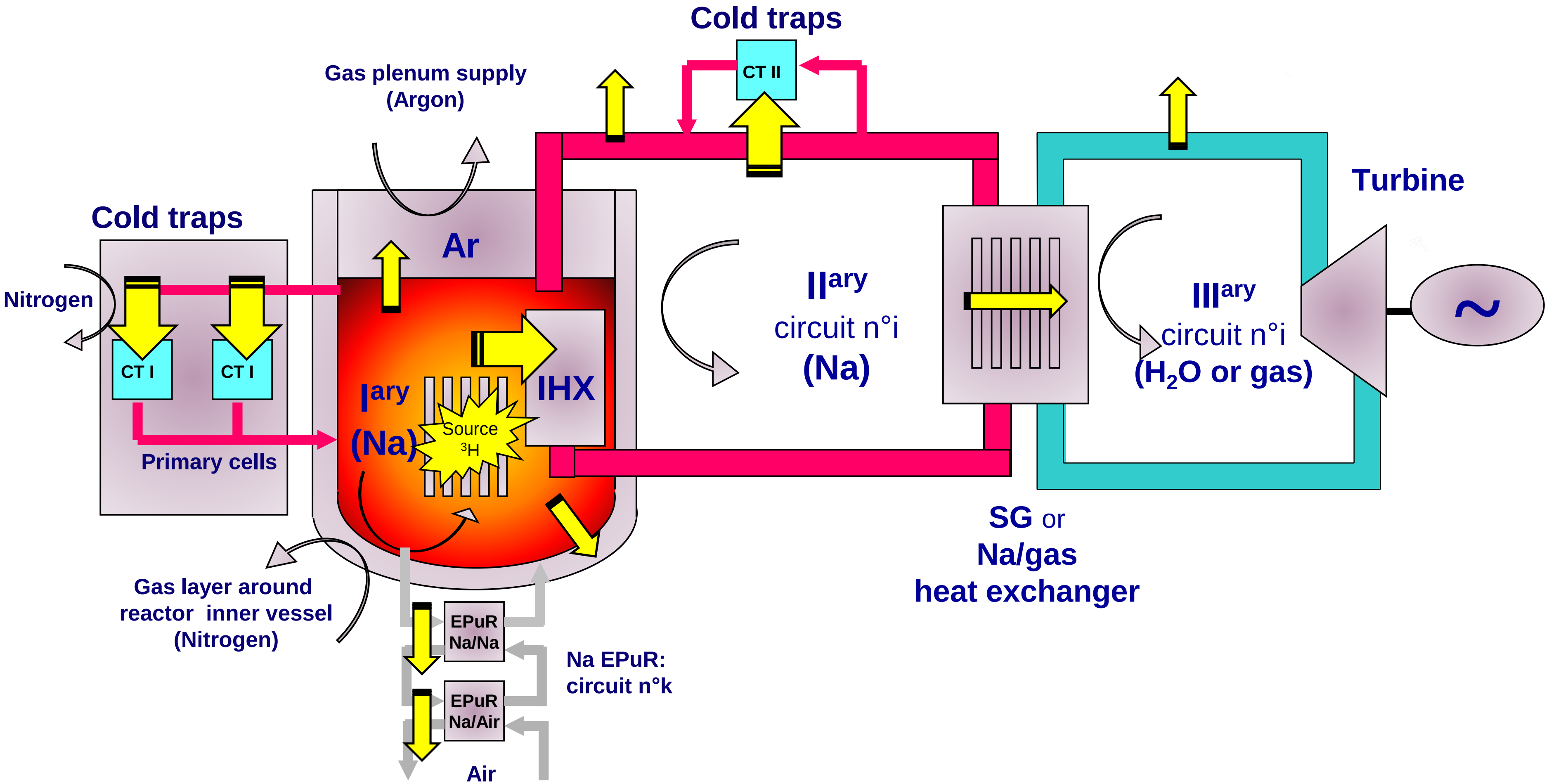
Assess tritium activities in the different media (Na, steel,…)

Tritium build-up in purification units

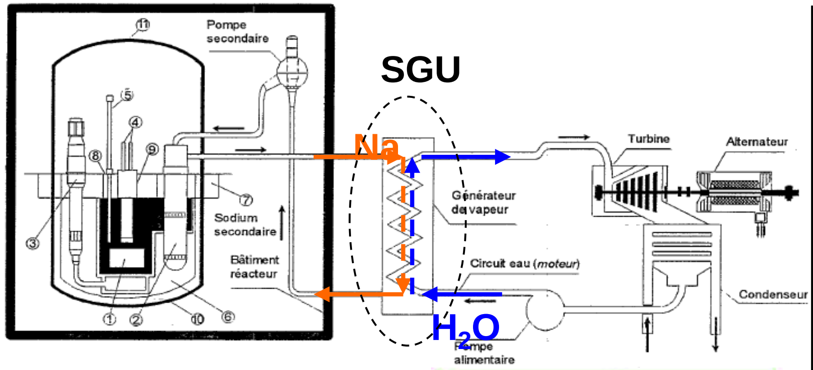
Similar code in Japan: TTT

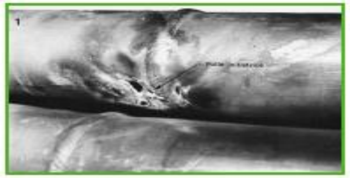


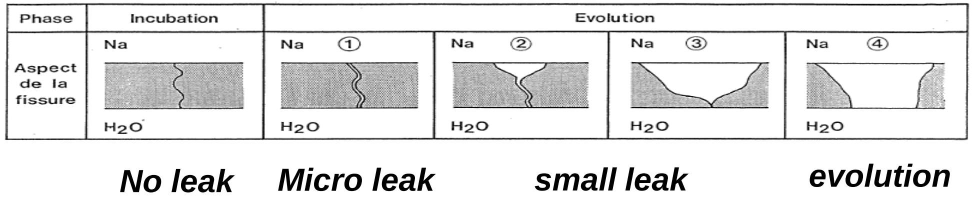
Tritium distribution in SFR



Sodium-water interaction in Steam Generator Unit







ORIGINS : Normal operation of steam generator induces damage of heat exchange tubes

tube corrosion : mainly in welding zones, inducing leaks due to cracking

thermal chocks : when under-saturated water is injected at super heater inlet (Phenix), inducing thermal fatigue,when fluctuation of heat exchange conditions

✓ *impossible tube expansion*: buckling, inducing differential expansion with envelope

✓ *tube bundle vibrations* : hydraulic effect of sodium flow, inducing tube wear

Na-H2O : a violent and exothermal chemical reaction

Main reaction

$Na + H_2O \rightarrow NaOH + ½ H_2$ + 162 kJ/water mole *(at 500 ° C)*

Complete, quasi-instantaneous and non-reversible reaction

Many secondary reactions

2Na + NaOH ←2 1→ [O2-]Na + [H-]Na ↔ Na2O + NaH

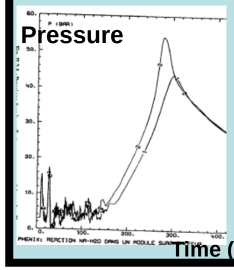
Equilibrium reaction depending on sodium temperature and hydrogen dissolved and hydrogen partial pressure equilibrium

Above about 300 ° C, and with sodium in excess,

hydroxide is decomposed in sodium oxide and hydride (reaction → 1)

Above 410 ° C, reaction (→2) occurs only if PH2 reach Pequilibrium in cover gas; The experimental conditions doesn't satisfy this condition; Thus the decomposition of NaOH is total.

Reaction rates depend on temperature



Temperature

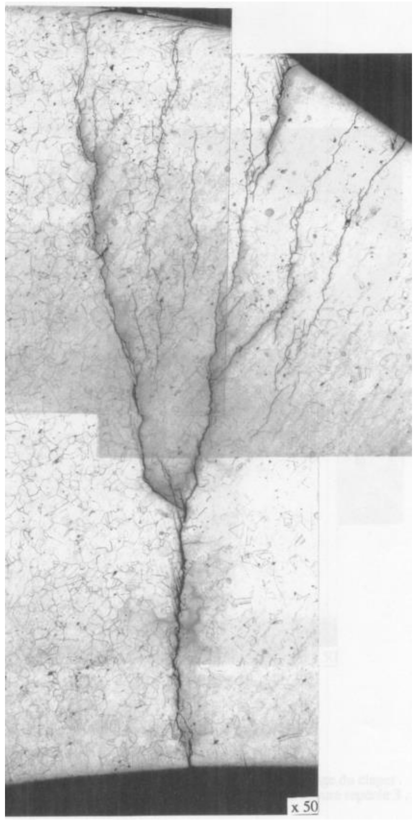
Effects: chemical,

mechanical,

thermal

Time (s)

Stress corrosion cracking after repair



Phénix : support de palier

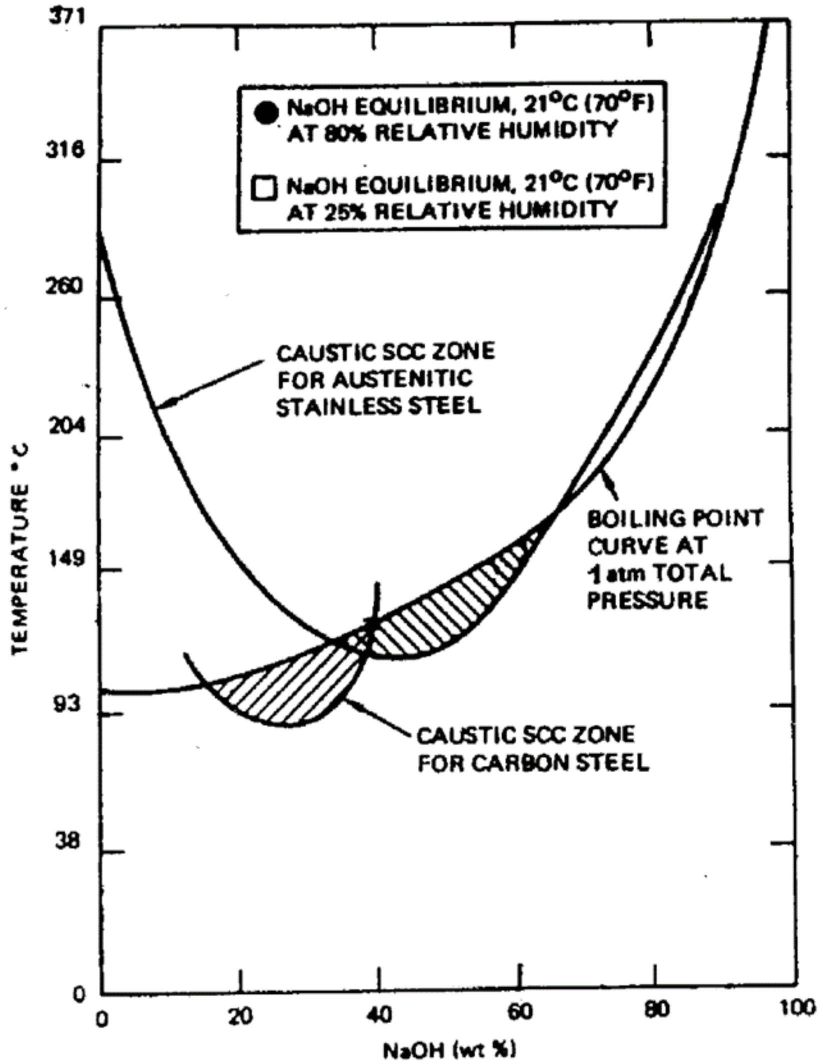
de guidage du clapet

- **Very localized corrosion with small amount of aqueous NaOH**
- **Corrosion Process characterized by transgranular cracks (austenitic steels)**

(Can be intergranular under low stresses)

- **Very fast phenomena**

→ Dedicated procedure to avoid this event

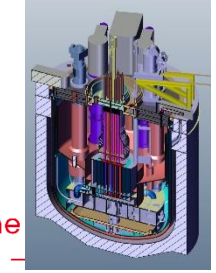


SFRs in France

Rapsodie
*(1967-**1982**)*
24 → 40 MWth
66 tNa

Phénix
*(1973-**2009**)*
250 MWe
1500 tNa

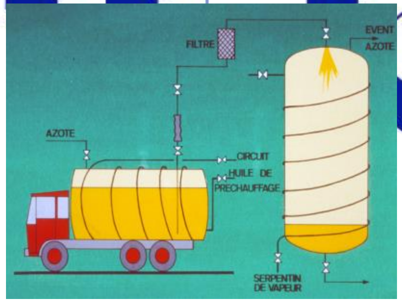
Superphénix
*(1985-**1997**)*
1200 MWe
5500 tNa



Astrid
*(2009-**2019**)*
600 MWe
then
Start-ups:
HEXANA
OTRERA

Na supply

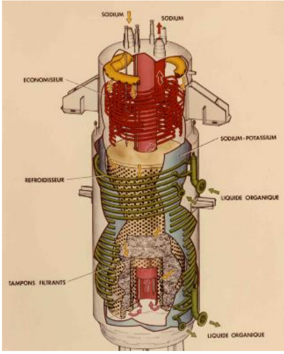
O, H
Impurities in Na

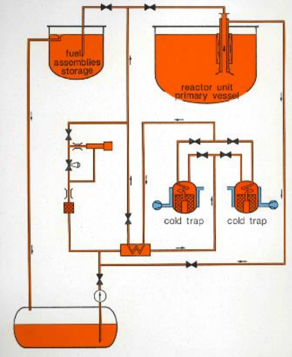


Process profd of Na Filtering

Reactor filling

O, H from structural material

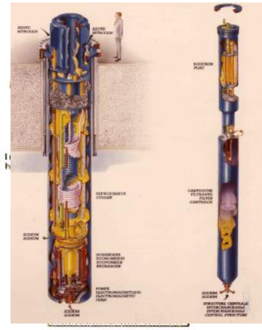


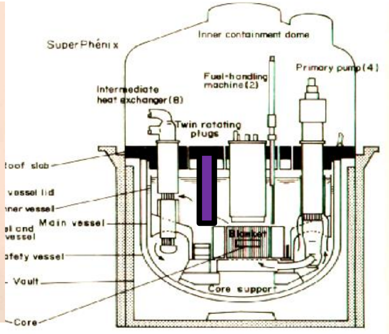


Start-up purification (cold trapping)

Continuous pollutions

H from SGU corrosion
O from covergas,
O, H from structural material
Activated corrosion poducts

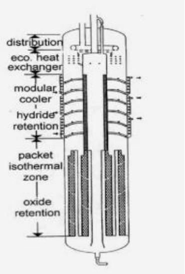


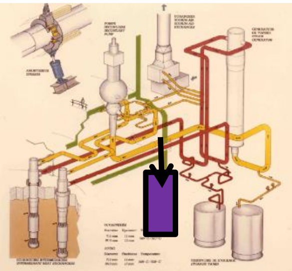


Steady-state purification
Or purification campaign
(cold trapping)

Incidental Pollutions

Na-H_2O reaction
Air ingress…





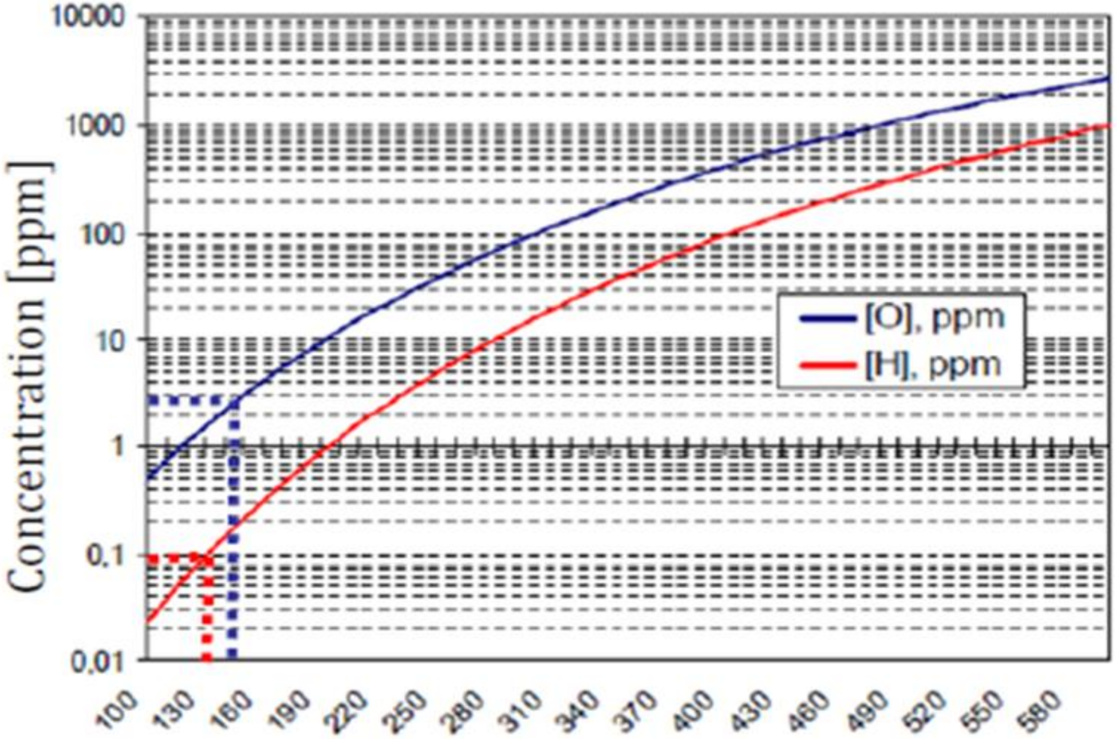
Steady-state purification
Or Purification campaign
(cold trapping)

O & H solubilities in liquid Na

Primary loop : $[O^{2-}]<3ppm$ → $Na_2O_{(s)}$

Secondary loop : $[H^-]<0.1ppm$ → $NaH_{(s)}$

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



Purification with a cold trap

•Na is first cooled thanks to an Integrated Heat Exchanger (« Exchanger Economizer »): T reaches a value close to Tsat

•Then Na goes through a cooler: temperature T reaches a value Tcp lower than Tsat.

•Crystals are produced (nucleation + growth) on cold walls or meshed packing. Nucleation occurs when T< Tpt.

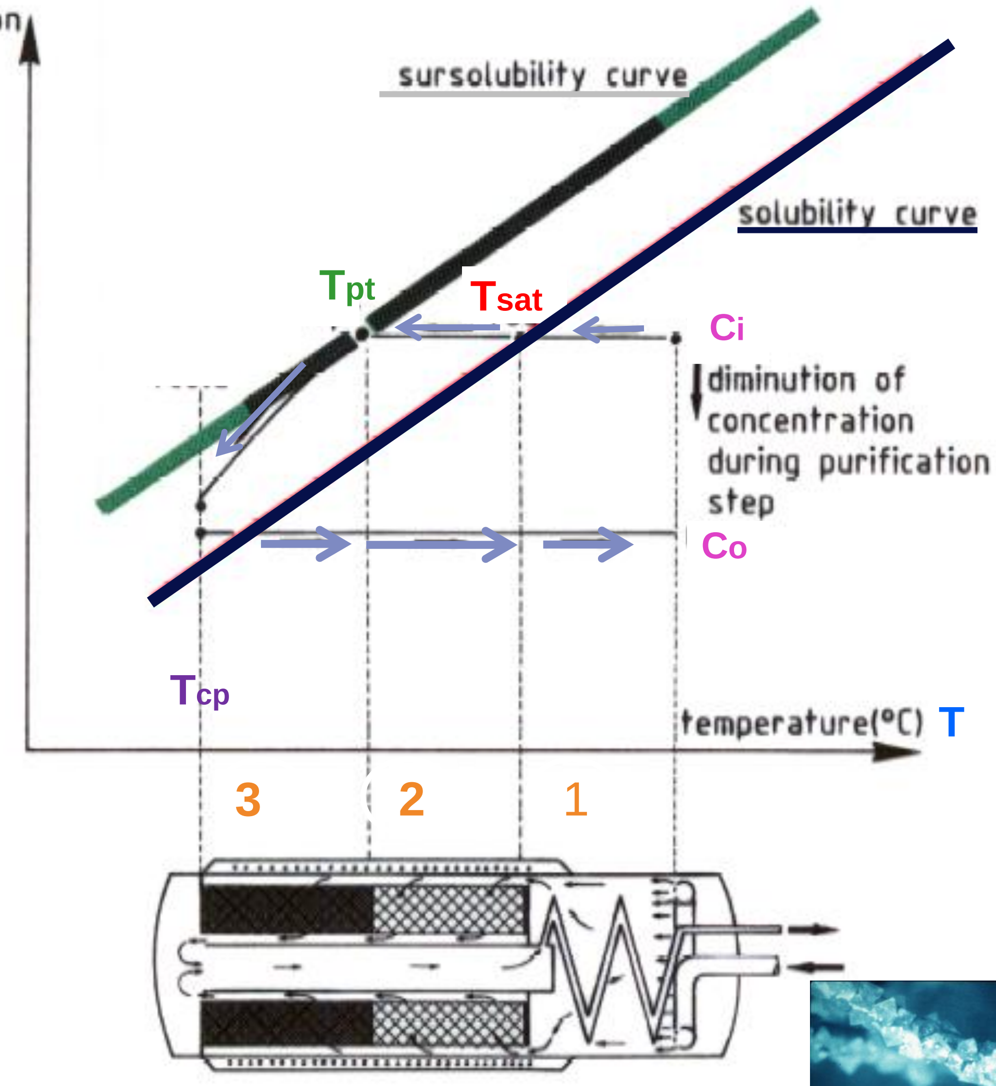
• The Na flow is then heated, thanks to Integrated Heat Exchanger.

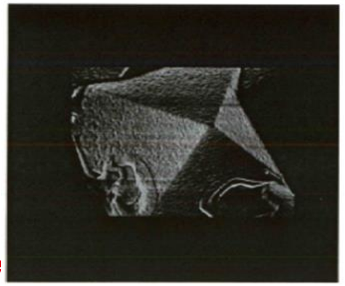
➔ Tcp: Tcold point

➔ Tsat: Tsaturation

➔ Tpt: Tplugging temperature

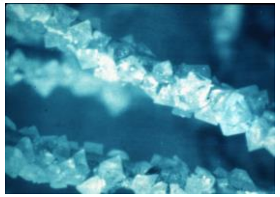
➔ Ci: Cinlet Co: Coutlet





REGULAR GROWTH (X500)

DENDRITIC GROWTH (X20)



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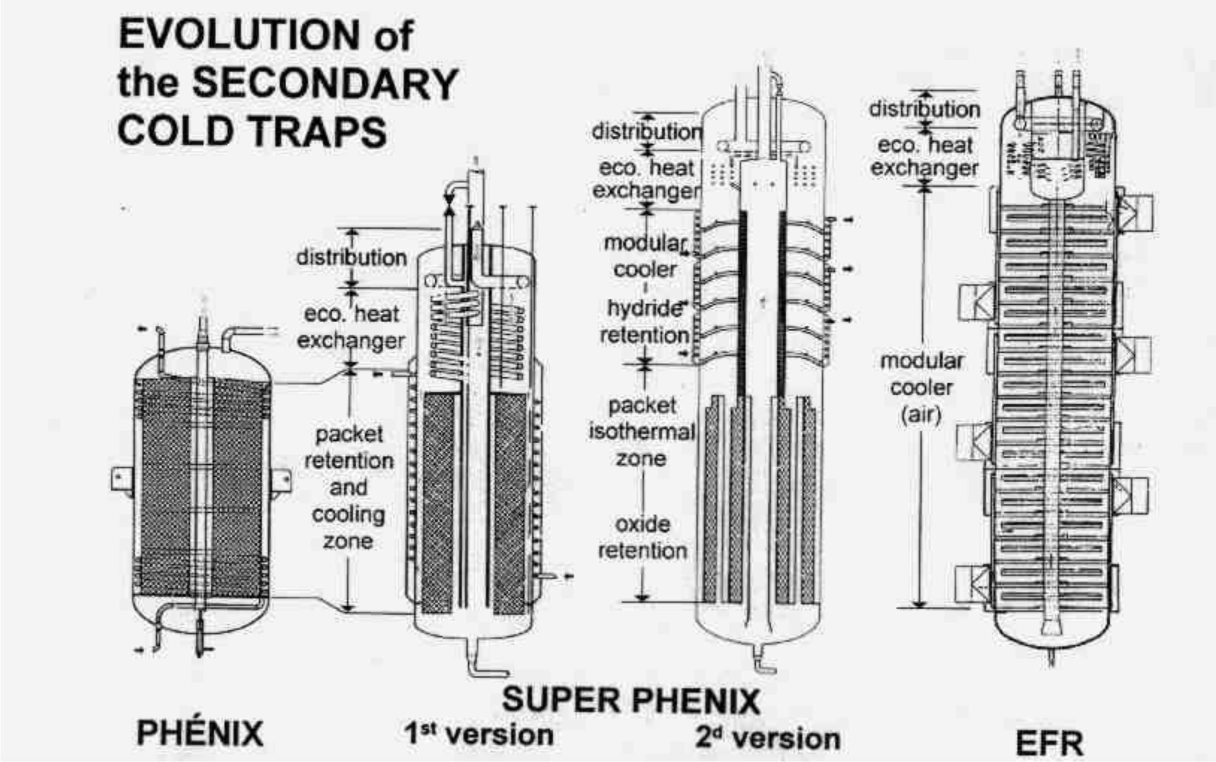
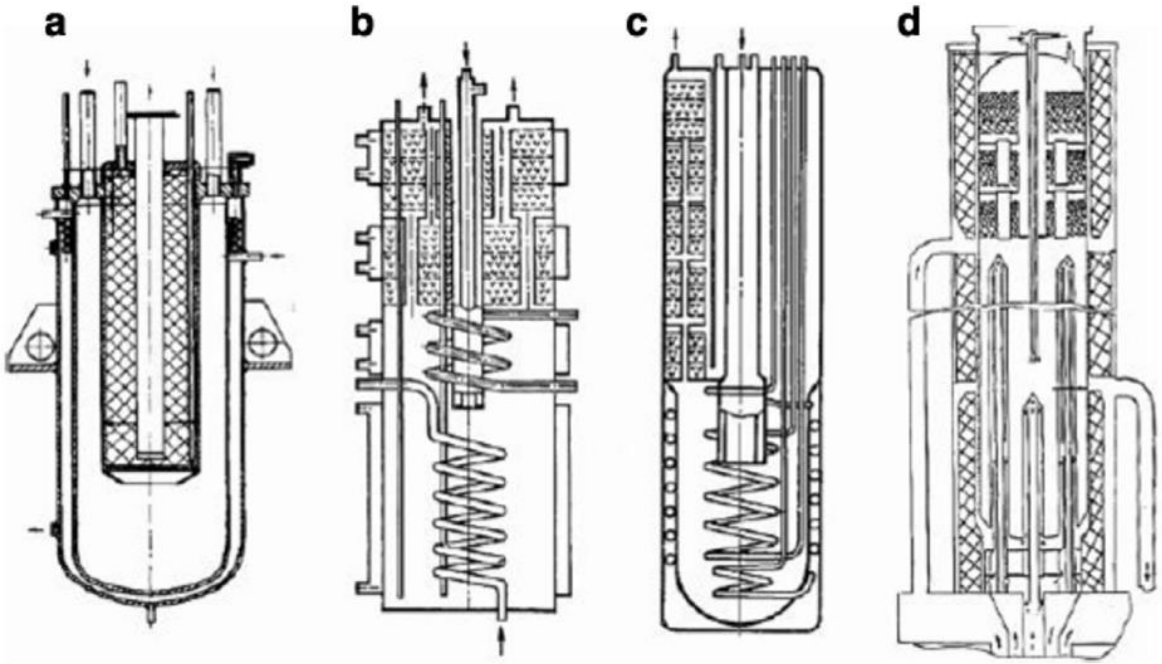
Cold trap design: examples



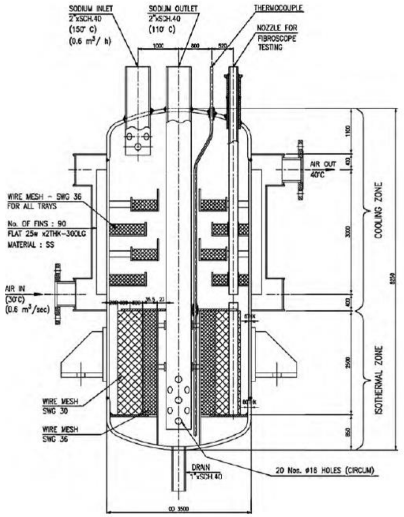
France

F.A. Kozlov et al./Nuclear Energy and Technology 2 (2016) 5–13

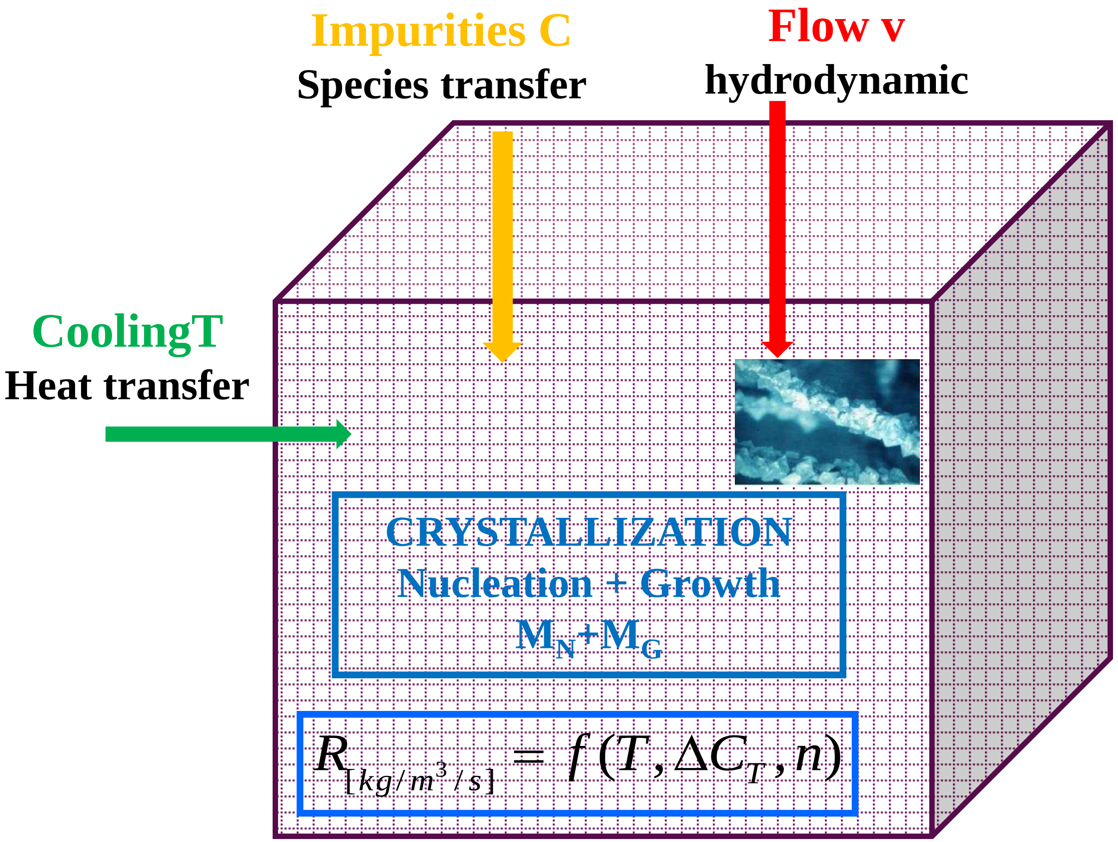


Russia

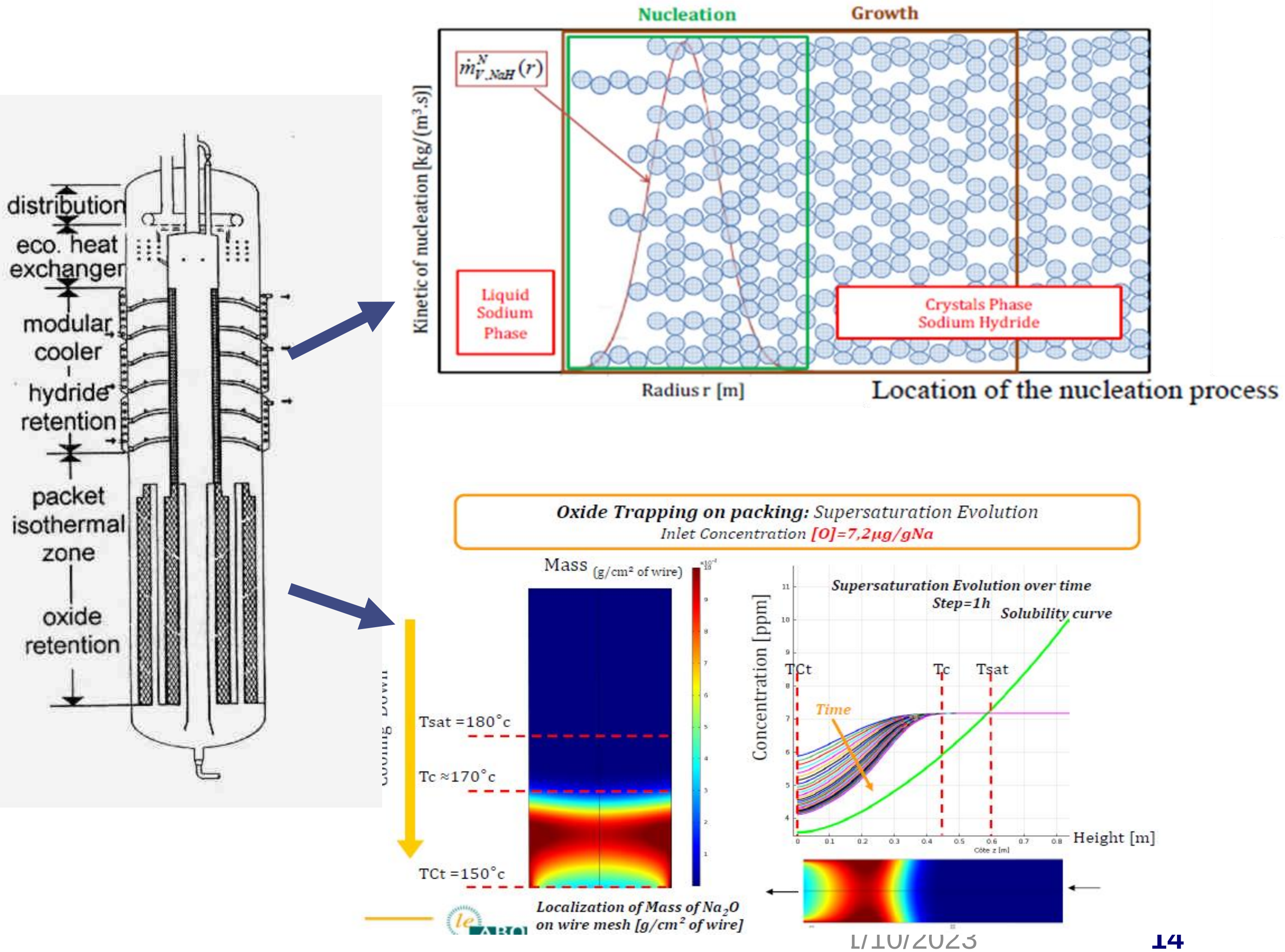
India



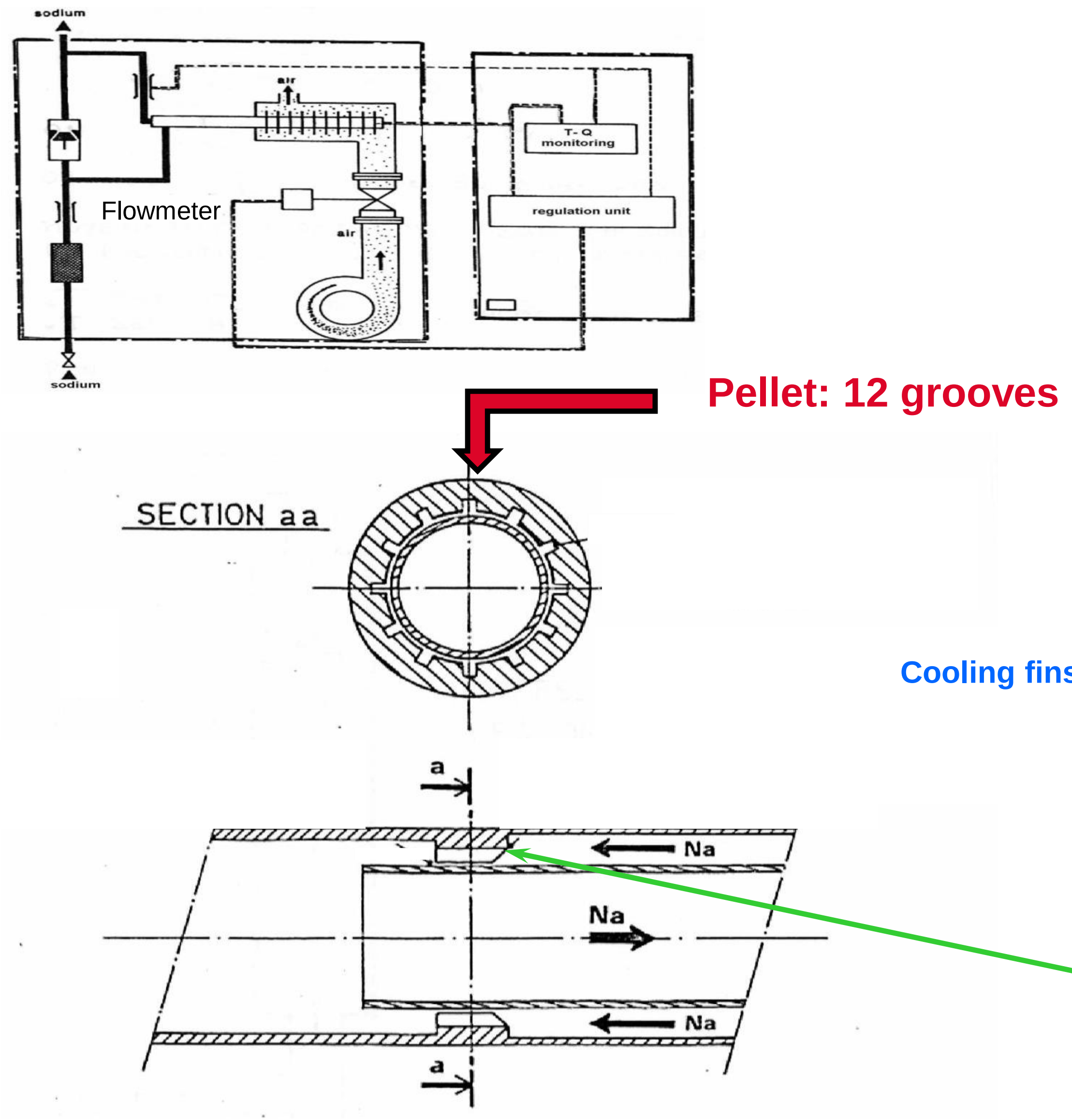
Mass transfer phenomena:

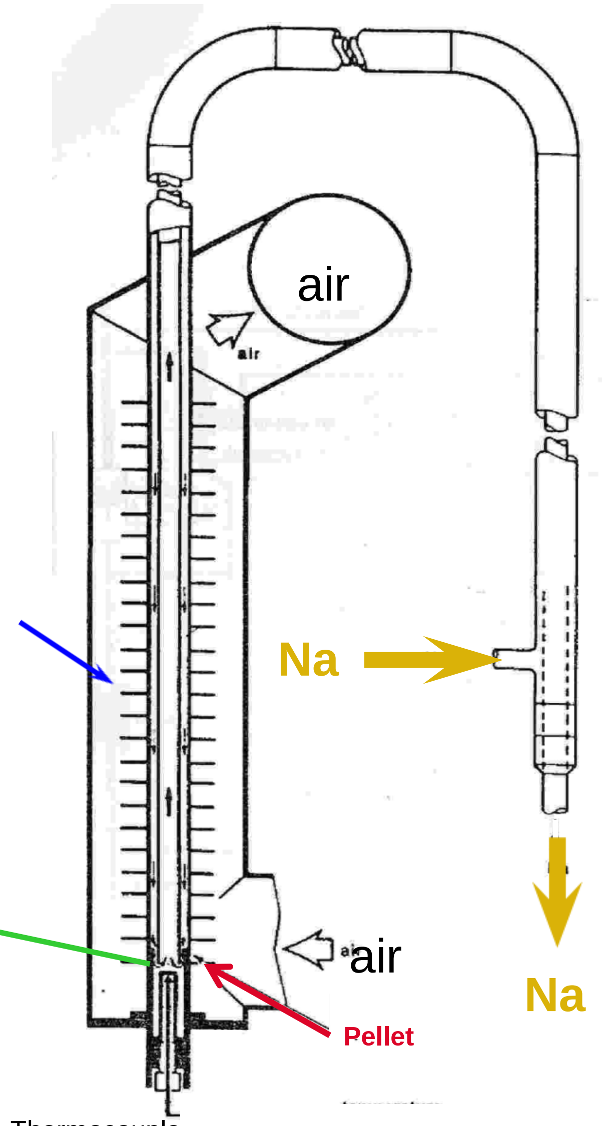


ANAÏS code (Comsol-Multiphysics)

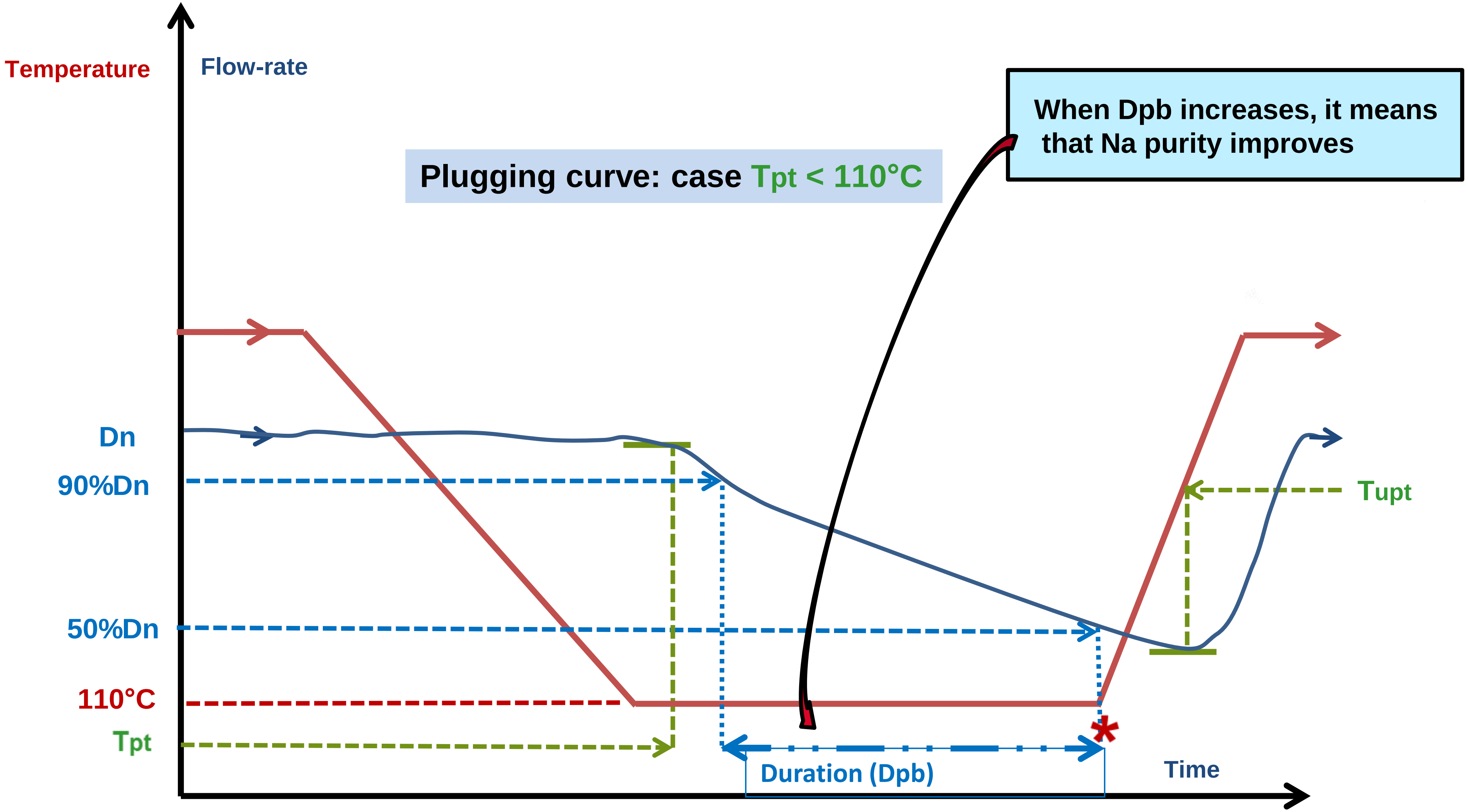


Plugging-meter





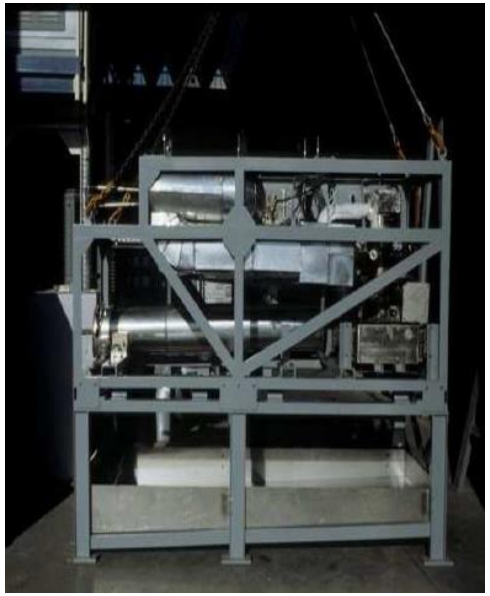
Plugging Un-Plugging curve

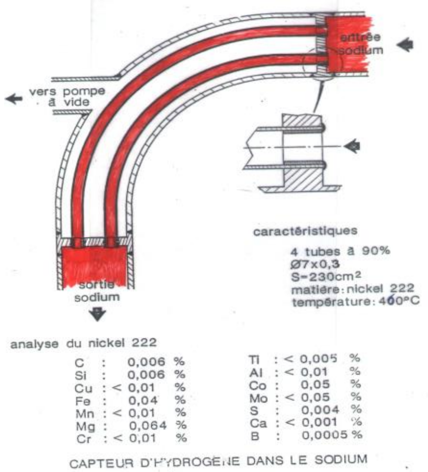


Dn: nominal flowrate

* = minimum Flow-rate value which initiates temperature increase

Hydrogen-meter





Excellent operational feedback from Phenix & SPX (and also from international feedback)

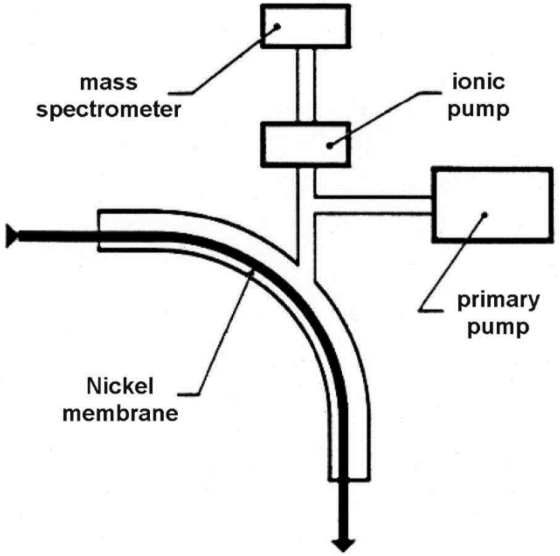
; nevertheless tracks for improvement:

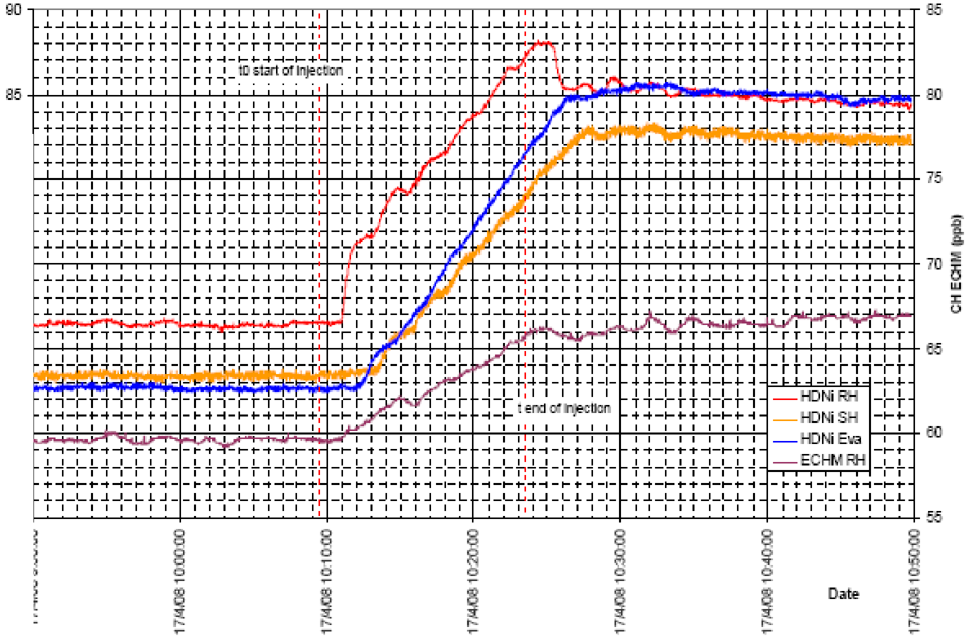
Reduction of Na transit time

Signal processing

Other complementary solutions developped:

(Acoustic detection, electrochemical H-meter,…)



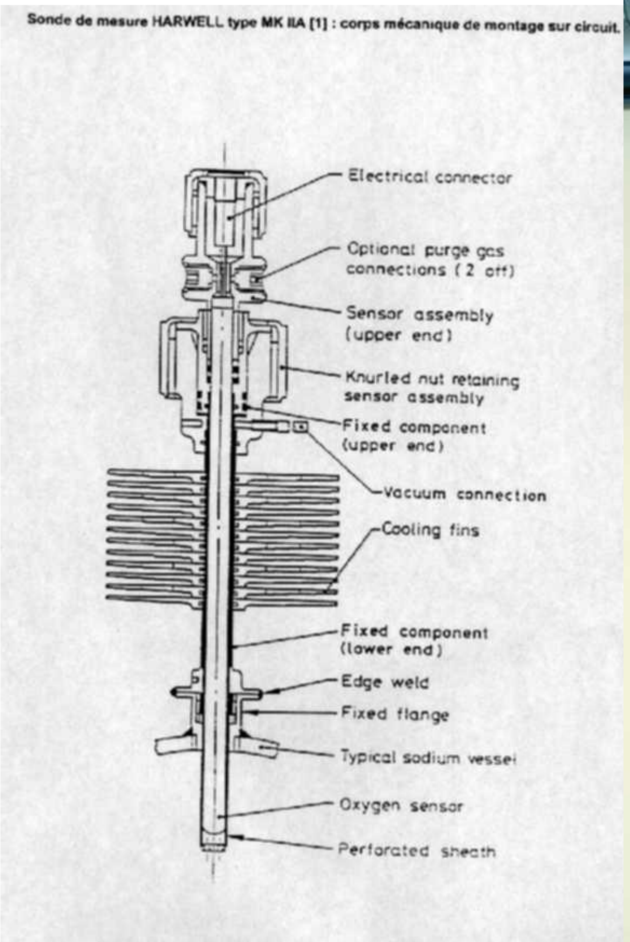


Electro-chemical H-meter (CaBr2-CaHBr)

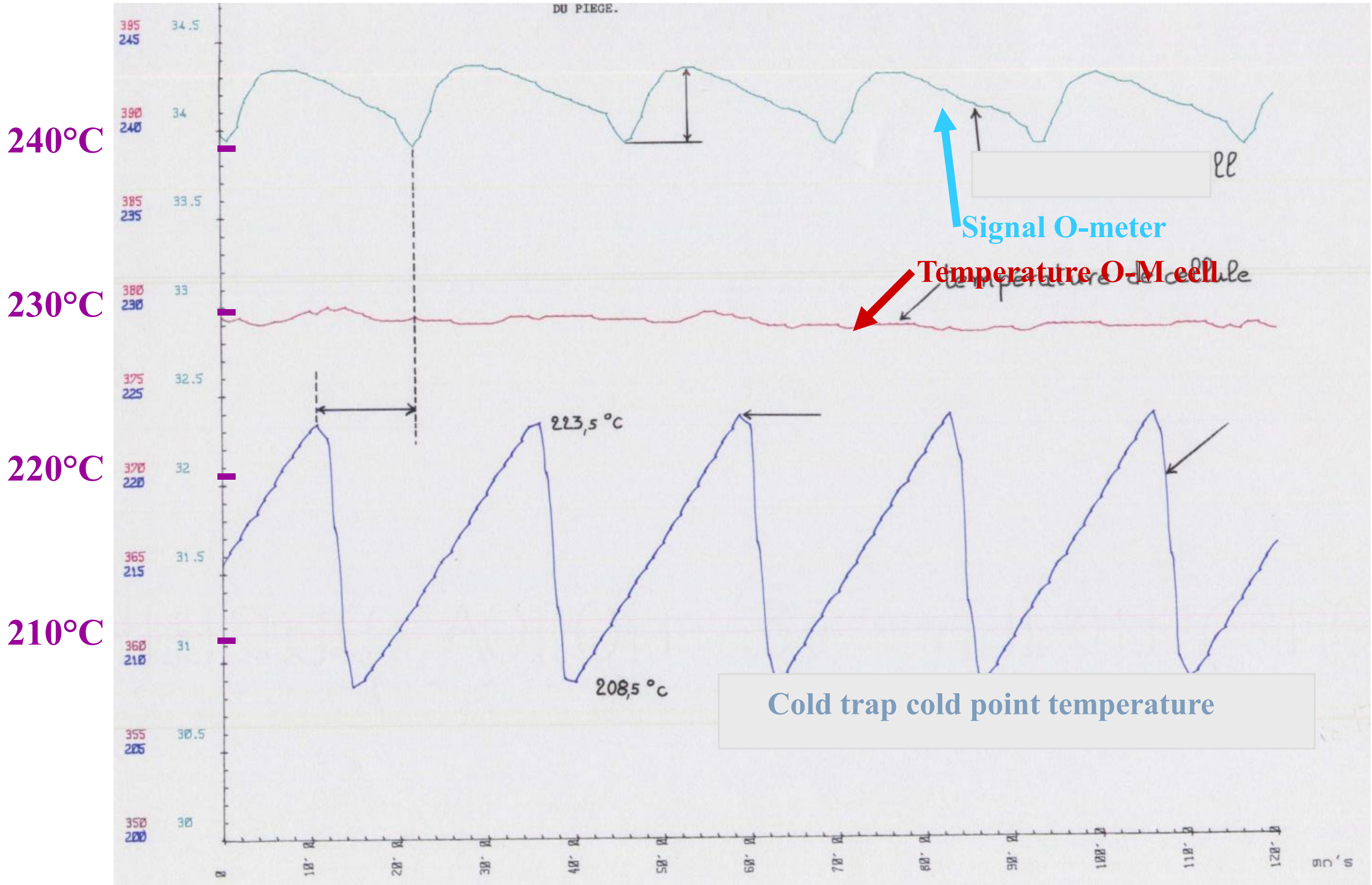
(Courtesy of IGCAR)

Experiment carried out PX
➔ comparison between ECHM and
HM + Ni membrane (3 HM)

Oxygen-meter with electrolyte ThO_2-Y_2O_3



Oxygène-mètre Harwell



➔ Very good consistency between O signal and [O] fluctuation induced by cold point temperature

➔ Currently new developments of O-meters for Na: specific to O and more accurate than Plugging-meters

➔ Necessity to calibrate periodically

Na purification for Cesium

→ Reticulated vitreous carbonaceous (RVC) traps : adsorption on RVC

Efficient process ; operation at T around 200°C

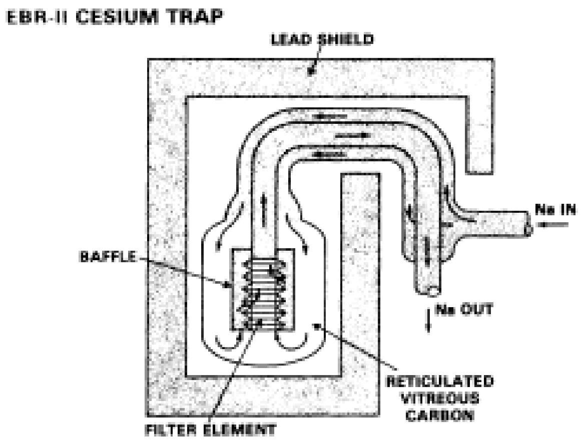
(possibility to reduce contamination by a factor 10 for each transfer through the trap)

Applied to EBR2, BOR60, RAPSODIE, …

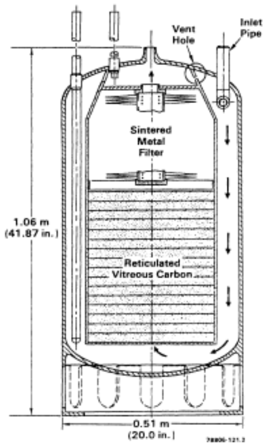
Nota : necessity to take into account delay before Na treatment and decay ^{137}Cs/ ^{22}Na (Feedback from RAPSODIE)

3 cartridges adsorbed about 0.49 TBq ^{137}Cs

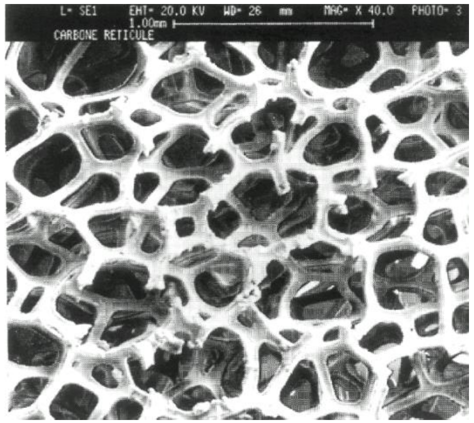
➔ Will be applied soon for primary sodium of PHENIX, prior its treatment (conversion into NaOH)



EBR2 : piège RVC



FFTF : piège RVC



RVC

French Experience with sodium technology – Examples of achievements
Training at the sodium school (operated since 1975 - >7000 attendees)

In-depth training session

Sodium technology and loop operation
(2 options : 5 or 8 days)

Practical training modules

Intervention on sodium loop
2 days

Sodium circuit operation
3 days

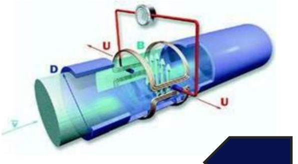
Sodium purification
3 days

Basic training

Sodium safety and risk control
1 day

Sodium decommissioning training programme :

- Sodium facility dismantling (5 days)
- Cleaning and decontamination of components (3 days)
- The characteristics of NaK and its associated risks (3 days)



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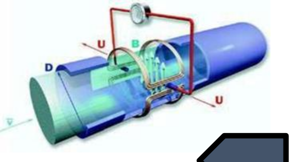

Thank you for your kind attention

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