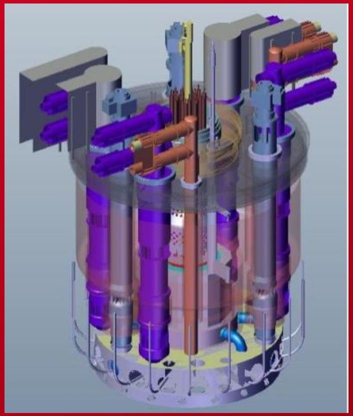
DE LA RECHERCHE À L'INDUSTRIE



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Joint ICTP-IAEA Workshop on
"Physics and Technology of Innovative Nuclear Energy Systems for Sustainable Development"
Trieste Italy
2022 December 12th – 17th

SODIUM COOLANT : FROM PROPERTIES TO DEDICATED TECHNOLOGIES
PART-2

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Sodium's chemical affinity for water

$$Na + H_2O \rightarrow NaOH + ½ H_2 + \Delta H$$

ΔH = -141 kJ/mole Na (NTP) (-162 with NaOH heat of hydration)

The reaction depends mainly on the type of contact:

Examples:

- Na introduced as drops in 10M sodium hydroxide (process destroying Na : NOAH)*
- Pressurised water introduced in Na of a SFR steam generator
- H_2O vapor (and possibly CO_2) introduced via an inert gas in a process to clean structures covered with a Na film (cleaning pit)
- Throwing a (small!) piece of Na in water in a physics laboratory... (Goal: Make noise to wake up the pupils!)

➔ *It all depends on the conditions and the objectives!*

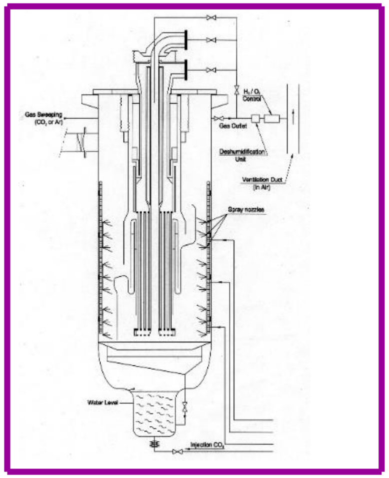
➔ *It is now generally decided that for Rankine cycle (SGU with steam) it is necessary to foresee an intermediate loop with Na (in order to avoid potential Na water reaction with active Na (primary) (important drawback compared to lead coolant)*

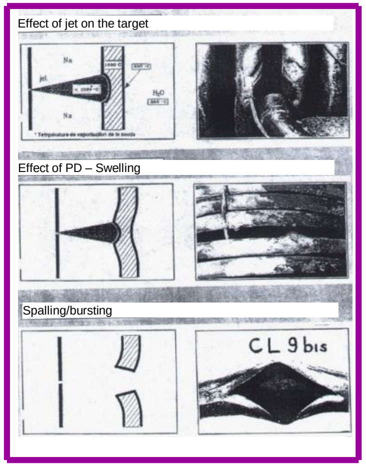
** Corresponding NaOH, process developed from 1983 and applied to Na from Rapsodie, PFR, KNK2, SPX, and in the near future to Phenix,…*

SODIUM'S CHEMICAL AFFINITY FOR WATER

Laboratory

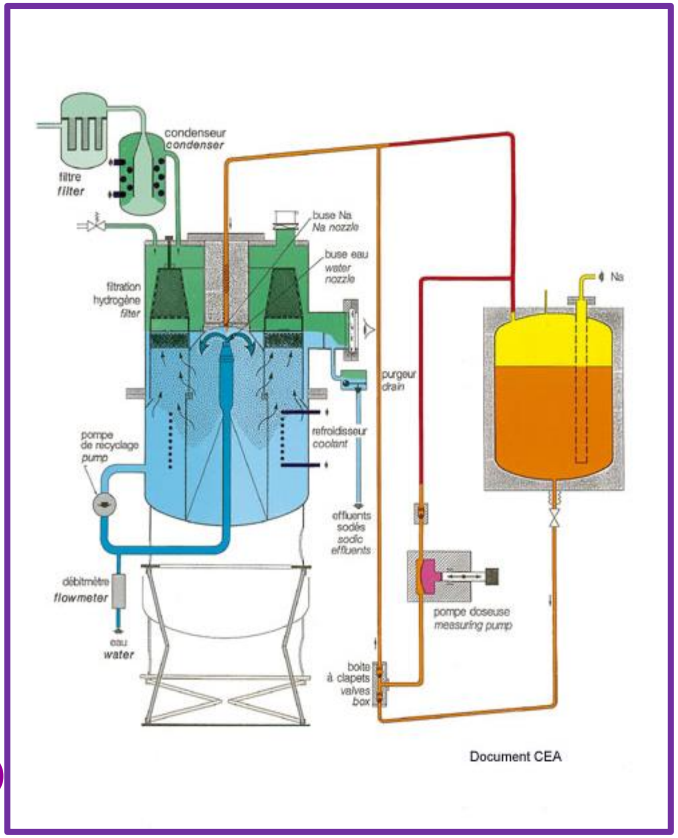
Cleaning pit (Phénix)



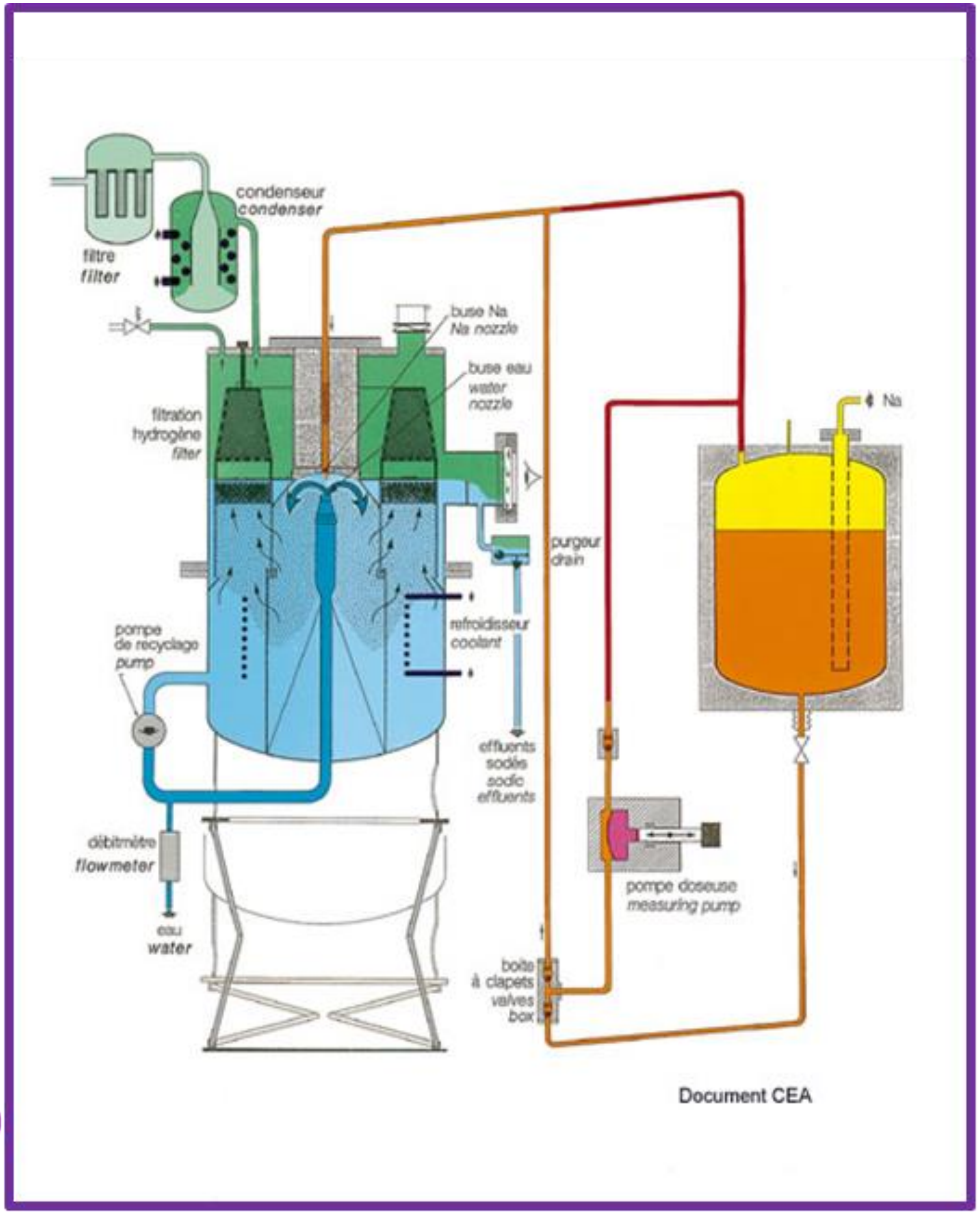


Steam generator

Na (Noah) treatment



FOCUS ON NOAH PROCESS



Na (Noah) treatment

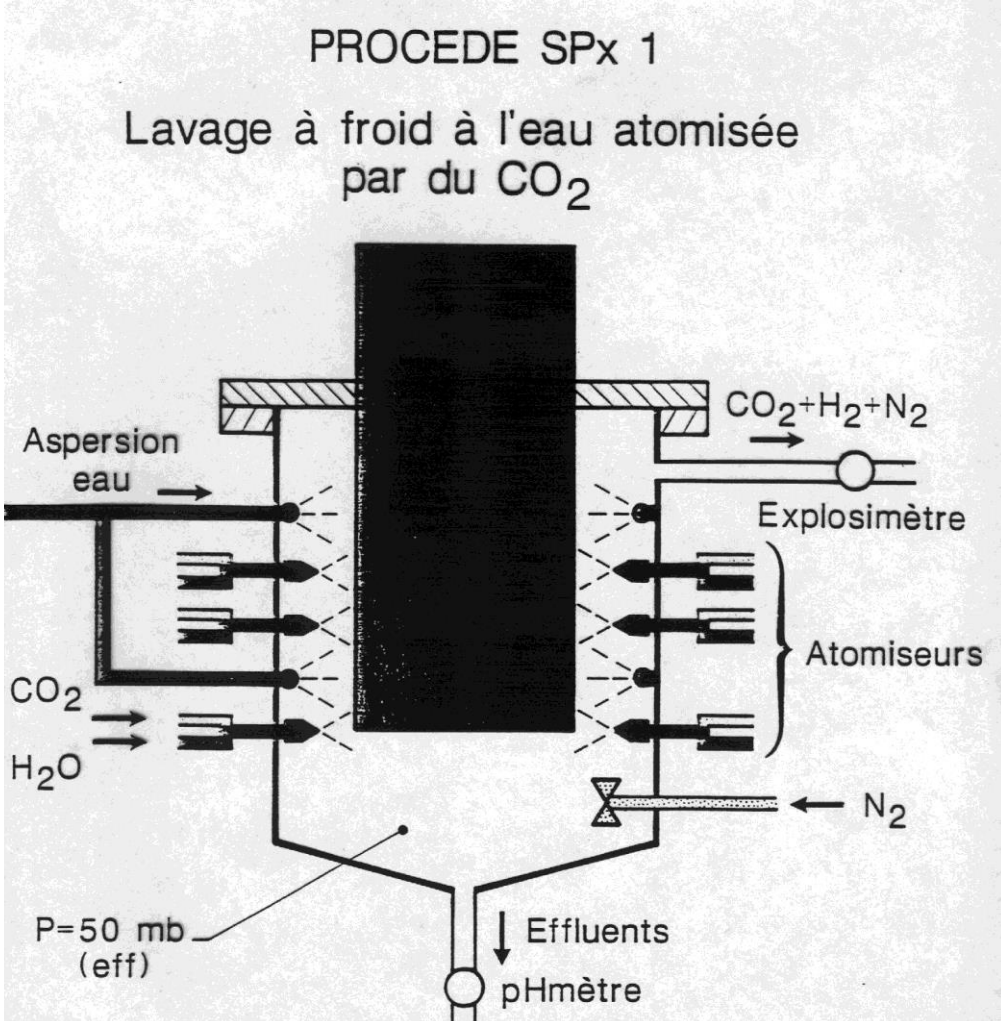
Exemple of cleaning process: SPX process (cold cleaning by CO2 and sprayed water)

Advantages

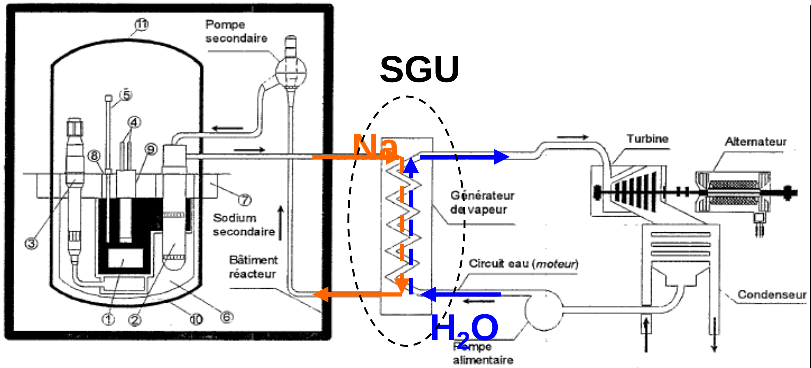
- Safe process
- Well controlled process
- No caustic corrosion

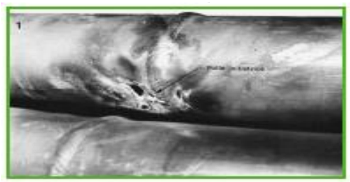
Drawbacks

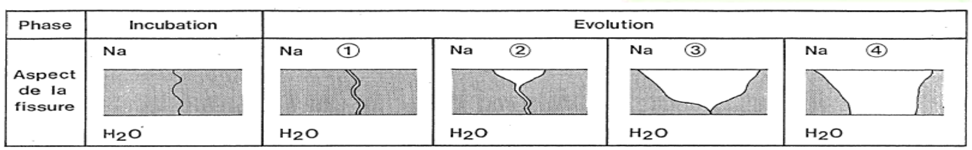
- Long process
- Process requiring a lot of gas
- Low efficiency in the baffles and gaps



Sodium-water reaction







No leak *Micro leak* *small leak* *evolution*

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

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Main reaction

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

Complete, quasi-instantaneous and non-reversible reaction

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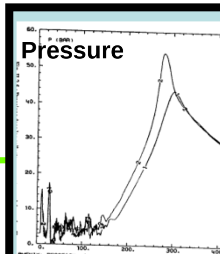
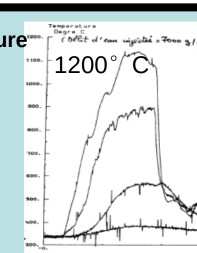


Effects: chemical,

mechanical,

thermal

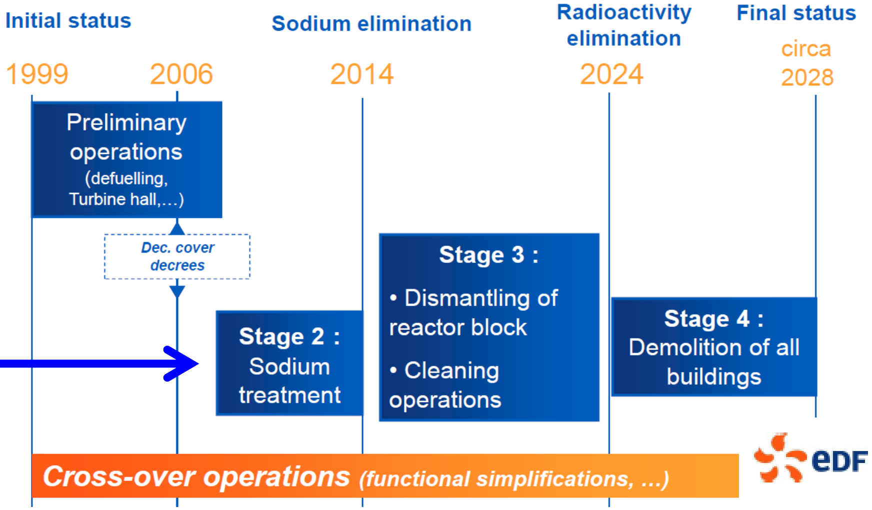


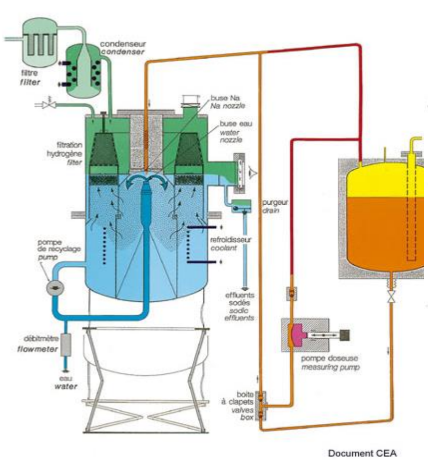
SFR DISMANTLING

- Na bulk treatment (ie NOAH Process) (Na-H2O process)
- Na residual retentions treatment after draining (carbonation)
- Cold trap treatment
- Components cleaning in cleaning pits,...

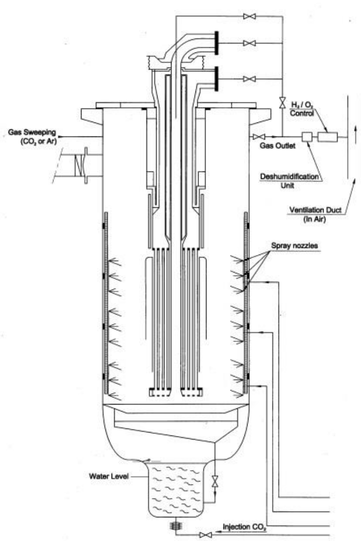
Environment to take into account: Na reactivity (air, water), NaOH, H_2, dosimetry, ...

Decommissioning schedule in 4 stages





NOAH Process



Cleaning pit

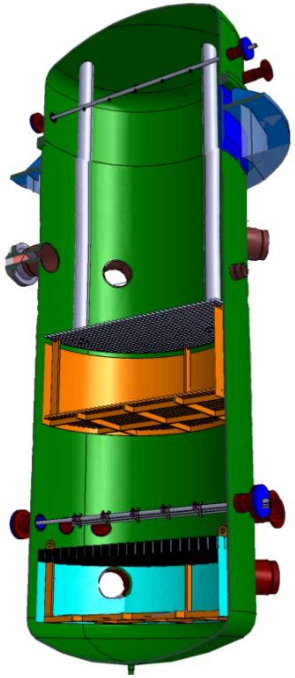
NaK treatment

Carbonation process

SFR DECOMMISSIONING: R&D IE COLD TRAP TREATMENT

ELA

- ELA = Enceinte de Lavage en Actif (radioactive sodium waste treatment process).
- Under development for the hydrolysis of residual sodium containing impurities such as **NaH**, **Na_2O** and **NaT** (tritiated sodium hydride).
- Implementation of the **sodium-water reaction** in a controlled and progressive way.
- Water sprayed on sodium wastes packed in a basket.
- High flow rate of inert gas.
- Main reactions involved:



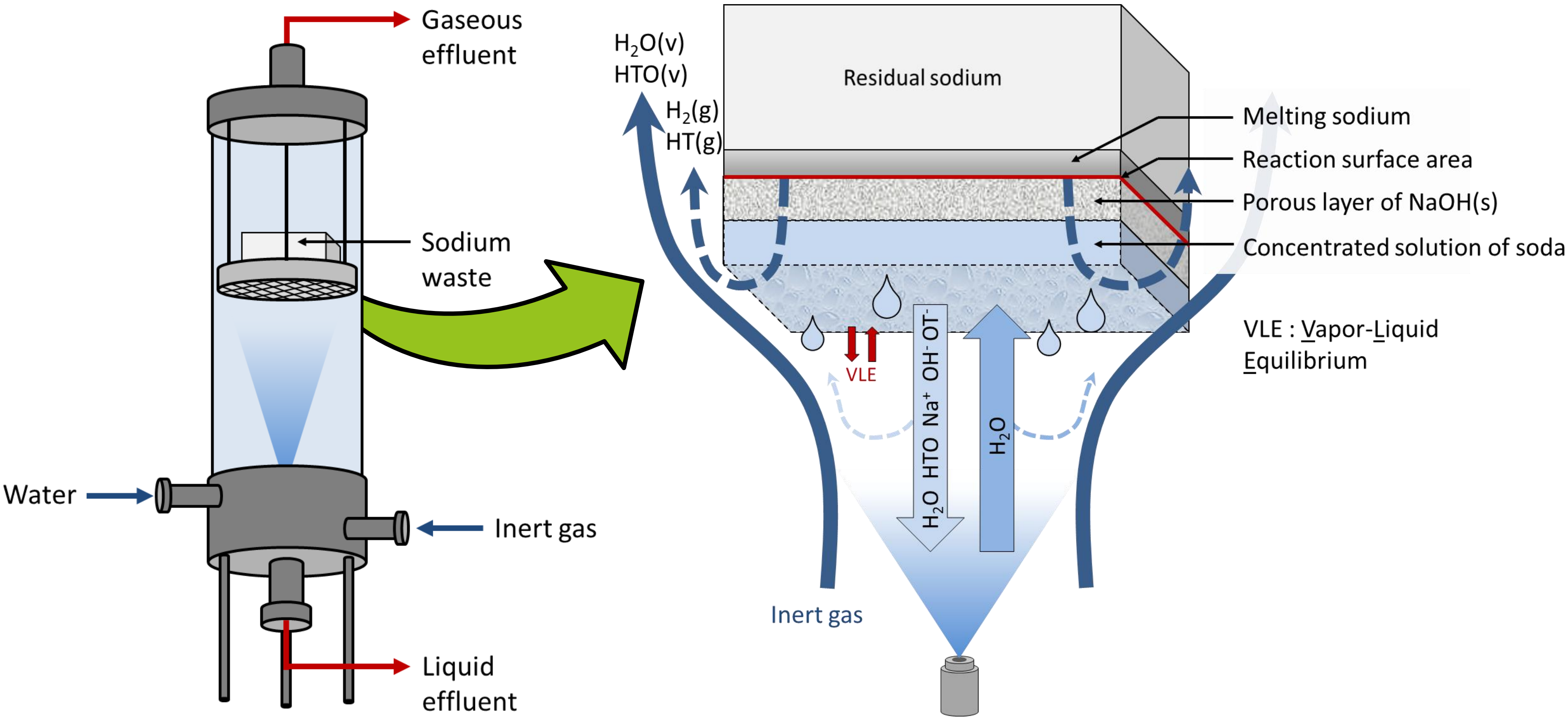
$Na_{(s)} + H_2O_{(l)} \rightarrow NaOH_{(s)} + \frac{1}{2} H_{2,(g)}$ ($\Delta_r H^0 = -141$ kJ·mol$^{-1}{}_{Na}$)

$NaH_{(s)} + H_2O_{(l)} \rightarrow NaOH_{(s)} + H_{2,(g)}$ ($\Delta_r H^0 = -82$ kJ·mol$^{-1}{}_{Na}$)

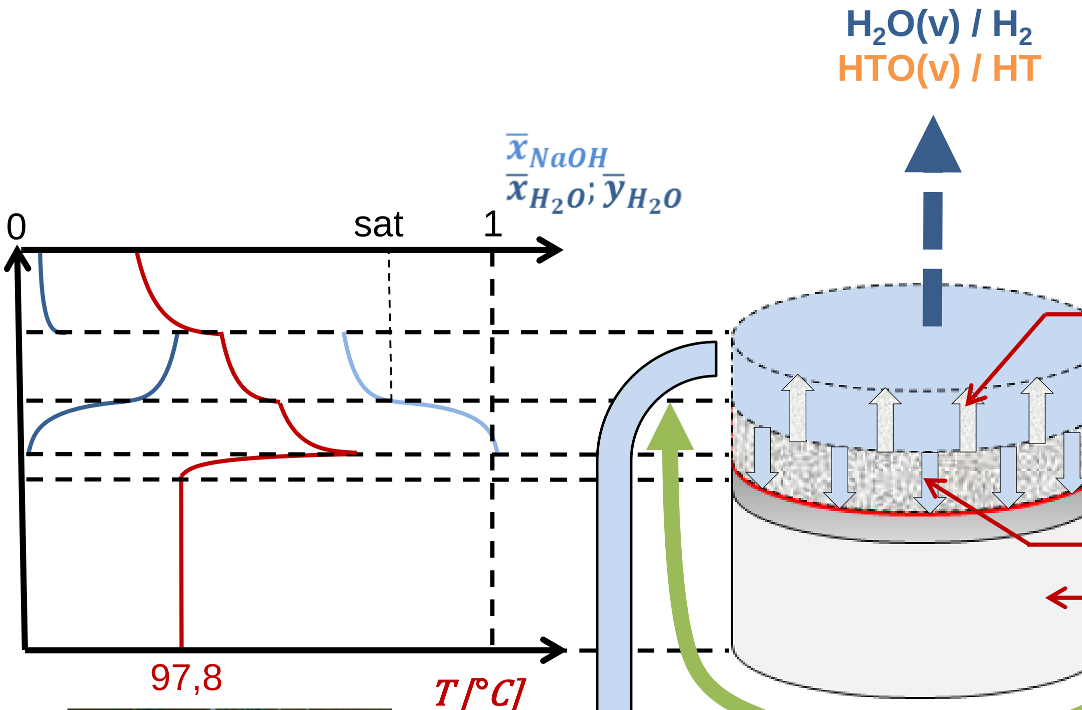
$Na_2O_{(s)} + H_2O_{(l)} \rightarrow 2\ NaOH_{(s)}$ ($\Delta_r H^0 = -76$ kJ·mol$^{-1}{}_{Na}$)

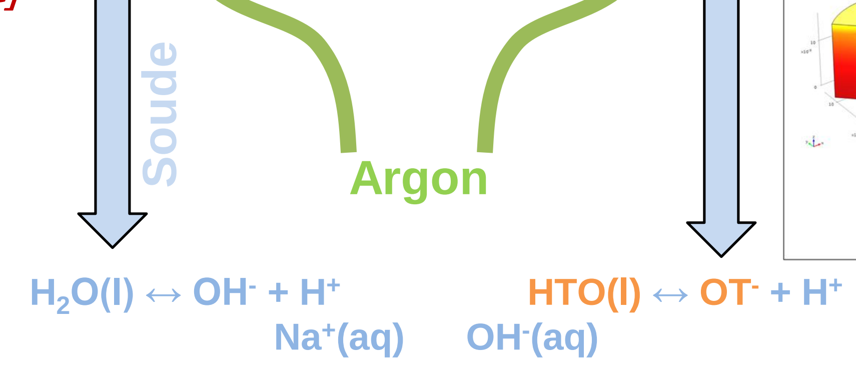
$NaOX_{(s)} \rightarrow Na^+_{(aq)} + OX^-_{(aq)}$ avec X=H ou T ($\Delta_r H^0 = -45$ kJ·mol$^{-1}{}_{Na}$)

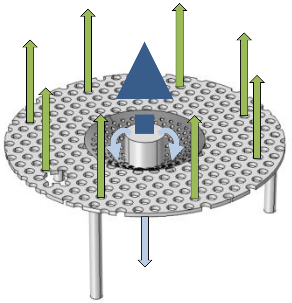
Phenomena involved in a sodium hydrolysis in ELA

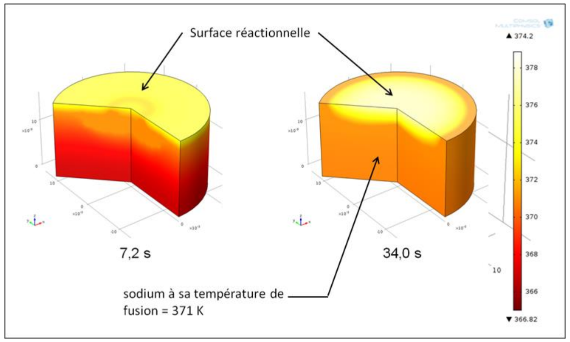


Phenomenological modeling









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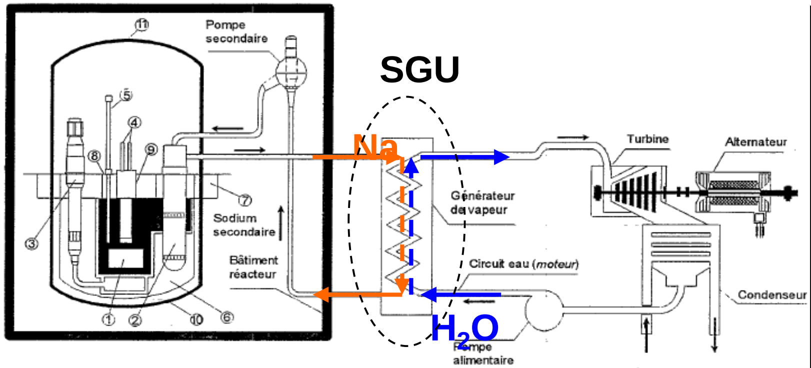

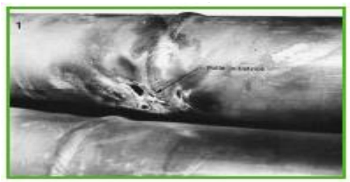

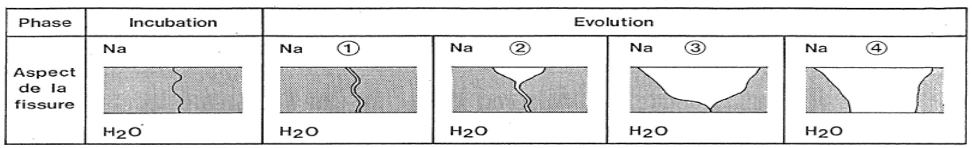

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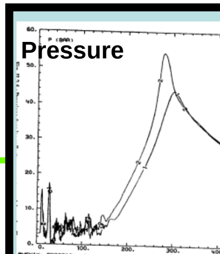

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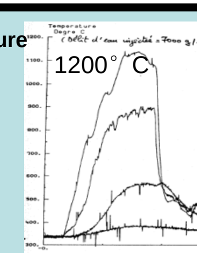
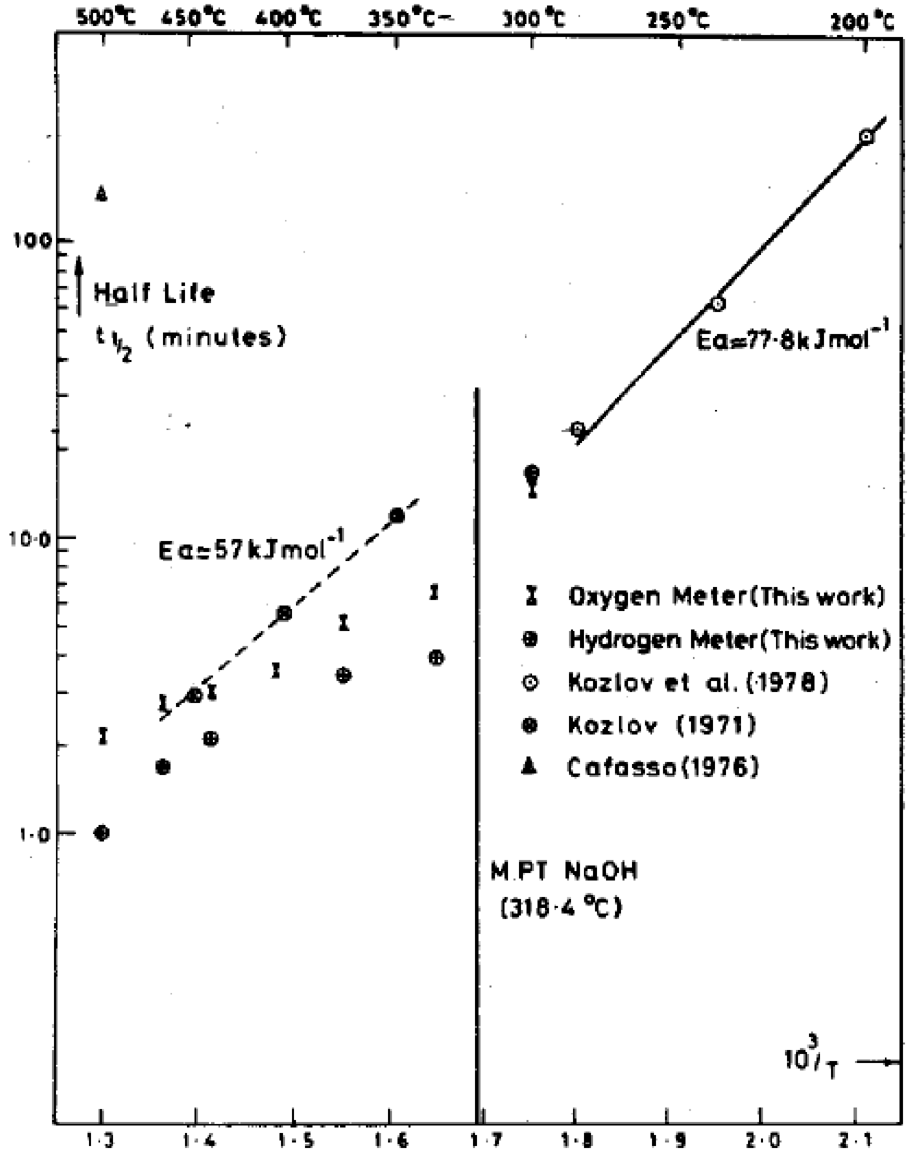


SODIUM HYDROXIDE DECOMPOSITION (FROM A. WITTINGHAM UK)



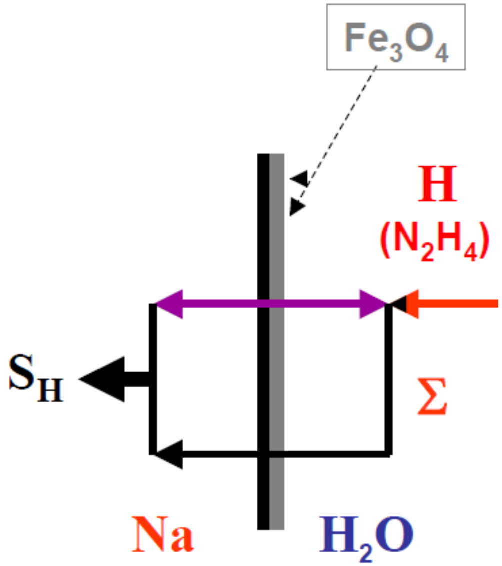
AQUEOUS CORROSION IN SGU PIPES

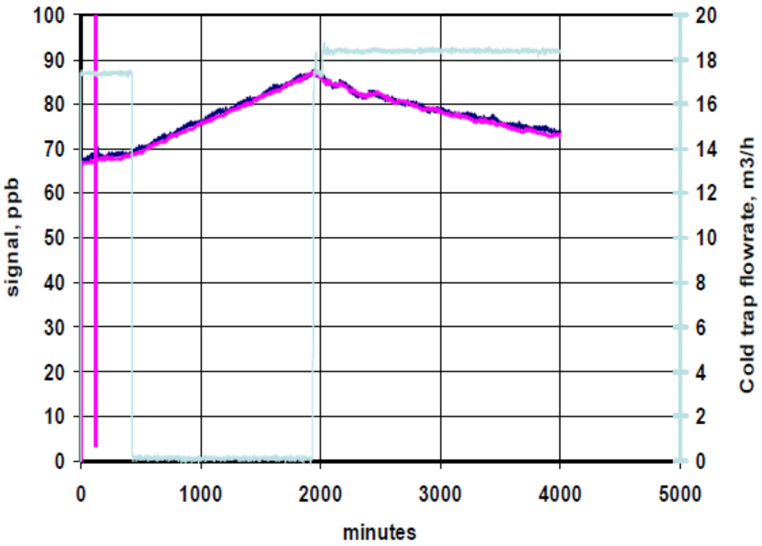
Aqueous corrosion of Steam Generator pipes: production of magnetite layer & production of hydrogen:

$3Fe + 4H_2O \leftrightarrow Fe_3O_4 + 4H_2$

Injection of hydrazine (or …) in water to mitigate aqueous corrosion (O reduction) but thermal decomposition:

$2N_2H_4 \leftrightarrow 2NH_3 + N_2 + H_2$





S_H measurement (cold trap shutdown then again in operation)

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)

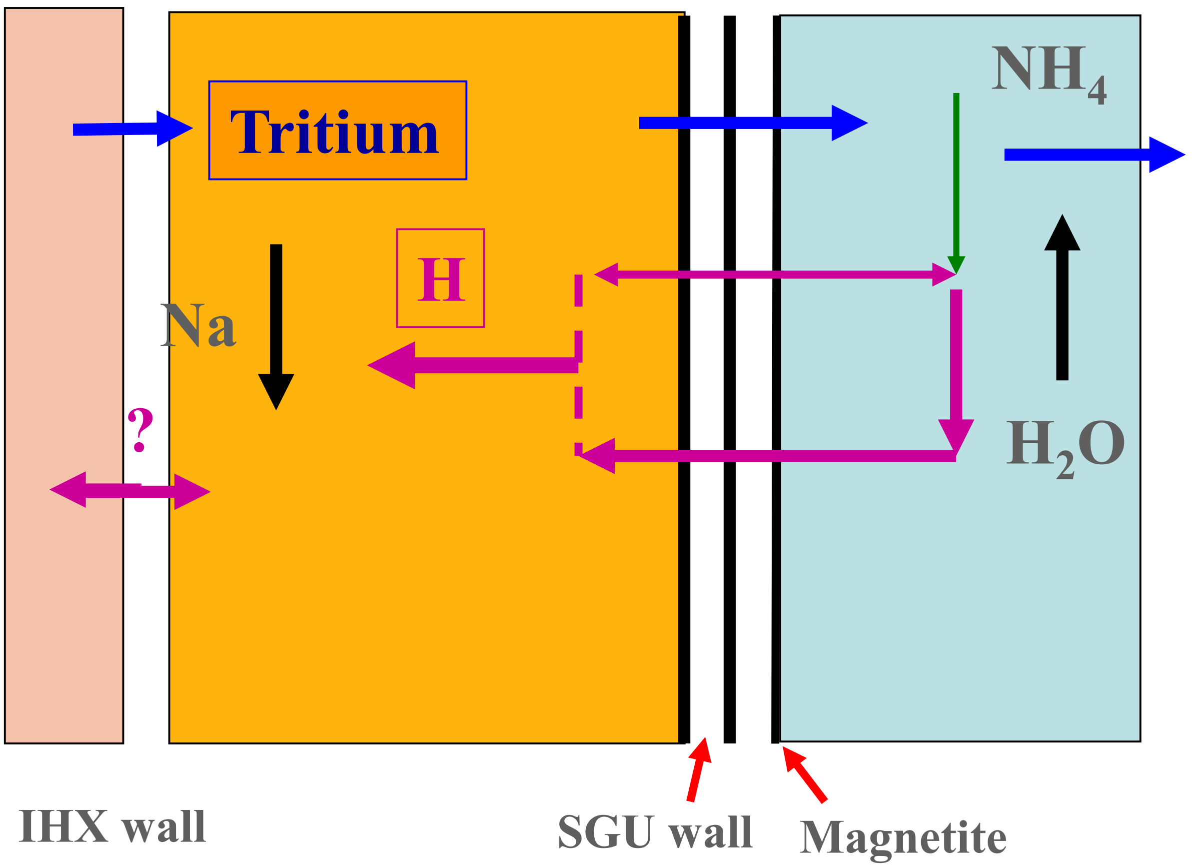
- at the design stage

- at the operating stage

guarantee that they are below the authorised thresholds

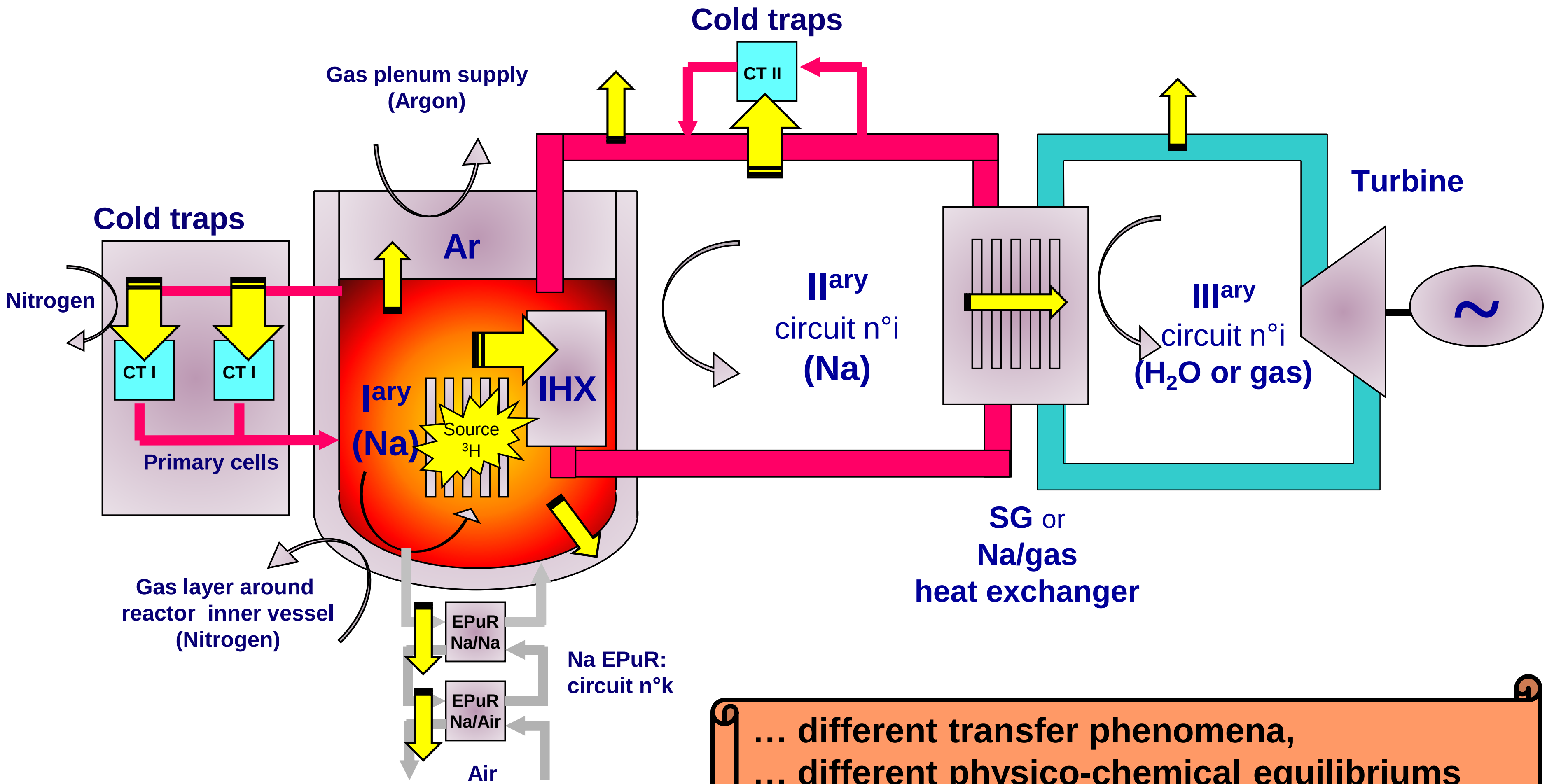
Assess tritium activities in the different media (Na, steel,…)

Tritium build-up in purification units



P. Brazzale, A. Chassery, Thierry Gilardi, C. Latgé, X.M. Meyer, X. Joulia
Modelling of a hydrogen permeation process from gas phase towards liquid sodium and experimental set-up for prototype testing.
Journal Chemical Engineering Research and Design, Vol 159 July 2020

MAIN TRITIUM TRANSFERS TO BE CONSIDERED IN A SFR REACTOR

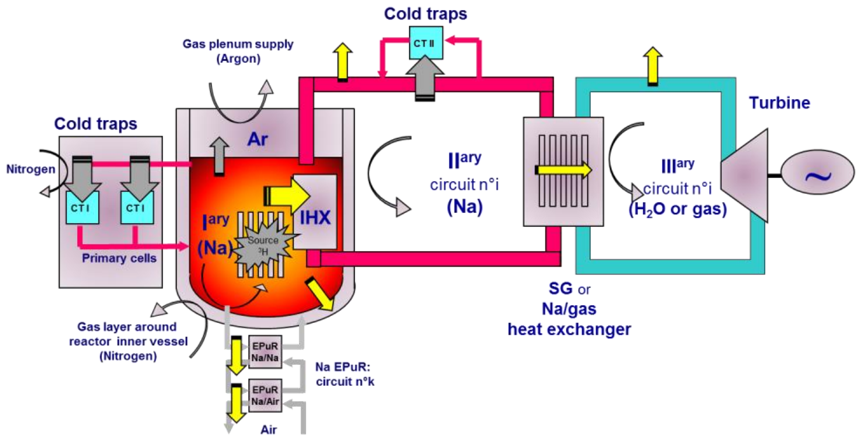


… different transfer phenomena,
… different physico-chemical equilibriums to be considered

MAIN TRITIUM TRANSFERS TO BE CONSIDERED IN A SFR REACTOR

Permeation through metallic walls

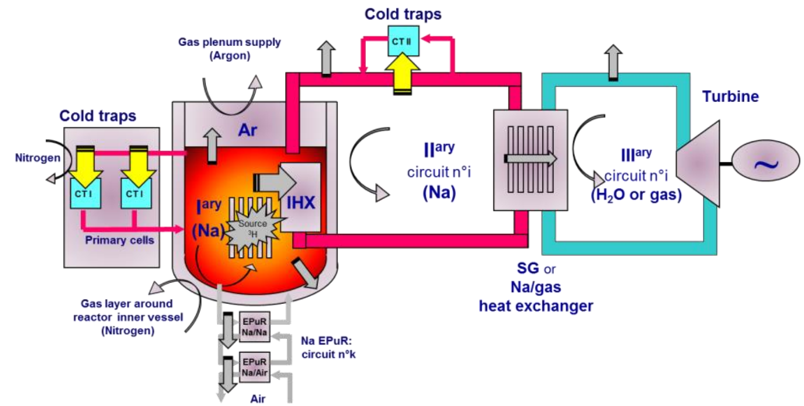
- Major part of tritium transfers between circuits
- Main contributions for permeation through:
  - IHX tubes (Na I^{ary} ➔ Na II^{ary}) , sodium circuits pipings (Na ➔ air atmosphere)
  - Complementary cooling down circuits



Cristallization of tritium in cold traps

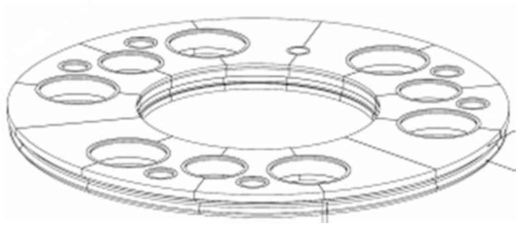
- Co-precipitation of NaT compound with higher amounts of sodium hydride NaH due to hydrogen production in tertiary circuits (water corrosion) and permeation through steam generators towards secondary sodium

- Major contribution of tritium trapping in secondary cold traps due to hydrogen higher concentrations in favour of co-precipitation
- Modeling with KUTIM code (TTT code in Japan,....)



GAS PLENUM IN THE PRIMARY VESSEL

A free level of sodium exits in the main vessel, above the core and under the upper closure of the vessel.
➔ allows for an easier design and operation of all the penetrations in the vessel that are necessary for (either during operation or maintenance):



- **fuel handling in the core**
- **movement of core control devices (neutrons absorber rods),**
- **core monitoring (instrumentation),**
- **handling of components other than fuel, that are located in the vessel (core feed pipes, pumps, heat exchangers, according to the design of the reactor,**
- **in service inspection of the vessel and its internal structures….**

Necessity to model the following items, in support to the design of the upper structures:
- **Heat transfer**, that occurs according to different mechanisms, mainly:
  - .convection in gas,
  - .radiation from the sodium surface towards emerged structures,
- **Generation of aerosols** that contribute to make the gas +/-transparent: absorption and then release of radiation): evaporation / condensation of sodium vapours.
- **Sodium deposits** and their potential oxidation.

POTENTIAL CONSEQUENCES OF AEROSOLS IN COVER GAS:

Impact on heat transfer:

Heat transfer, that occurs according to different mechanisms, mainly:
-convection in gas,
-radiation from the sodium surface towards emerged structures,

- Evaporation / condensation of sodium vapours. Sodium deposits but very limited amounts

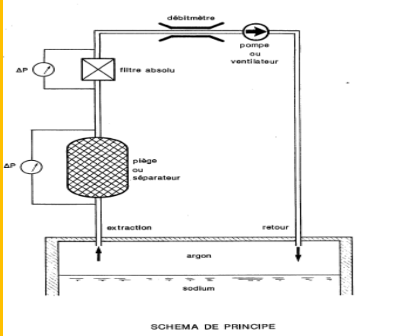
➔ Potential mechanical consequences on handling or rotating systems,…due to Na deposits (condensates):
Difficulties with control rods of PHENIX (one event),
➔ *Gradual decrease of magnetic lifting surface; lifting force<rod weight (lifting of the rod impossible)*
➔ *local cleaning solved the problem*

➔ Impact on viewing technologies in cover gas,…

➔ Impact on thermal insulation performances

➔ Impact on contamination and dosimetry (Cs,…)

➔ Impacts on decommissioning …



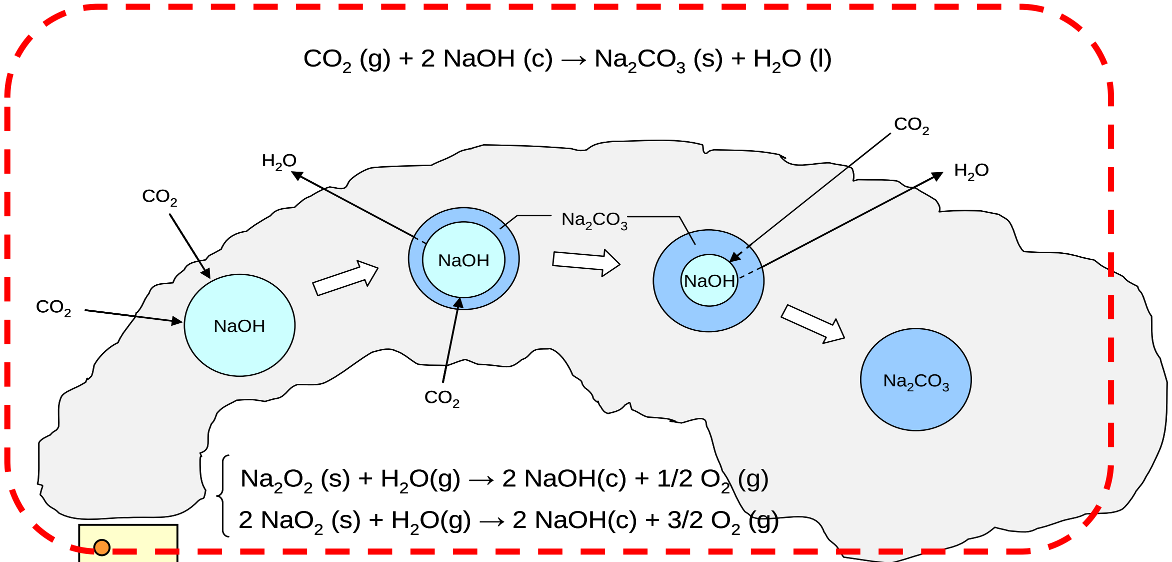
➔Evaporation kinetics:

Based on $Sh = 0{,}643.(Gr.Sc)^{0.25}$ (Boolter relation)
$R_{evap} = 0.643\ D.\rho_s/\Phi\ .\ (Gr.Sc)^{0.25}$ kg/s.m²

With $Gr = g.\ \Phi^3/\nu^2.(1-\gamma s/\gamma\alpha)$
And $Sc = \nu/D$
With :
- **D = diffusion coefficient (m²/s)**
- **ρ_s = Na density at Na-gas interface (kg/m³)**
- **Φ = diameter of the free surface (m)**
- **ν = viscosity (m²/s)**
- **g = 9.81 m/s**
- **γs = gas density at Na-gas interface (kg/m³)**
- **$\gamma\alpha$ = gas density at infinite (kg/m³)**

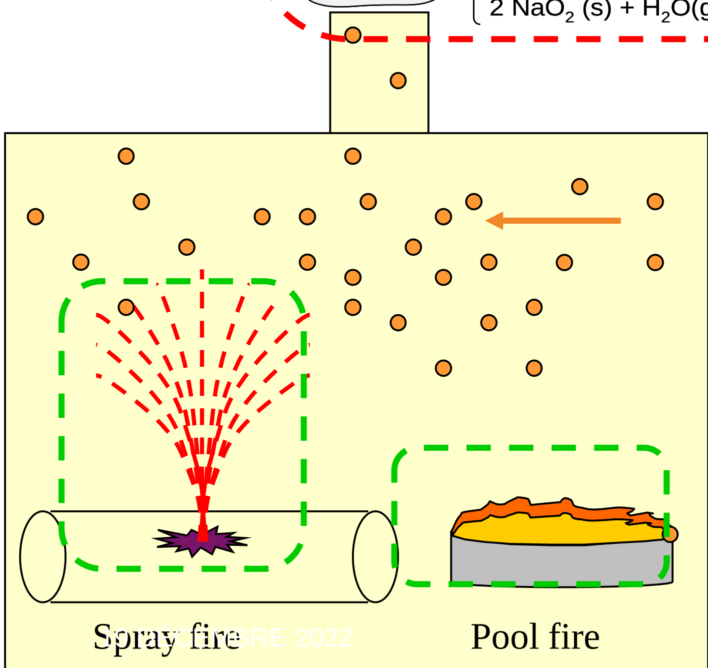
Gas circuits are equipped with condensers and aerosol traps

Main steps of sodium fire aerosols impact evaluation



③ Calculation of atmospheric dispersion and chemical conversion: carbonation of NaOH aerosols

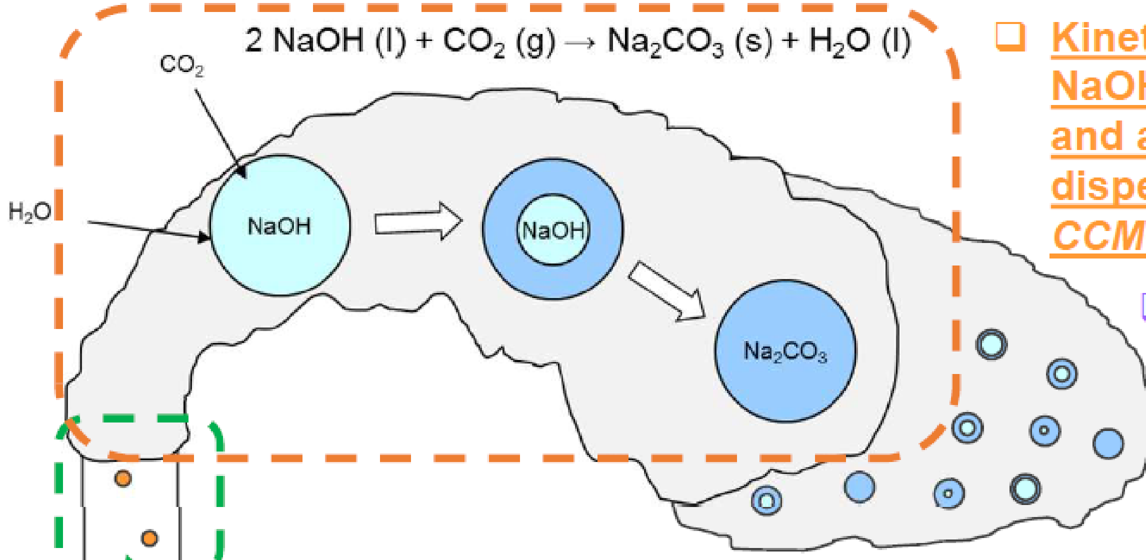
Comparison of aerosol products concentrations with toxicity exposure limits



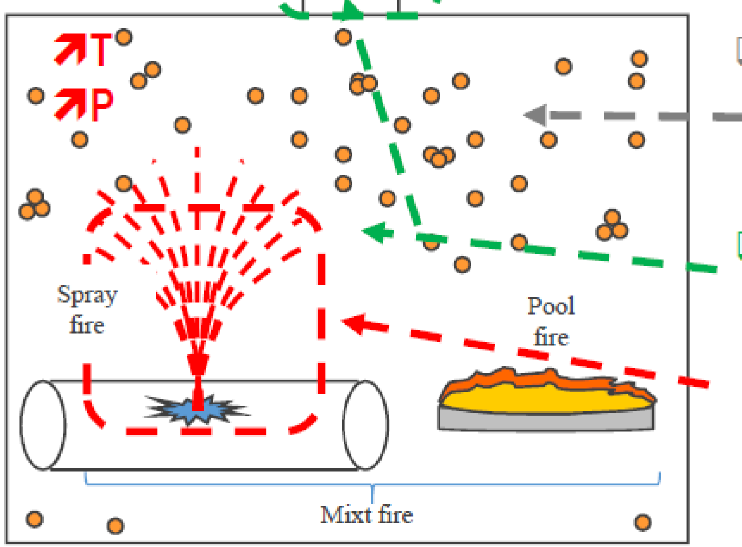
② Calculation of sodium aerosols release outside the building

① Calculation of aerosols production from sodium fire

FOCUS ON SODIUM FIRE RISK – MAIN STEPS OF EVOLUTION



- **Kinetic model (CEA) for NaOH aerosols carbonation and atmospheric dispersion (*CERES, STAR CCM+*)**
- **Toxicological impact evaluation (safety approach)**



- **Evaluation of aerosols behaviour inside the building: batch calculation with *CONTAIN-LMR***
  - ➔ aerosols retention: sedimentation, deposition models
  - ➔ granulometry: agglomeration models
- **Evaluation of sodium spray combustion and consequences: *FEUMIX***
  - ➔ T and P evolutions
  - ➔ production and release flowrates of sodium fire aerosols
- **Evaluation of sodium spray fragmentation: modelling in progress with *Neptune CFD***
  - ➔ droplets sizes and velocities distribution

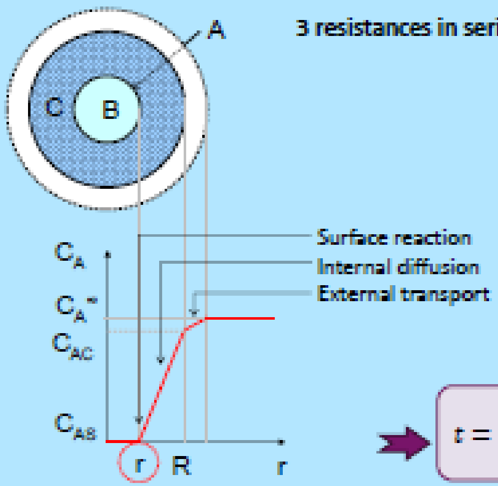
CARBONATION KINETICS

Kinetic model for aerosol behaviour:

CO_2 (g) + 2 NaOH (l or s) → Na_2CO_3 (s) + H_2O (l)

based on a shrinking core model

A (g) + ν B (l or s) → C (s) + D (l)



3 resistances in series with the transfer of CO_2 (A):

- External transport: $J_A = 4\pi R^2 k_D (C_A^\infty - C_{AC})$
- Internal diffusion: $J_A = 4\pi r R D_e \dfrac{C_{AC} - C_{AS}}{R - r}$
- Surface reaction (1st order): $J_A = 4\pi r^2 k_R C_{AS}$

Assumptions:

- Limiting step = internal diffusion
- Fast reaction / internal transfert flow : $C_{AS} = 0$
- Concentration gradient in the boundary layer negligible : $C_{AC} = C_A^\infty$

$$t = \frac{\rho_B R_0^2}{4 M_B D_e C_A}\left[1 - (1 - X_B)^{2/3} + \frac{1 - (1 + \alpha X_B)^{2/3}}{\alpha}\right]$$

with : $\alpha = \frac{z}{2} - 1$ and $z = \frac{v_C}{v_B} = \frac{\rho_B M_C}{\rho_C M_B}$ expansion coefficient

Physical state of initial NaOH

Clough and Garland (1970) :

RH < 35 % : NaOH solid particles

RH > 35 % : NaOH droplets / hydrated particles

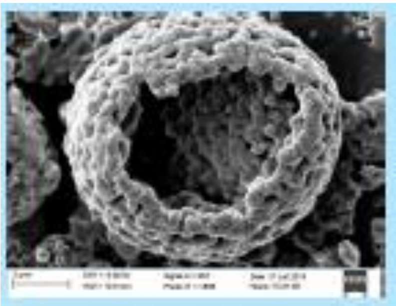
Cooper (1980):

$$\frac{R_{hydrated}}{R_{dry}} = \frac{0{,}87}{(1 - RH)^{1/3}} \quad for\ 0{,}35 < RH < 0{,}99$$

$\rho_B \approx 2100$ kg/m³ (solid)

$\rho_B \approx 1400$ kg/m³ (solution)

$\rho_C \approx 2500$ kg/m³ (solid)



STUDIES ON THE CHEMICAL BEHAVIOUR OF SODIUM FIRE AEROSOLS DURING ATMOSPHERIC DISPERSION

A. Plantamp [1], T. Gilardi [1], H. Muhr [2], C. Perrais [1]

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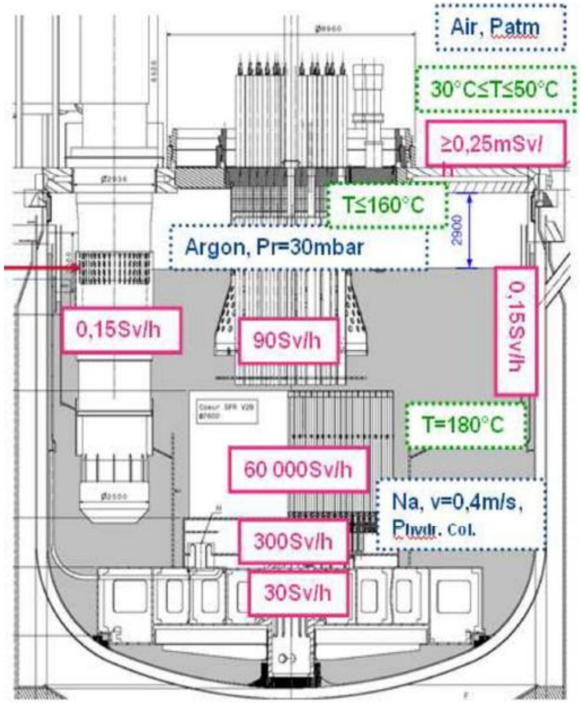
Bât 208 – 13108 Saint Paul les Durance, France

[2] LRGP CNRS UMR 7274 - ENSIC / Université de Lorraine
1 rue Grandville - BP 20451 - 54 001 Nancy, France

UNDER-SODIUM REPAIR

For non-removable components, repair operations will be performed in a gas environment.

➔ **If the faulty area is located under the sodium free level, the gas-tight system will have to contain the inspection and repair tools, to protect them from the surrounding Na**



Repair scenario for in-sodium structures:

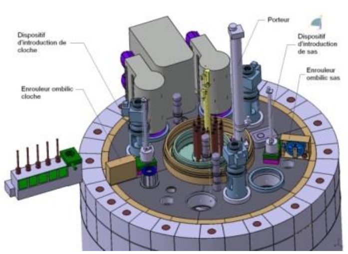
- removing the sodium (after bulk draining),

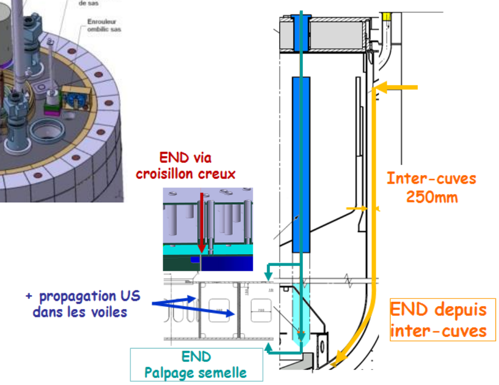
- machining and welding.

Tools:

- laser and as back-up solution conventional tools brush or gas blower for sodium removal, milling machine for machining and TIG for welding (feasibility demonstrated in the 1990s)

➔ **In-pile examination or repair requires robotic carriers. These carriers have to be compatible with the Na environment, either in the cover-gas plenum or in gas after sodium draining, or even under Na.**





For ISI and repair: key point: access taken into account from the early stage of the project

BRAYTON GAS-POWER CONVERSION SYSTEM

In support to ASTRID: Development of innovative compact heat exchanger technology to provide solid technological basis for a Brayton Gas-power conversion system.

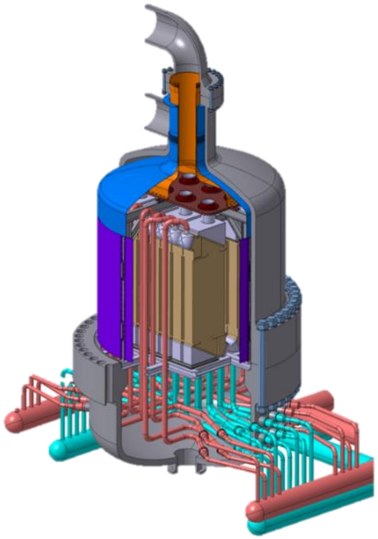
➔ **Key issue:** Design of the gas-side (which determines the heat transfer resistance of the heat exchanger) of the Na-N2 heat exchanger.

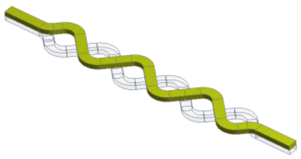
➔ Compact technologies necessary for the present application because of the low heat transfer capacity of N2.

➔ **PSHE (Plate Stamped Heat Exchanger)**, has been first identified since it potentially provides the most compact solution: complex 3-D flow of the PSHEs ↗ heat transfer performances but low mechanical resistance of this technology for high-pressure flow.

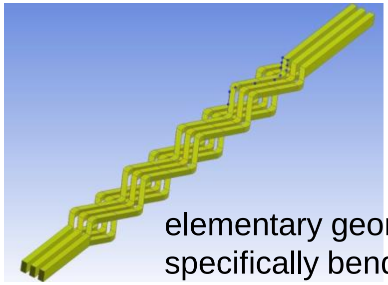
➔ Another technology that can potentially stand this pressure difference: the **PCHE (Printed Circuit Heat Exchanger)**, using diffusion bonding as welding process.

➔ in order to increase the heat transfer coefficient (and the global compactness), studies carried out to design a channel were the fluid flow is as much 3-dimensional as possible, keeping a global good mechanical resistance.

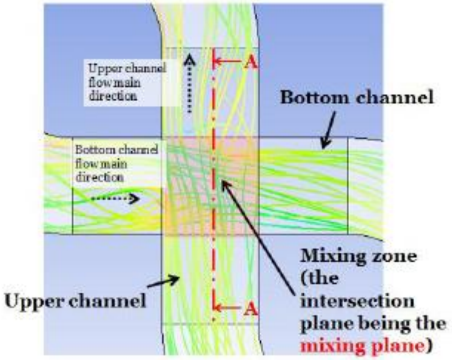




superposition of two single PCHE wavy channels in phase opposition



elementary geometrical elements, specifically bends, straight channels and mixing zones



Ref: F.Vitillo, L.Cachon, P.Millan « Thermal-hydraulic analysis of an innovative compact heat exchanger channel flow. » ((**CEA-ONERA Toulouse**) International Journal of Thermal Sciences (2014)

Sodium-Gas compact heat exchanger

Heat exchangers ->large component (190 MWth)

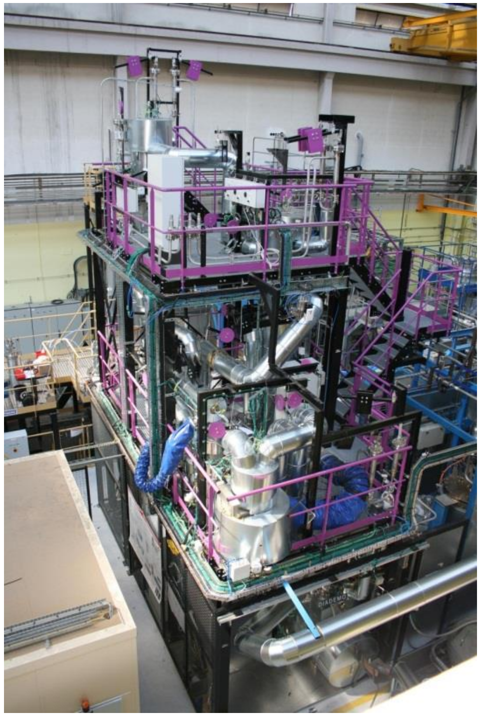
1 component = assembly of 8 compact heat exchanger “module”
2 module designs with / without external pressure vessel
(Collaboration with Rolls Royce/UK)

R&D focused on :

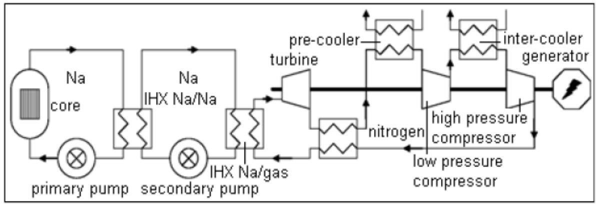
1 - fabrication/performances of heat exchanger « module »
  Fabrication process under development (HIP) ->small scale prototypes
  Test program (DIADEMO test loop, 2013-2015)

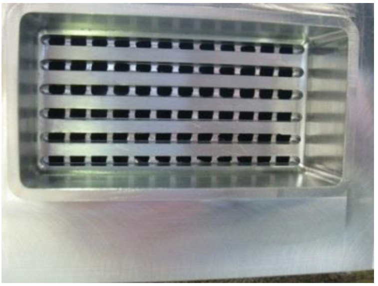
2 - characterization of HIP-316 L material

3 - specific inspection needs and applicable technics

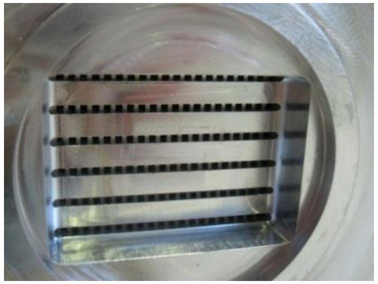


DIADEMO Facility
(CEA Cadarache)

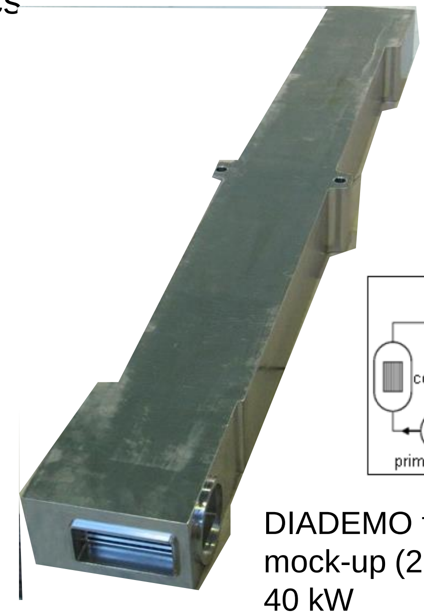




Sodium chanels entry



Gas chanels entry



DIADEMO test
mock-up (2013)
40 kW

Electro-Magnetic Pump for large Na flow-rates (2m³/s)

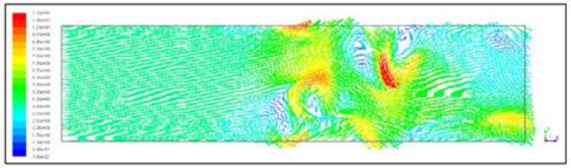
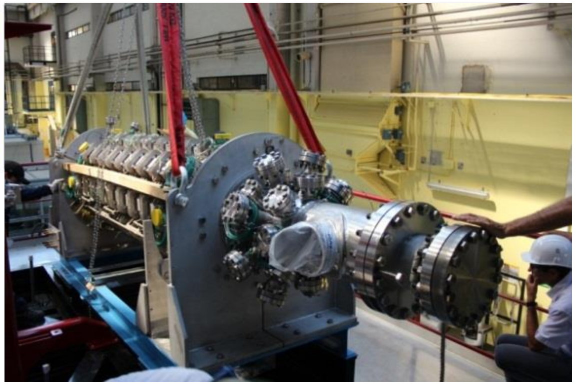


Figure 67: Vectors of velocity; v [m/s]; ε = 2.6; t = 1s.



Primary pumps

Mechanical pumps, conventional design

Secondary pumps

(ALIP: annular linear electromagnetic induction pump)

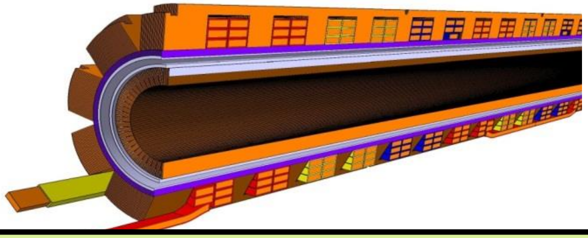
Design: collaboration with Toshiba/Japan

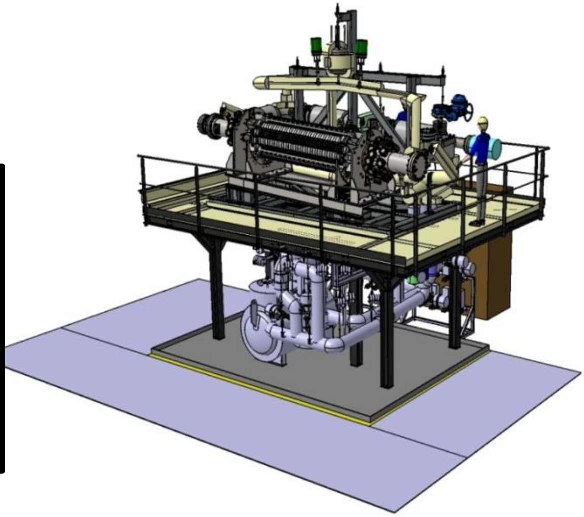
R&D: collaboration with IPUL, University of Latvia, CNRS – SIMAP Grenoble

Dynamic behavior of Electromagnetic pump, MHD code assessment

Test program (PEMDYN, 2014-2015)

Small scale prototype





Instabilities identified with large flow-rates (1450 m3/h) in ALIP pumps
Lack of data: necessity to understand them and estimate their consequences on the pump efficiency.
Modeling with ANSYS, COMSOL/FLUENT…and validation with MHD tests in IPUL-Salaspils and CEA-Cadarache; identification of pulsatory phenomena at high Rm. Amplification of perturbation in velocity field…

Ref: L. Goldsteins, L. Buligins, Y.Fautrelle and C. Biscarrat
Numerical quasi stationary and transient analysis of annular linear electromagnetic induction pump
Proceedings of COMSOL Conference 2013 (Rotterdam-NL)

GISEH PLATFORM

Facilities devoted to thermal-hydraulics tests

Name of the facility: PLATEAU – 1^{st} mockup of the hot plenum MICAS

Hydraulic studies can be done with water

Experimental objectives:

PLATEAU is a modular platform in water design to perform some hydraulic and thermal hydraulic test programme on large scale mockup (1:6 to 1:8).
The 1^{st} mockup called MICAS will model the upper plenum (hot collector).

Specifics:

PLATEAU thermal-hydraulic loop
Facility has been commissioned in 2014 (3^{rd} quarter)

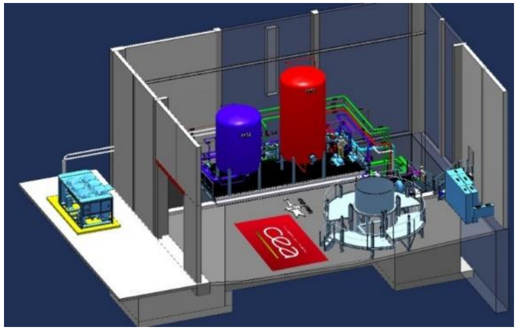
First mock-up (MICAS) (1:6 - 360°)
Connexion to PLATEAU in 2015

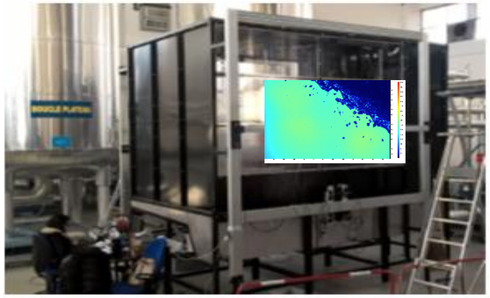
➔ **For each test section, main characteristics:**

WATER LOOP
Different types of tests
- **isothermal steady state test condition**
- **thermal transient state test condition**

T° : 10 to 60°C
P : 2 bars in the core area of the mock up
Patm at the free liquid interface with air
Q : 0 to 350 m^3/h

➔ **Other tests (Na fragmentation…)**



GISEH PLATFORM

Facilities devoted to thermal hydraulics in fuel assemblies

Name of the facility: **BACCARA**

Experimental objectives:

Achieve the hydraulic and mechanical test qualification on ASTRID's fuel assemblies, control rod , irradiation devices… in full scale configuration (single object)

Specifics:

Facility has been re-qualified in 2014

Design and building of the first test section 2015

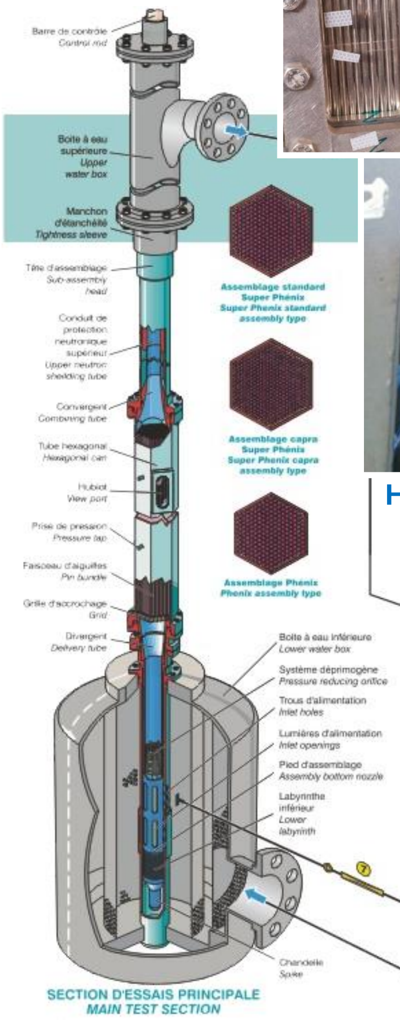
➔ For each test section, main characteristics:

T: **[30 to 90 ° C]**

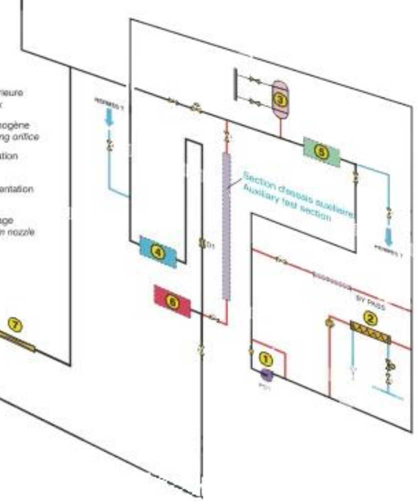
P: **[4-15 bar]**

Q medium flow rate : **[0 to 250 m³/h]**

Scale: **1:1**



Hexahub test section for SPX



PAPIRUS Platform

CEA experimental platforms (high temperature liquid sodium facilities)

Maximum sodium inventory around 300 tons (and now around 100 tons)

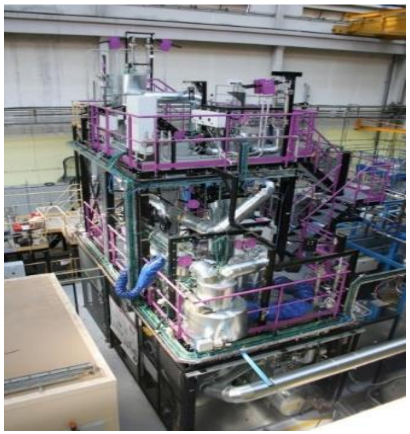
More than 60 years of operation

No major events with environmental consequences

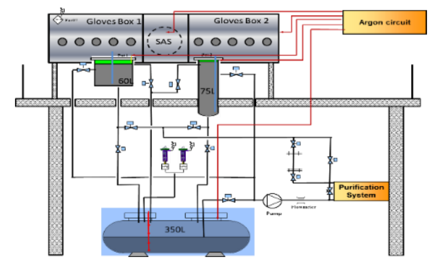
C. Latgé, P. Le Coz, O. Gastaldi, F. Gauché, N. Devictor.
"The ASTRID Project and related R&D on Na technology"
Conference PAMIR Riga (Latvia) June 2014

PAPIRUS –Experimental Platform Focus on some facilities

DIADEMO
First Mock-Up
Na-Gas Heat Exchanger



MECANA
instrumentations development,
gas characterization,
ultrasonic telemetry or imaging)
mechanical solutions (robotics arms)



PEMDYN
(Electro-magnetic Pump)

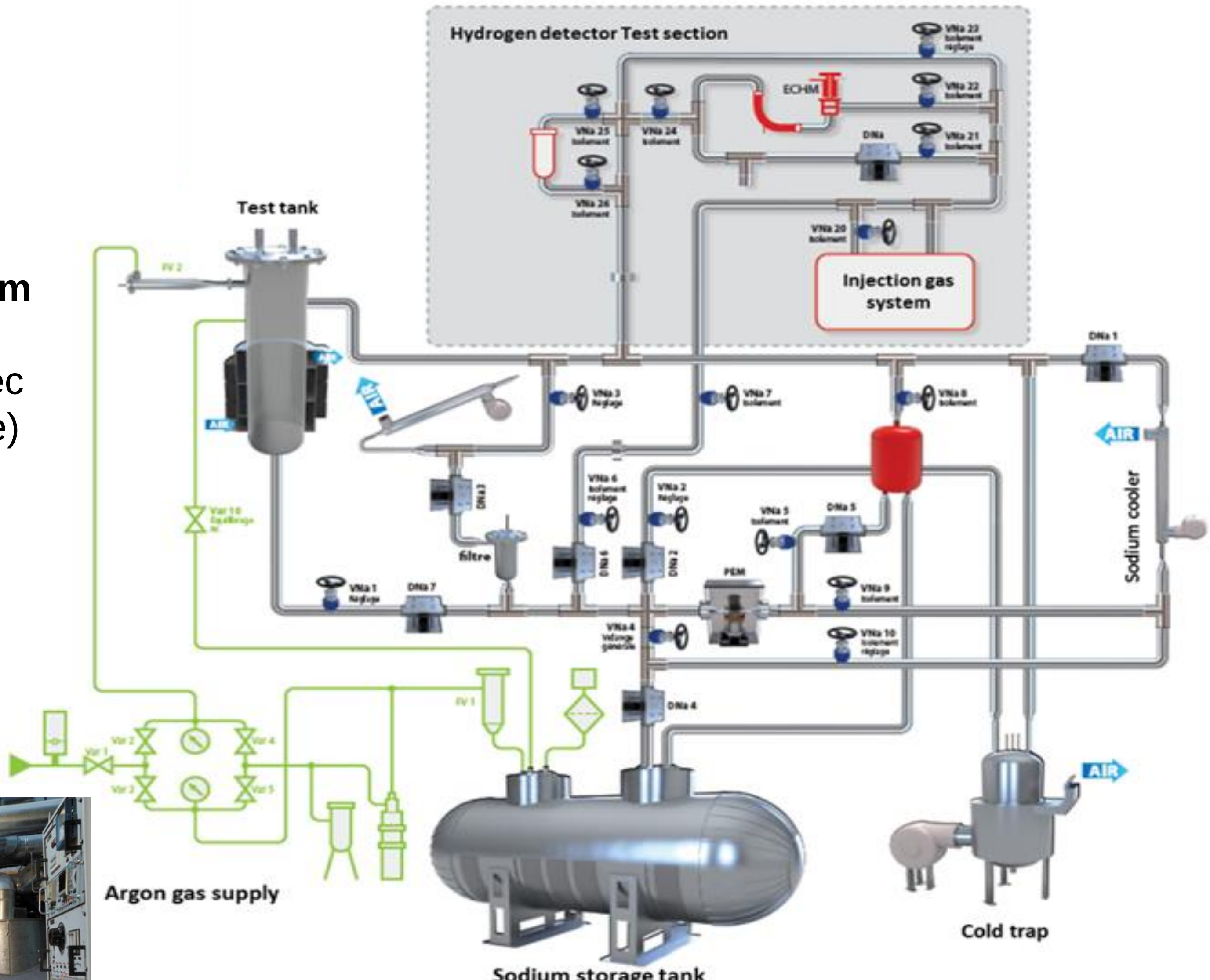
FUTUNA 2
(Na leak detection)

OVERVIEW OF A SODIUM LOOP: DEVOTED TO EDUCATION & TRAINING

Example of sodium loop:
Superfennec
(Cadarache)

sodium

Argon gas



C. LatgéE, F. Beauchamp, L. Gicquel “Teaching Sodium Fast Reactors in CEA”
GIF Symposium October 2018 Paris, France

CONCLUSIONS

Sodium is a very attractive coolant for various applications, ie chemistry, basic research, energy...

Sodium has been selected as a SFR coolant due to its very attractive properties.

It can be underlined the following points:

- **Low activation of Na allows easy handling operations, Na treatment, …**
- **Materials corrosion in Na is low and well mastered,**
- **Coolant purification is easy and efficient**
- **Dosimetry is well mastered**
- **Due to its opacity (a characteristic of liquid metals), In Service Inspection of the reactor mainly with Ultra Sound systems**
- **Thermal stresses on structures well assessed, thanks to improved computations and global hydrodynamics validation.**
- **Na water reaction is well mastered**
- **Sodium fires: large efforts to mitigate these potential events.**

New improvements are currently developed to improve safe operation and technologies.

Thank you for your kind attention!

Merci beaucoup pour votre attention!