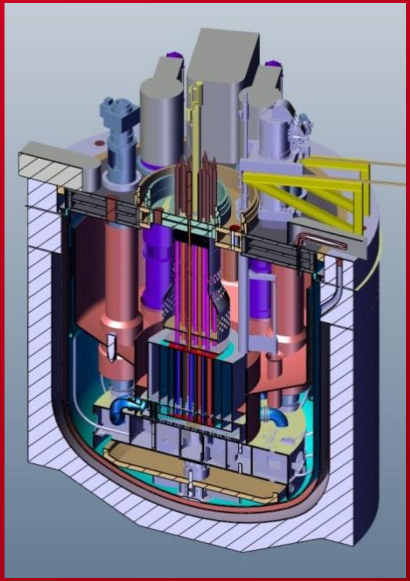
DE LA RECHERCHE À L'INDUSTRIE



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Séminaire

FLUIDES CALOPORTEURS POUR LES RNR

Académie des sciences

Fondation Simone et Cino del Duca, Paris 8e
19 et 20/02/2013

Sodium properties and behaviour in primary vessel of a Sodium Fast Reactor

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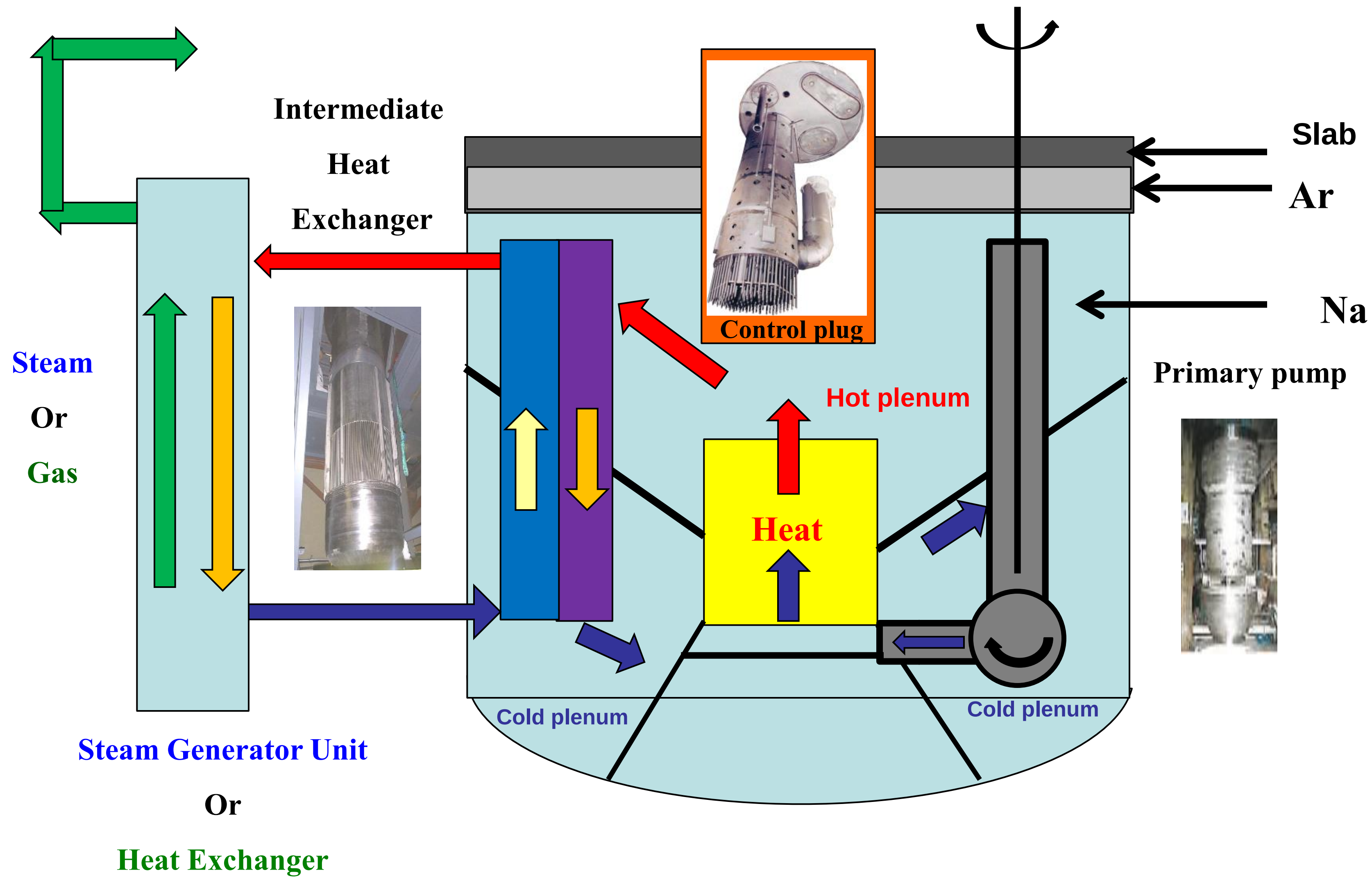
PRIMARY CIRCUIT OF SFR (POOL CONCEPT) 1/2



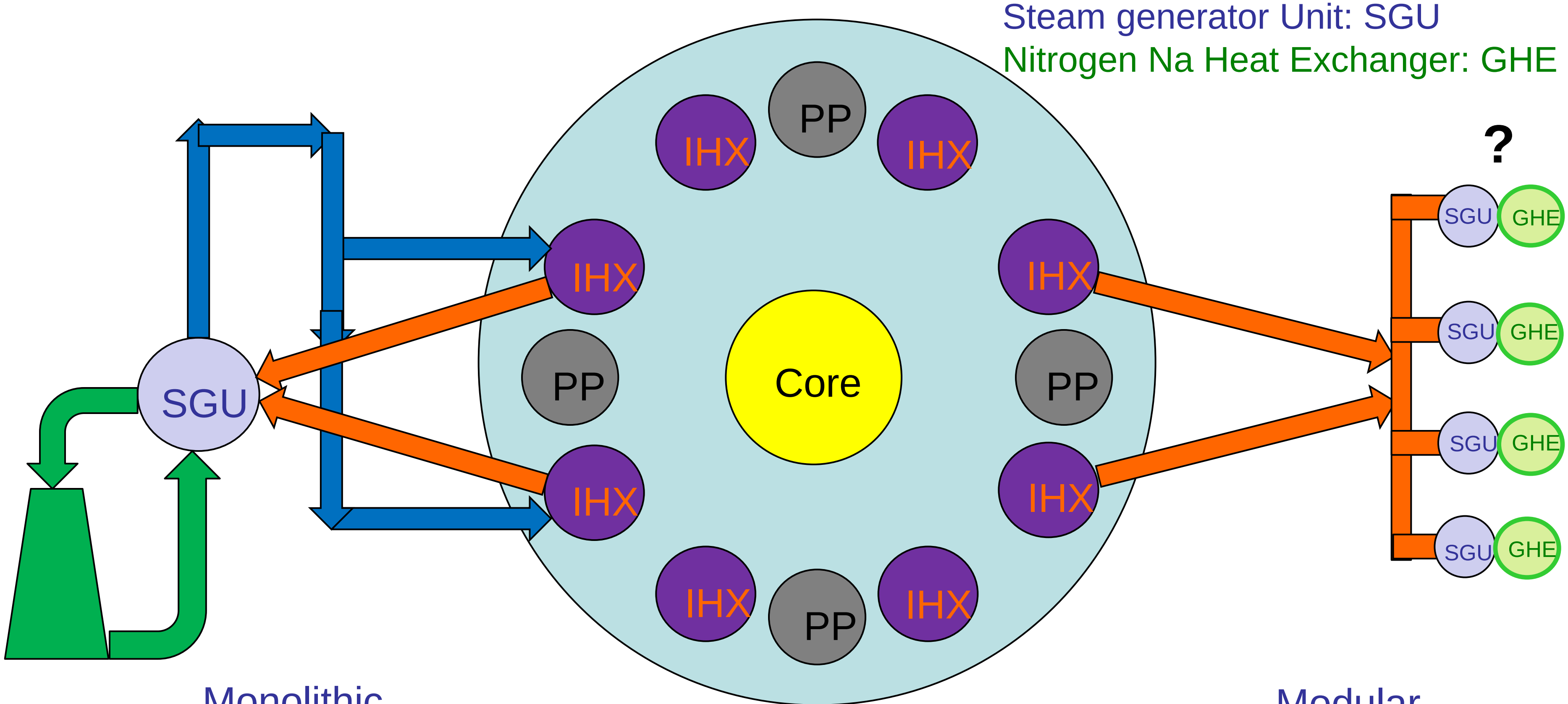
PRIMARY CIRCUIT OF SFR (POOL CONCEPT) 2/2

Primary pump: PP

Intermediate Heat Exchanger: IHX

Steam generator Unit: SGU

Nitrogen Na Heat Exchanger: GHE

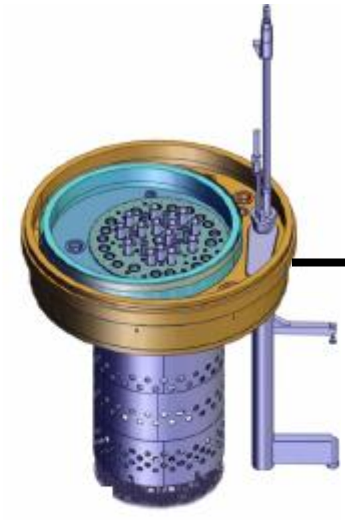


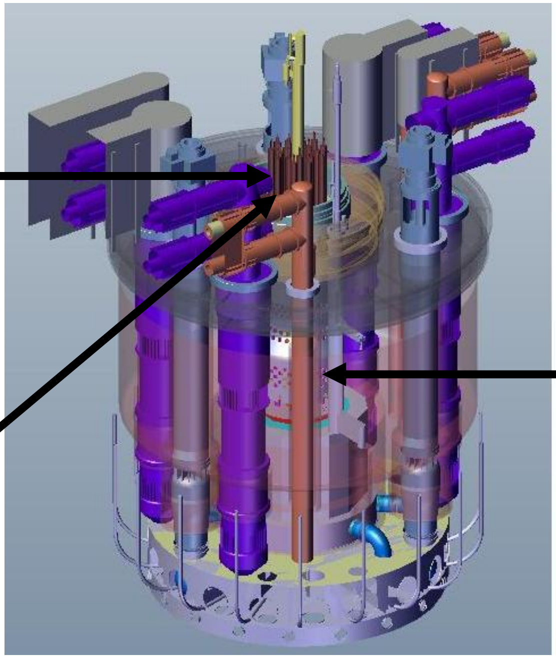
Monolithic
Steam generator

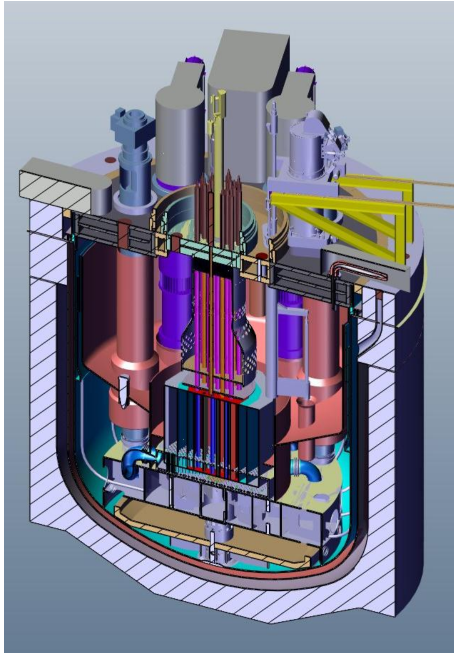
Modular
Steam generator
Or
Gas Heat Exchanger

View of the ASTRID primary system

Handling systems







Control rods

Fuel Assemblies

GENERAL PROPERTIES OF NA

A low melting point at 97.8°C:

– allowing shut-down for ie handling operations at T below 200°C, ie 180°C,

– avoiding risk of freezing in the SGU, particularly if the SGU is used as a DHRS,

– favouring periodical inspection campaigns, at relatively low temperatures.

A large range of temperature in liquid phase (97.8°C- 881.5°C):

– usually, the cores of SFR had a positive void coefficient (in case of absence of Na (ie boiling) insertion of reactivity inducing a power transient.

– for ASTRID, design by CEA of a new core with an overall nil void coefficient.

A low density and low viscosity:

– due to the similitude between Na and H_2O density and viscosity,

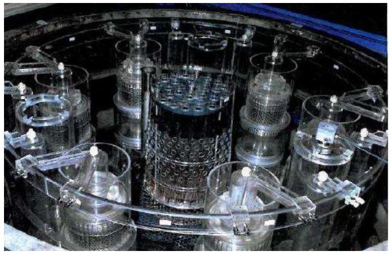
➔ experimental thermo-hydraulic studies and code validation with water.

– low density of sodium favors passive and mastered fuel relocation by gravity in a core catcher, in case of core destruction, avoiding possible recriticality.

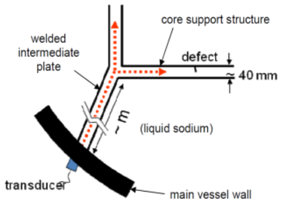
– low density allows also having passive shut-down systems, by gravity.

– low density favors US transmission in structures, due to the large Δ of density between steels & Na.

No specific toxicity, large availability and cheapness



Integral mock-up Colchix 4 for EFR (water)



C. Latge, P. Agostini et all "*Liquid Metal Fast Reactors cooled by sodium or lead: issues and synergies*". IAEA Technical Meeting On Fast Reactor Physics & Technology IGCAR KALPAKKAM (India) Nov 2011

NEUTRONIC PROPERTIES OF SODIUM

- **Has little slowing effect on neutrons produced by fission, does not change fast spectrum properties**
- **Has low capturing power (small cross section)**
- **Doesn't produce any alpha contamination (ie ^{210}Po)**
- **Has low level of activation***

***But must be of "nuclear quality"**

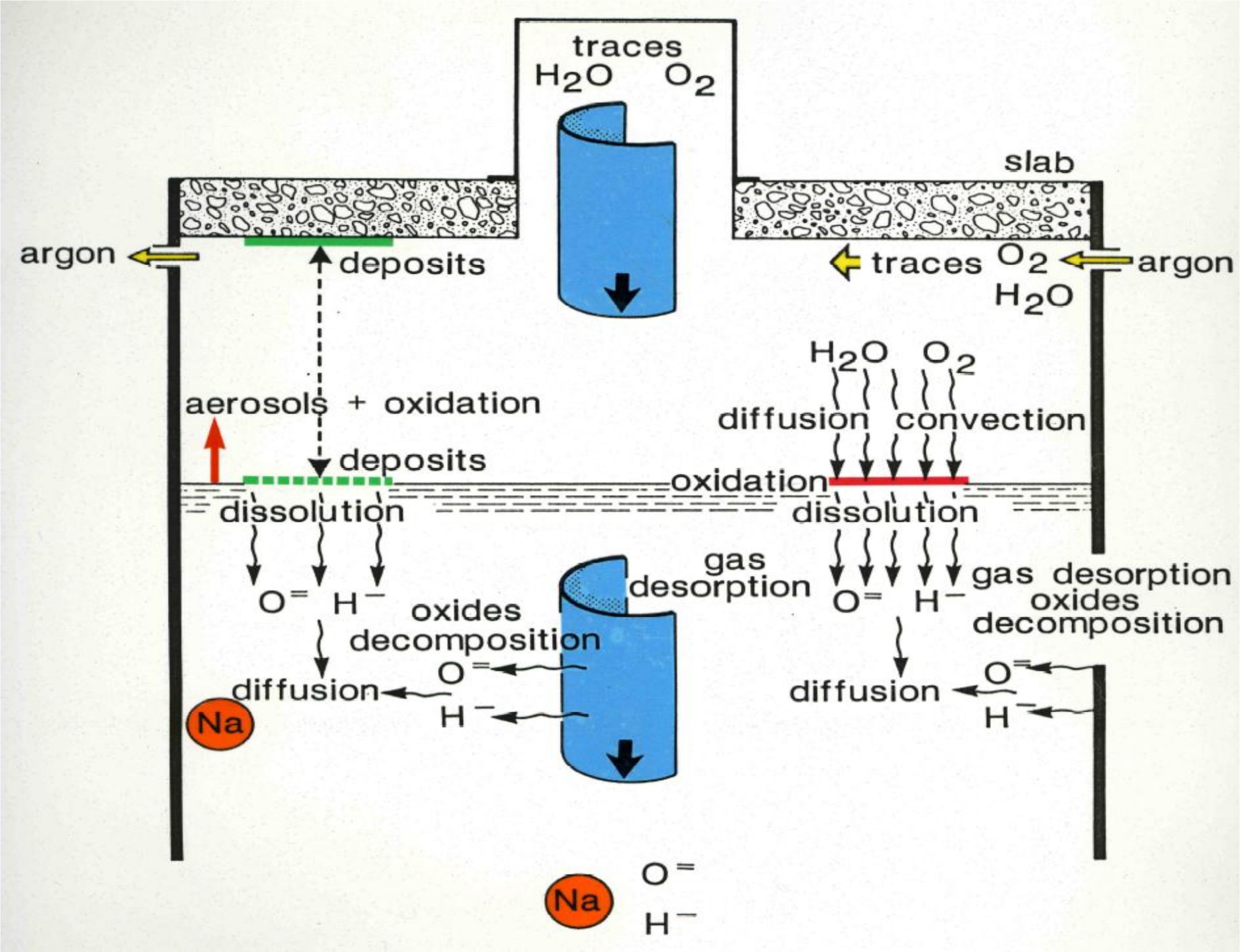
NEUTRONIC PROPERTIES OF SODIUM

Reaction	Product		Types of decay	Half-life
n, γ (21)	$^{24}_{11}Na$		β- (1) 0.28 MeV(0.05%) β-(2) 1.39 MeV (99.94%) β- (3) 4.14 MeV (0.003%) γ (1) 1.00 MeV(0.001%) γ (2) 1.37 MeV (99.992%) γ (3) 2.75 MeV (99.94%) γ (4) 2.87 MeV (0.000 2%) γ (5) 2.87 MeV (5.2 %) γ (6) 4.24 MeV (0.0008%)	14.98 h
n,2n (21)	$^{22}_{11}Na$		β+(1)0 ,545 MeV (89.8%) K (1) 1.567 (10.11%) K (2) 2.842 (0.0002%) β+(2) 1.820 MeV (0.06%) γ 1.275 MeV	2.60 y
n, p (2)	$^{23}_{10}Ne$		β-4.39 MeV (67%) 3.95 MeV (32%) 2.40 MeV (1%) γ 0.44 MeV (33%) 0.47 MeV (100%) 0.88 MeV (8%)	38 sec
n, α (2)	$^{20}_{9}F$		β-5.42 MeV (100%) γ 1.63 MeV (100%)	11 sec

NUCLEAR GRADE SODIUM (MSSA): SPECIFICATIONS

Silver	< 5	Activation
Barium	< 5	Clogging
Boron	< 5	Nuclear reactions
Calcium	5	Clogging
Carbon (total)	10	Mechanical properties
Chlorine + bromine	15	Corrosion
Lithium	< 5	Tritium
Sulphur	20	Corrosion
Uranium	< 0,1	Nuclear reactions
Aluminium	< 5	…………
Chromium	< 3	
Copper	< 3	
Tin	< 2	
Magnesium	< 2	
Manganese	< 2	
Molybdenum	< 5	
Nickel	1	
Lead	< 2	
Potassium	~ 300	Gas blanket activity
Titanium	< 5	
Vanadium	< 3	
Zinc	< 2	

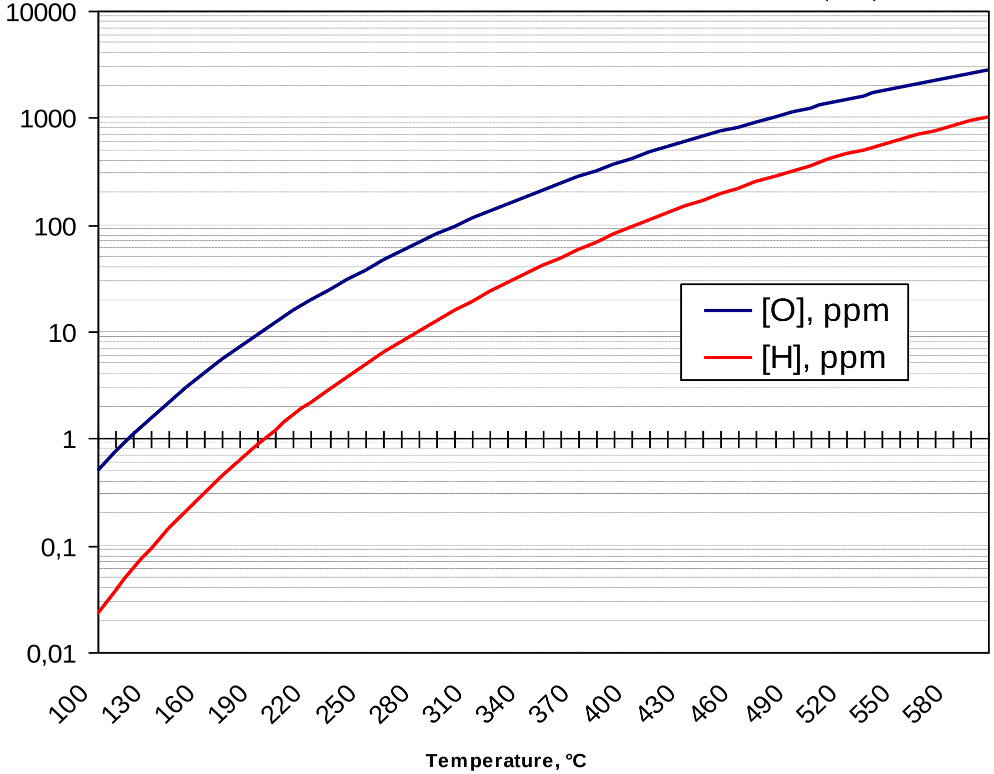
POLLUTION


traces
H_2O O_2
slab
argon
deposits
traces O_2
H_2O
argon
H_2O O_2
aerosols + oxidation
diffusion convection
deposits
oxidation
dissolution
dissolution
gas
desorption
$O^=$ H^-
oxides
decomposition
gas desorption
oxides
decomposition
$O^=$
diffusion
H^-
Na
$O^=$
H^-
diffusion
$O^=$
H^-
Na
$O^=$
H^-

SOLUBILITIES OF O AND H IN SODIUM

Wittingham solubility law

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

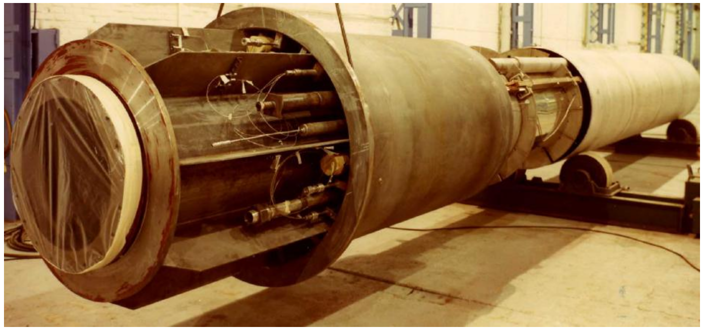


Noden solubility law

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

O and H solubilities are negligible close to 97.8° C

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

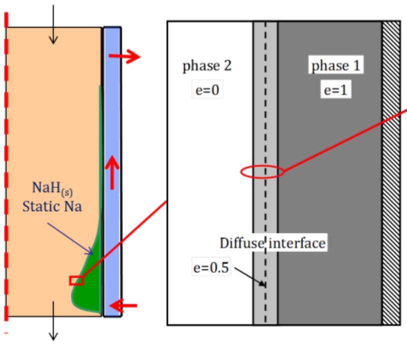


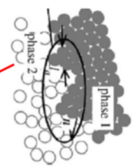
C. LATGE, *"Sodium quality control, In International Conference on Fast reactors"*, Kyoto, Japan, (December 2009).

Quality of Na has been always well mastered with cold traps, in normal or transient situations (start-up purification, large air pollution in SPX)

MODELING OF MASS TRANSFER IN COLD TRAPS

A deposit sodium hydride front view as a diffuse interface

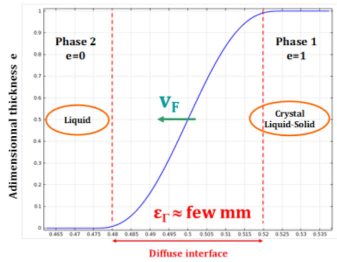




v_F: Crystllization front velocity

Function of Nucleation and Growth kinetics, ***defined on wire mesh packing*** cold trap.

Introduction of a new variable « e » to determine the phase field: Na/NaH



$$\frac{\partial e}{\partial t}+\overline{v_{FS}}.\nabla e=\beta\nabla\left[(\varepsilon_\Gamma\,\nabla e)-e(1-e)\left(\frac{\nabla e}{|\nabla e|}\right)\right]$$

β refers to a reinitialization parameter (m/s)

Crystallization Front velocity

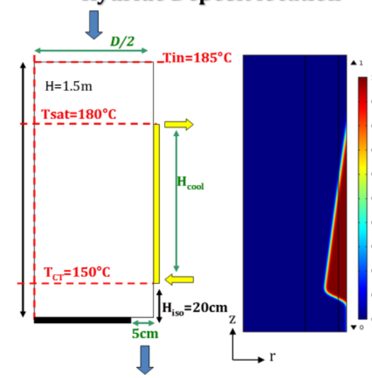
Front velocity corresponds to the translation rate of the diffuse interface, such that each elementary volume over the interface keeps the same porosity during its translation. Hence, over the thickness of the diffuse interface, the material derivative of porosity is set to be equal to zero:

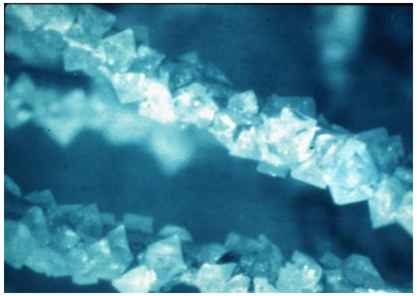
$$\frac{D\phi}{Dt}=\frac{\partial\phi}{\partial t}+v_F(r)\frac{\partial\phi}{\partial r}=0$$

$$v_F(r)=\|\vec{v}_F\|=\frac{\left|\frac{\partial\phi}{\partial t}\right|}{\left|\frac{\partial\phi}{\partial r}\right|_{fixed}}\quad for\ [\partial\phi/\partial r\neq 0]$$

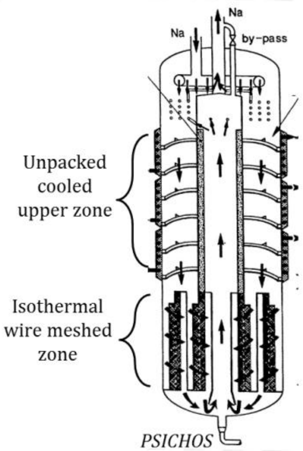
Parameter to initialy define

Exemple of Sodium Hydride Deposit location





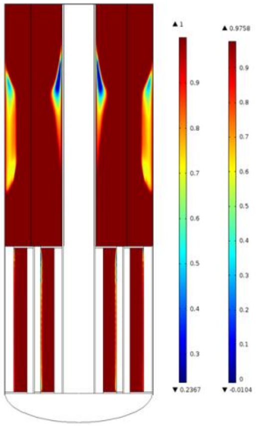
N. Khatcheressian et all *“Development of a mass transfer model for Na purification system in a SFR”.* IAEA Conférence FR13 Paris March 2013



PSICHOS SuperPhenix secondary loop Cold Trap

- Both Impurities: H and O
- Hydrogen crystallization on cold walls
- Cocristallization on wire mesh packing
- Duration: > 5 years
- Purification specifications to apprehend
- Design and operation to optimize

Porosity profils on walls and packing



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

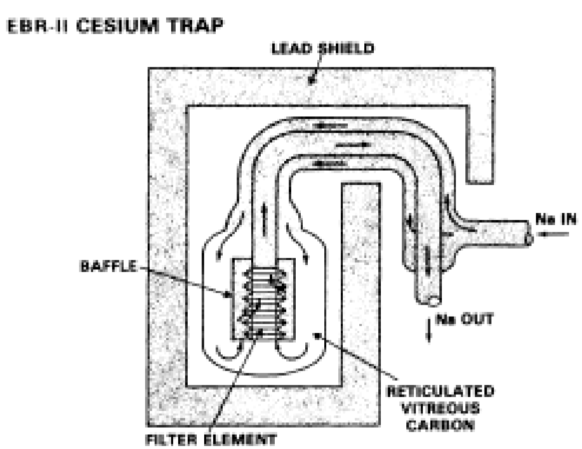
Efficient process ; operation at T around 200°C

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

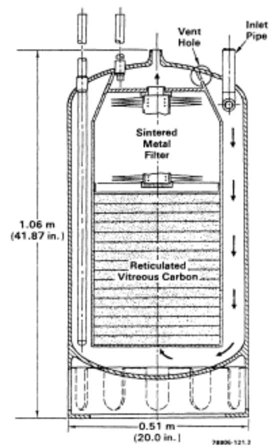
Applied to EBR2, BOR60, RAPSODIE, …

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

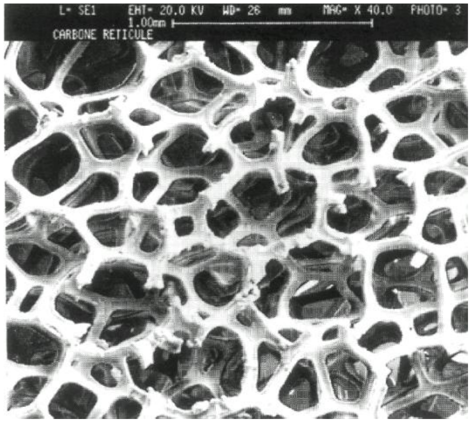
3 cartridges adsorbed about 0.49 TBq ^{137}Cs



EBR2 : piège RVC

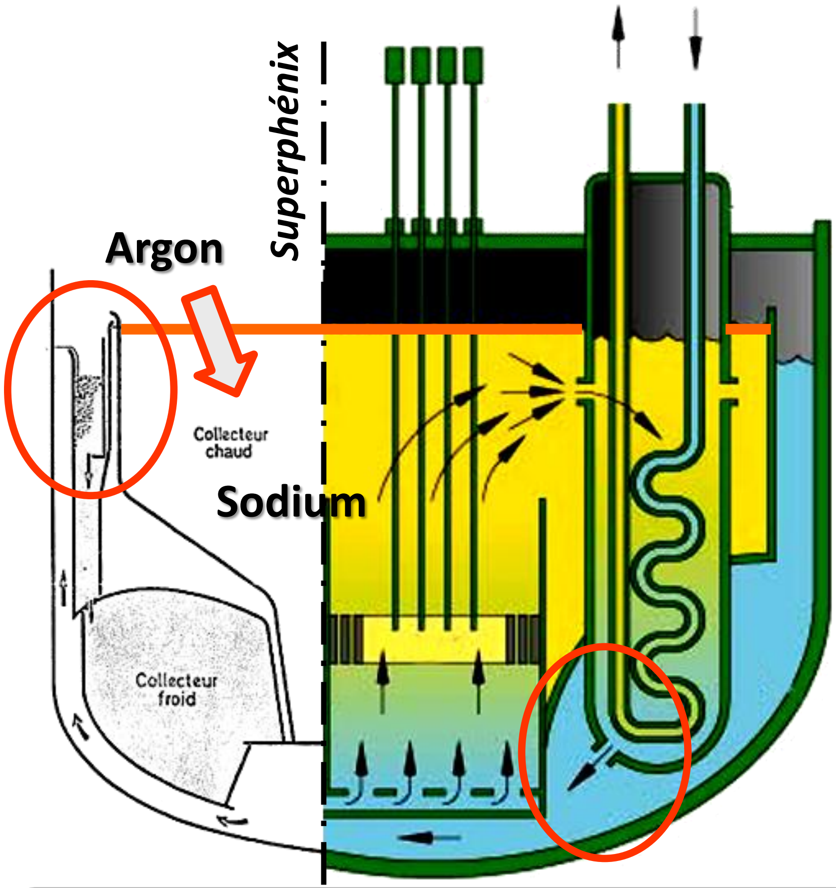


FFTF : piège RVC



RVC

Bubble presence in primary sodium



OBJECTIVES

CHARACTERISATION OF :

VOID FRACTION ($V_{BUBBLES}/V_{TOTAL}$)
($\tau \approx 2{,}5.10^{-6}$ for Superphénix)

MICROBUBBLES RADII HISTOGRAMS
($10\mu m \leq R \leq 100\mu m$ pour SPX – estimation)

CAUSES

- Dissolution ► Nucleation in oversaturated areas (Henry's law)
- Entrainment phenomenon
  - Weir (« waterfall effect »)
  - Pumps shafts
  - Vortex
- Neutronic reactions (^{41}K ► ^{41}Ar, B_4C ► He…)
- Auxiliary circuits

CONSEQUENCES

- Acoustic properties modifications of liquid Na
  - Attenuation
  - Velocity
- Risk of gaz pocket accumulation

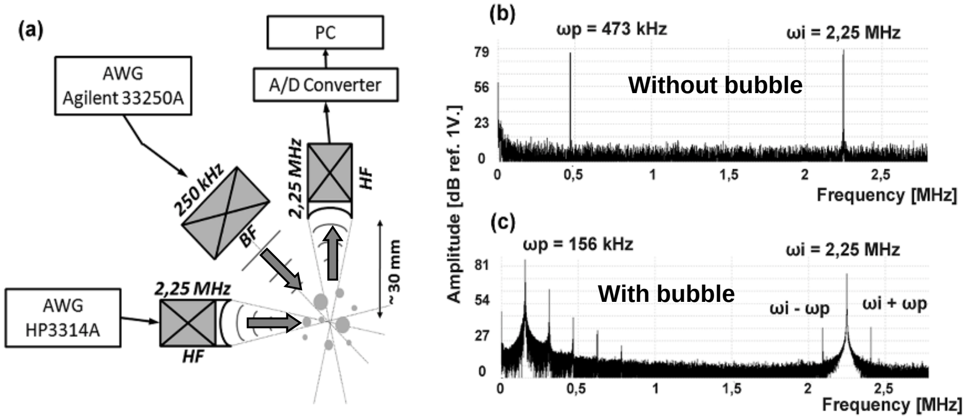
ISSUES

- The mastery of the origins of this gas presence
- The evaluation of its consequences
- The validation of computational codes (VIBUL…)
- The response to a request from French Nuclear Safety Authority

Microbubbles characterization – Acoustical techniques 1/2

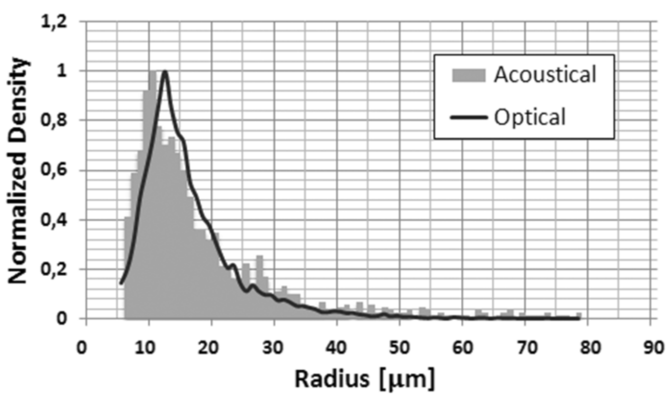
Nonlinear frequency mixing (HF-LF or HF-HF)

- Based on the nonlinear behavior of a resonant bubble
  - A resonant bubble insonified with two frequencies leads to the apparition of mixed frequencies



  - Detection of resonant bubbles allows determining the radii bubble histogram

Histogram obtained with HF-BF mixing



- Excellent results have been obtained in water[1]
- Experiments with sodium compatible transducer and then in liquid sodium are scheduled

[1] M. Cavaro, C. Payan, J. Moysan, F. Baqué - Microbubbles cloud characterisation by nonlinear frequency mixing – J. Acoust. Soc. Am., Express Letters, 129(5), EL179-EL183, May 2011

Are ECFM usable as free gas detector?

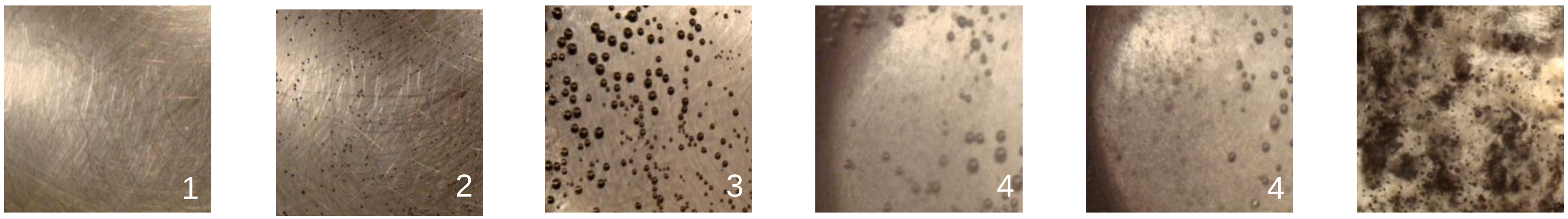
If yes, what are its limits (void fraction and bubble sizes)?

Is the characterisation (not only the detection) possible?

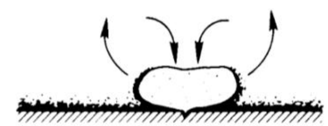
NA BOILING ACOUSTIC DETECTION

The Principle

- **Example: Boiling Water**

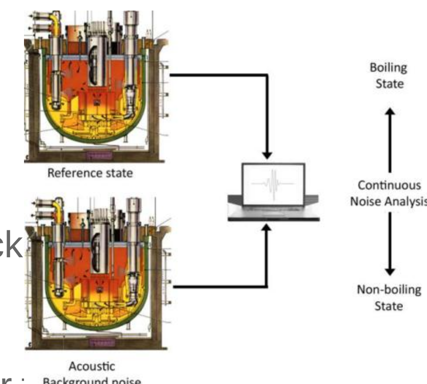


1. Water heating. Nothing happens
2. Non-condensable gasses (N_2, O_2, …) nucleate
3. The bubbles of non-condensable gasses grow
4. Visually we observe a small turbulent zone
   whilst a hissing sound is heard: Subcooled Boiling



- **The Sound Source:** Small, practically invisible bubbles condense after a contact with the sub-cooled liquid
- **Acoustic detection is thus possible at the earliest stage!**

Motivation



- **Detect Boiling inside Sodium Fast Reactors**
  - Prevent any positive reactivity insertion by void reactivity feedback
  - Prevent degradation of heat transfer and fuel failure
- **Detect Initiating accidents such as subassembly blockages**
  - **Now**: by detecting delayed neutron precursors in the coolant after
  - Better: detect boiling before fuel damage occurs

M. Vanderhaegen et all *“R&D program for French SFR on the description and detection of sodium boiling phenomena during sub-assembly blockages”* 2011 Annima Conference Gent Belgium.

ACOUSTIC BOILING SOUND

Sodium Boiling inside subassemblies

- No subcooled boiling due to very gradual temperature profile
- Nucleation with practically non-existent superheat
- Direct formation of large liquid slugs
  - High expansion ratio
  - Gradual temperature profile
- Direct slug flow pattern in typical mini-channels of SFR fuel assemblies
- **Conclusion**: bubbles are a first approach

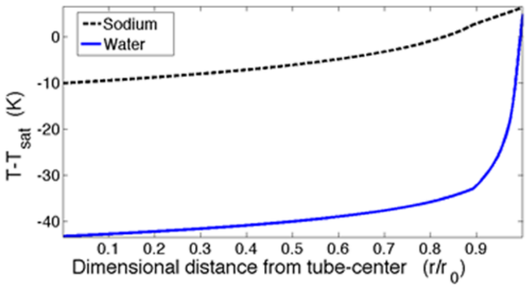


Fig. Temperature profile at the onset of boiling (tube ϕ=3mm). Re=10^4. $q_{Na} = 2MW/m^2$, $q_{H_2O} = 0,5MW/m^2$.

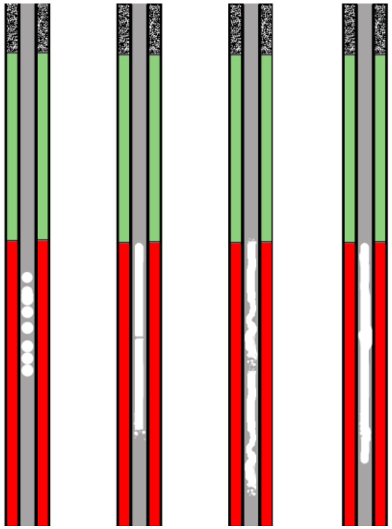


Fig. Flow patterns in mini-channels. From spiral train, over slug to annular flow regime

Physical Phenomena

- **Bubble nucleation pressure pulse**
  - Pressure wave proportional to superheat, thus **very small**
- **Bubble volume oscillation pressure pulse**
  - Pressure pulse depends on oscillation amplitude
  - Can be considered **very small** for slug flow
- **Bubble Condensation pressure pulse**
  - Vapor temperature decrease, thus vapor pressure does too (Ideal gas law: $pV = nRT$) implosion follows
  - The bubble's internal pressure increase again and a rebound with shock wave follows. Can be **very large**.

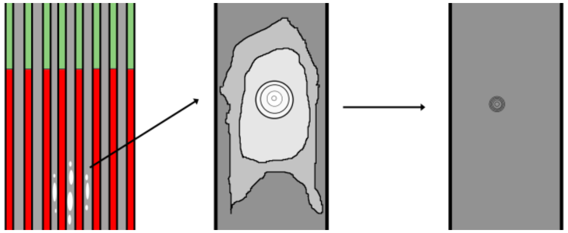


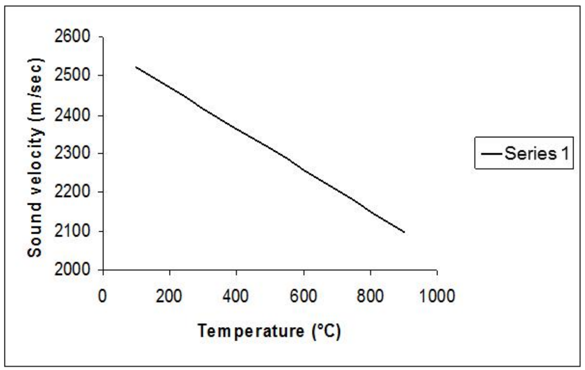
Fig. Example of Condensation inside an SFR assembly

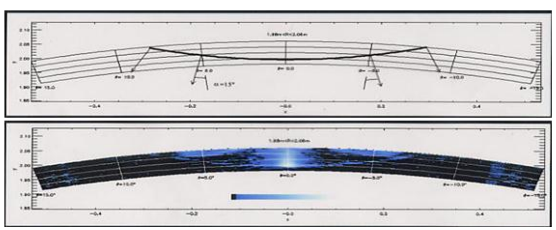
SODIUM OPACITY: ULTRA-SOUND TECHNOLOGIES

- **As all liquid metals, sodium is opaque;**
- **necessity to develop adapted technologies for telemetry and visualization**

Sound velocity in sodium varies little with temperature and is given by the following relationship:

$$C\ (m/sec) = 2577.2 - 0.5234\ \theta \qquad 100 < \theta < 370°C$$

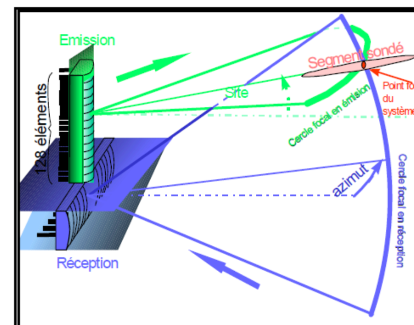




Consequences: **Property used for telemetry and visualization in sodium facilities, and for acoustic detection of events in Na**

F. Baqué et all: *"Sodium Fast Cooled Fast Reactor: R&D Program for improving periodic examination and repair"* . Science and technology of nuclear installations Journal, July 2012

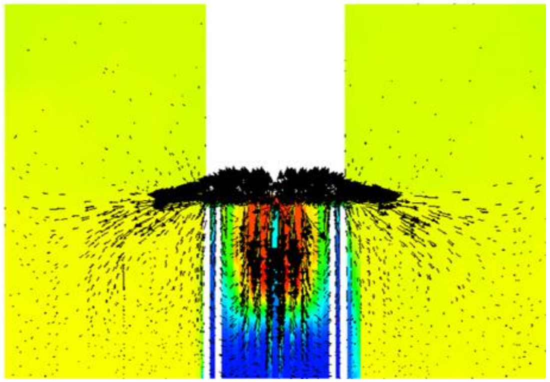
Multireflector mock-up



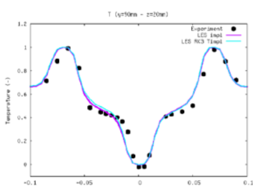
Imarsod antenna

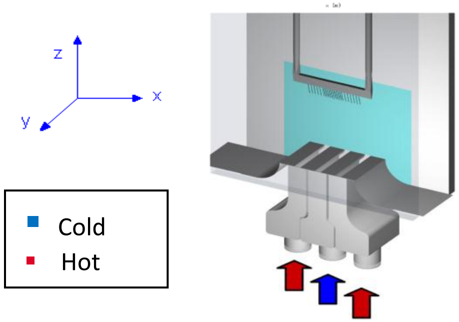
- Surface mapping (imaging) of submerged structures/components,
- Integrity inspection of structure/component surfaces (including the detection and sizing of opened cracks),
- Determination/confirmation of robotic system positioning,
- Fuel assembly identification,
- Detection, localization and sizing of immersed objects (including migrating bodies).

US measurement of T at the subassemblies outlet: Evaluation of potentialities of this innovative method



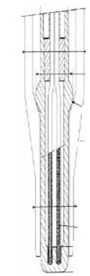
Temperature and speed vector field in sodium-cross section of a SFR reactor (CFD simulation)

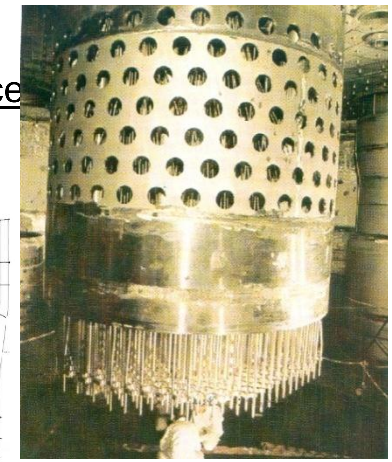




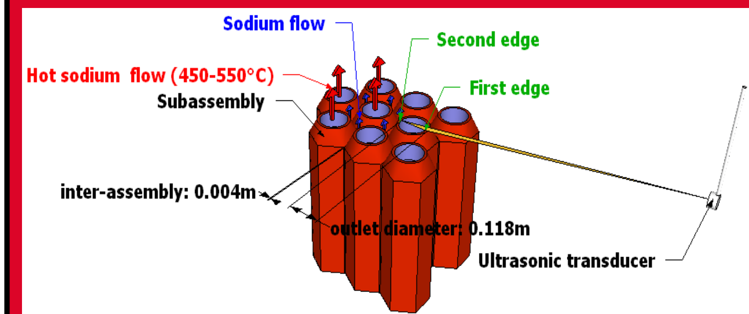
PLAJEST experiment geometry *

Thermocouple restrictions: need of a thermowell above each monitored subassembly, minimal distance between thermowell and subassembly outlet.





≈350 thermowells, containing 2 thermocouples each. (Time response SPX: 1.1s)



Patent in 1985: McKnight and al. (UKAEA)

Advantages: fast, localized, non-invasive, simultaneous measures on several subassemblies).

Ultrasounds propagation depends of :

- Temperature: Inhomogeneities of temperature inside the sodium (ΔTmax=50K)

Speed flow field: Turbulent flow (Re=60 000), speed (about. 4 m.s^{-1}), speed gradient (1.5m.s^{-1}.cm^{-1}).

➔ Induces deviation and diffusion of ultrasounds.

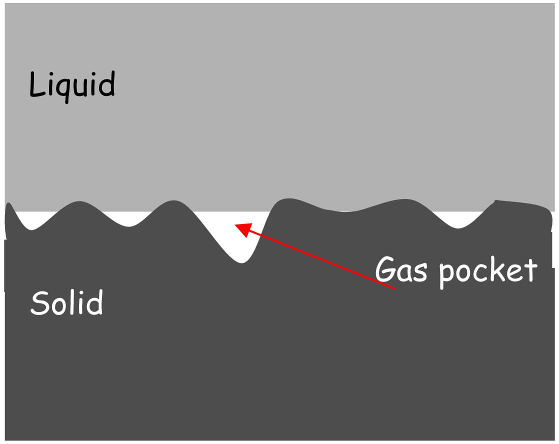
Goal: Define an appropriate model for ultrasonic propagation (in T, v field)

N. Massacret et all: *"Simplified modeling of liquid sodium medium with temperature and velocity gradient using real thermal-hydraulic data. Application to ultrasonic thermometry in SFR".* DENVER - 39th QNDE Congress July 2012

WETTING PHENOMENA

Wetting phenomena, which depend of gas adsorption, structural material oxidation,… are key interface phenomena between the coolant and the structural material. Therefore it is considered as a key factor with regards the following items:

- **accuracy of measurements** for some instrumentation devices such as ultra-sonic based traducers, electro-magnetic flow-meters, electro-chemical cells,…
- **interactions between structural material and liquid metal**: corrosion, embrittlement, stress corrosion cracking….
- **mass transfer** such as activated corrosion products, tritium,…
- **thermal exchanges in Heat Exchangers**, liquid metal targets,…
- **Technology developments, cleaning of residual layer,…**



➔ Due to non-significant material embrittlement in Na, there is no necessity to foresee coatings to prevent wetting and its deleterious consequences.

(except to prevent from wearing & fretting effects)

➔ Na: a strong reducer: a very good wetting is obtained, even at low temperature *(ie T=180°C)* thanks to the possibility to reduce oxygen content down to a very low value (< 3ppm)

CORROSION IN NA

Background:

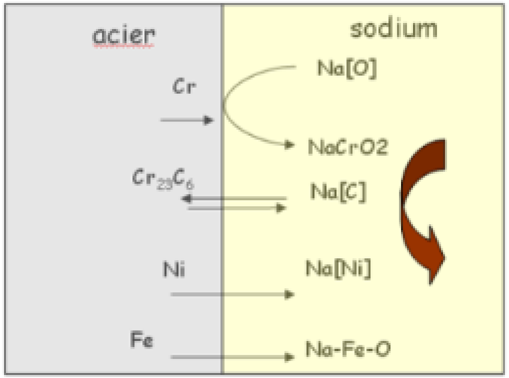
Very good compatibility of steels with pure sodium ([O]< 5 ppm) for steels used with operating conditions of the existing reactors.

Nevertheless, new needs for ASTRID and SFR

- Life duration for structures: 60 years (316LN…)

- New materials: ODS, advanced austenitic steels,….

Na	Normal conditions	Transients
1	370-550°C - max 650°C 8-12 m/s - [O] < 5 µg/g	850°C (s- min) [O] = 15 µg/g/ 100 h
2	300-550°C - some m/s [O] < 5 µg/g	[O] = 200 µg/g/ 2000h



Corrosion: homogeneous phenomena but several mechanisms: dissolution, oxidation, intergranular diffusion (C, O, H, B), mass transfer

Parameters: température, duration, hydrodynamics, [O], activities, minor alloy compounds (ie Mo), microstructure, neutron flux, ΔT (IHX)…,

Consequences:

- mainly release of activated corrosion products,
- réduction of thickness (to a less ext

Basic research required to improve the knowledge:

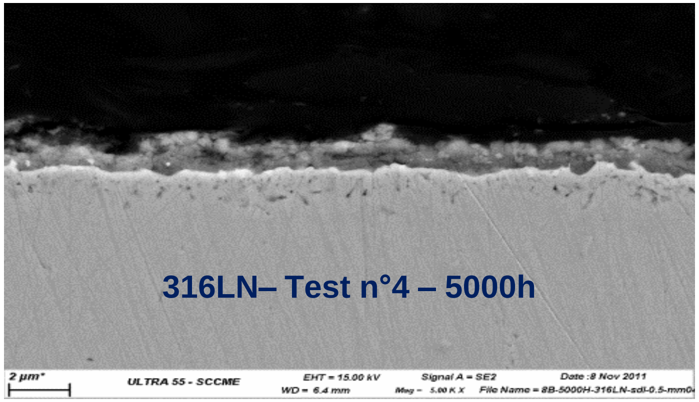
- ternary oxides behaviour (Na_4FeO_3 …),
- effect of solvation,
- diffusivities, …

Up to now Semi-empirical modeling:(Baqué – Thorley)

➔ Development of new corrosion models

➔ On-going development of a new transfer model (OSCAR-Na)

CORROSION IN NA



- Kinetics available up to 5000 h at 550°C for [O] < 10 µg/g
- Ferritic steels more sensitive to oxidation and carburization than austenitic steels
- 9Cr steels have a similar behaviour

CORRONa facility (CEA-DPC)

JL Courouau et all “*Corrosion by oxidation and carburization in liquid sodium at 550°C of austenitic steels for sodium fast reactors*” FR13 Paris March 2013

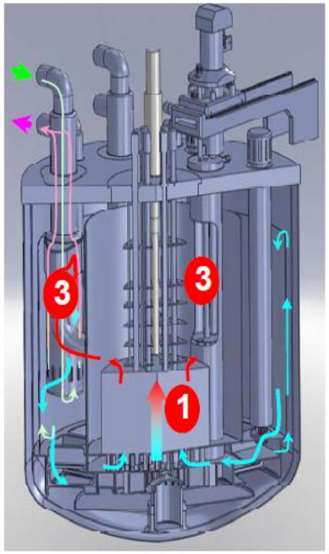
ACTIVATED CORROSION PRODUCTS IN NA

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, …)



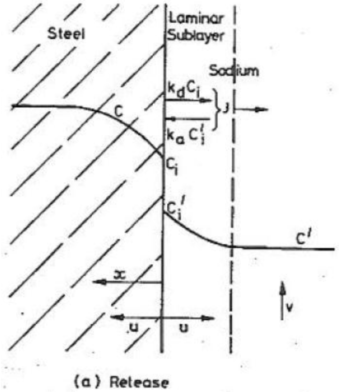
1) **Release from the activated cladding**
   - Bulk corrosion of cladding steel
   - Preferential release of highly soluble elements

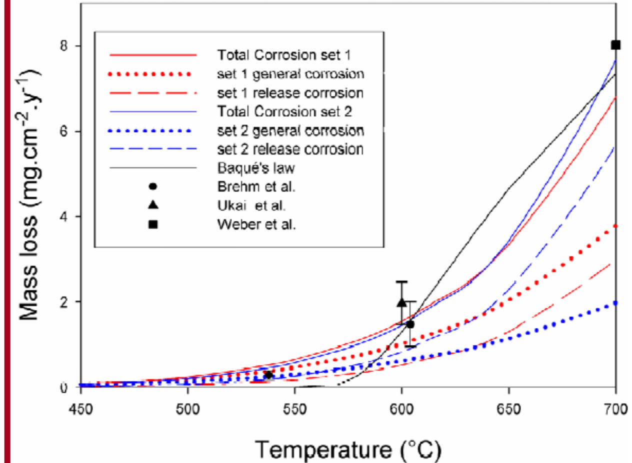
2) **Transfer in the flowing sodium**
   (parameters : T, velocity, [O])

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

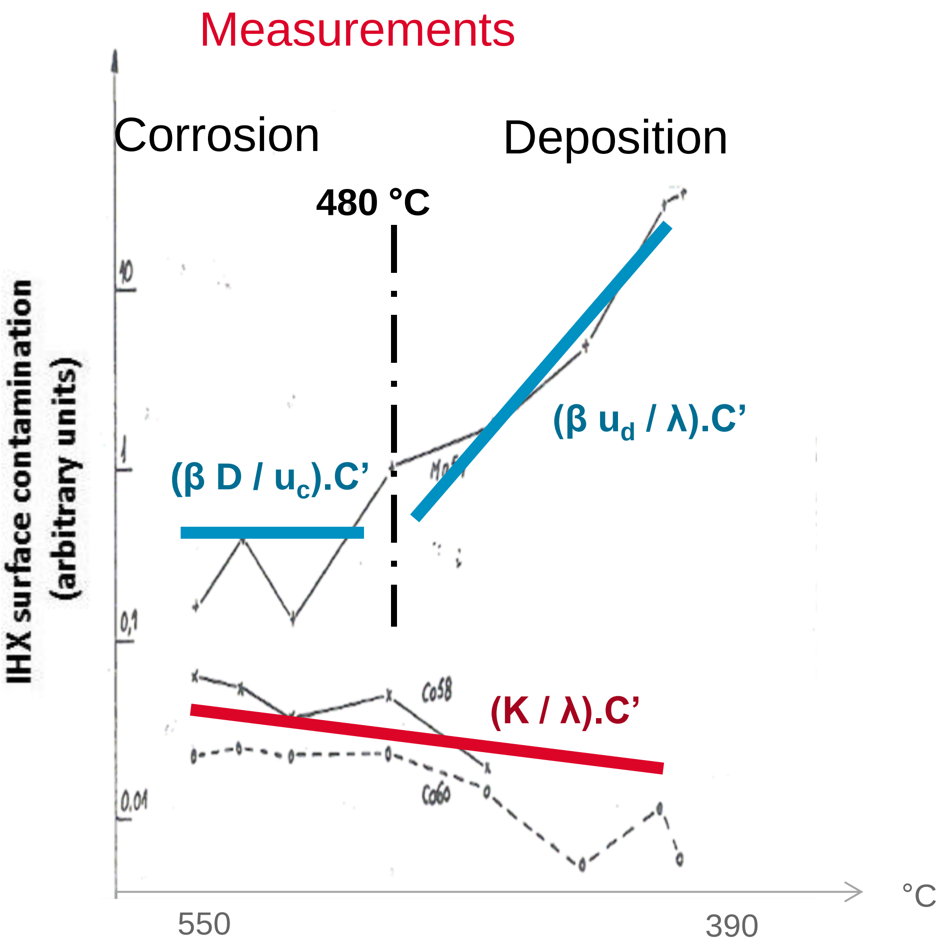


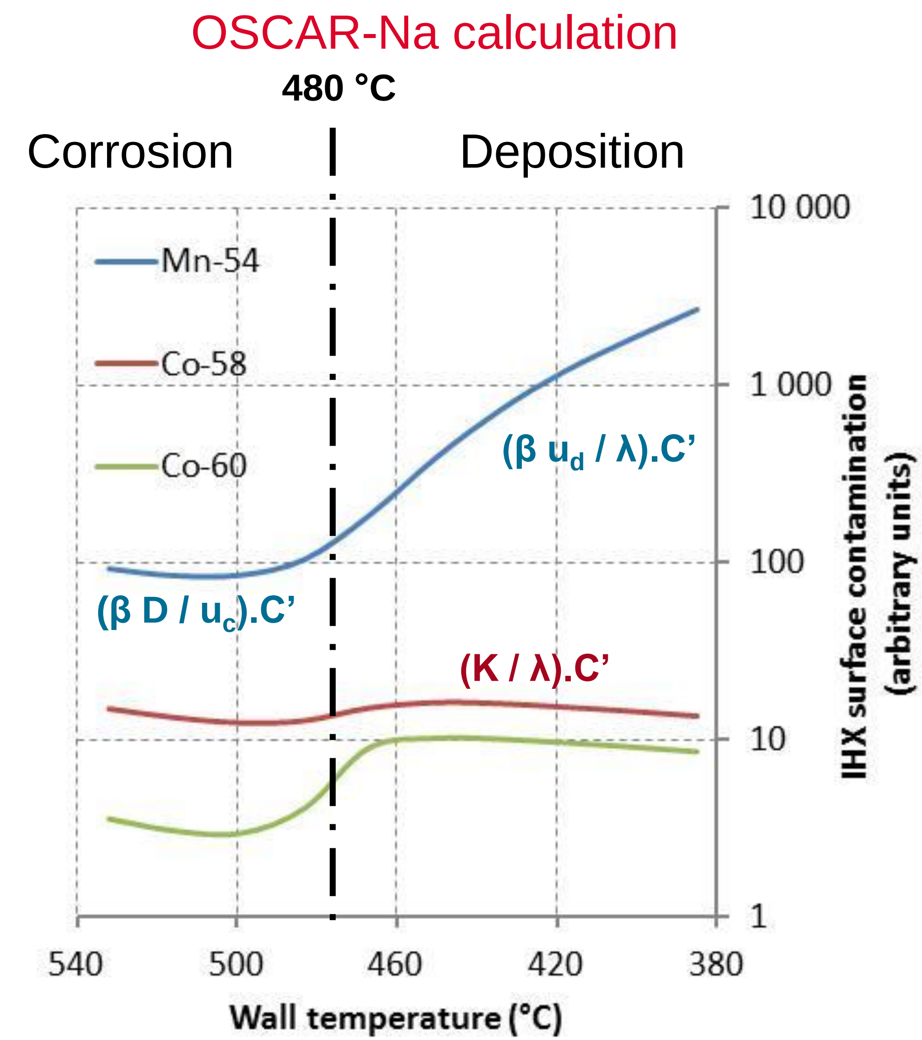


L. Brissonneau, "New considerations on the kinetics of mass transfer in sodium fast reactors: an attempt to consider irradiation effects and low temperature corrosion", Journal of Nuclear Materials 423 (2012) 67-78

Contamination and dosimetry in SFR are low in comparison with PWRs

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

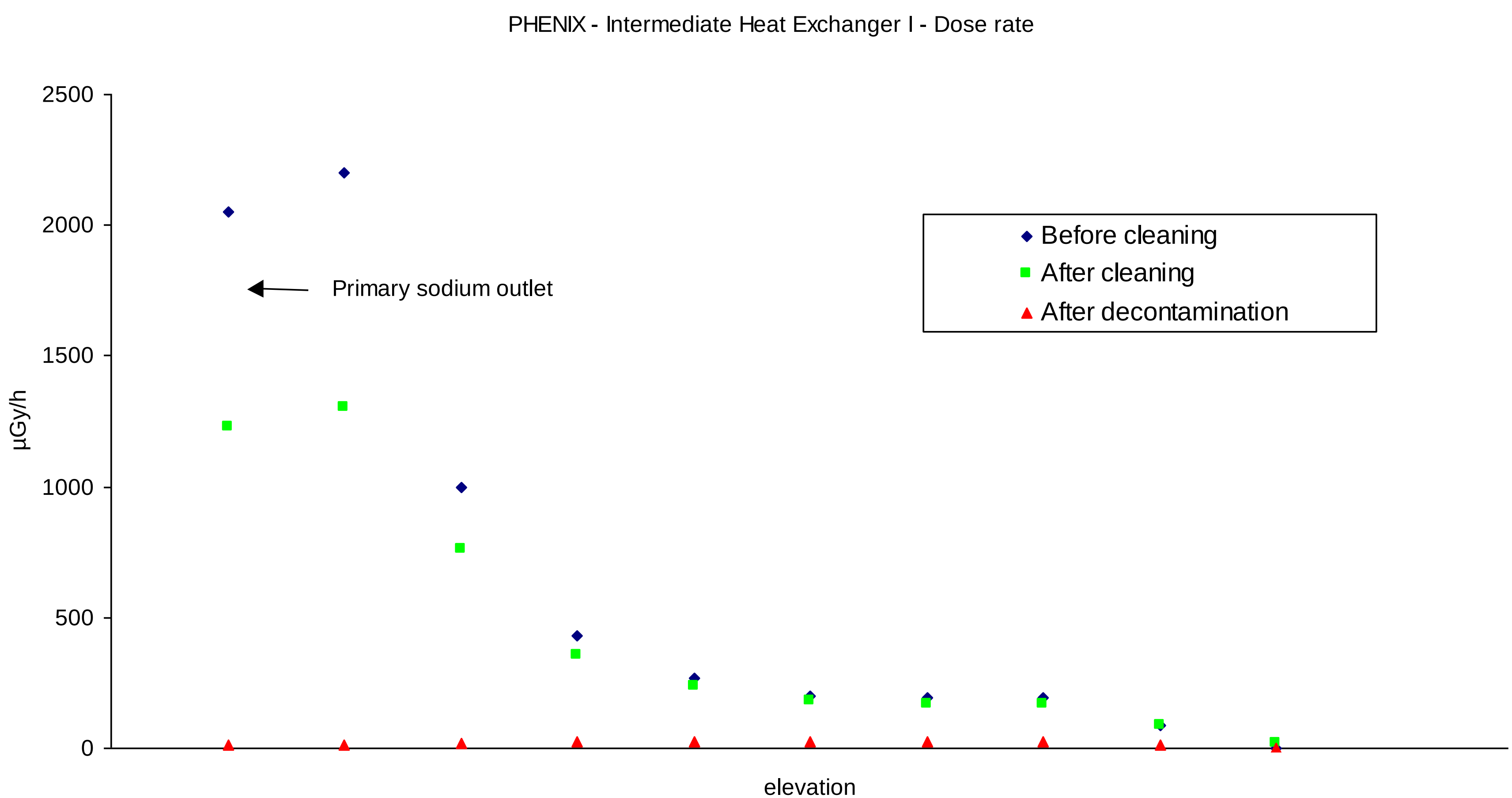




Global contamination as well as contamination profiles on PHENIX IHX are correctly simulated

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

PHENIX IHX ACTIVITY (EXEMPLE)



Prior to repair or inspection, Na cleaning (with steam) is well mastered, in safe conditions.
Decontamination with Sulfo-phosphoric process is very efficient
➔ Low dosimetry during handling operations

SACRIFICIAL MATERIALS FOR CORE CATCHER

SFR project: Enhanced safety requested

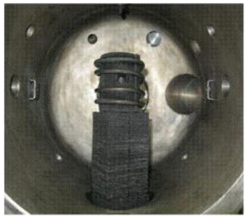
➔ Necessity to master the risk of a core meltdown accident

➔ Use of sacrificial materials to control the reactivity in the reactor and to prevent the recriticality*

- **Sacrificial materials**
  - Absorber materials: able to absorb neutrons coming from the nuclear chain reaction, ex: boron carbide B_4C in passive mitigation systems
  - Diluents: materials used in the core catcher, able to dilute the mixture of molten fuel and molten structures (=corium)
- **Objectives:**
  - To select the sacrificial materials for the SFR core catcher **(in VITI facility)**
  - To understand the behavior of the absorber material B_4C during interaction with corium, from chemical and thermodynamic point of view

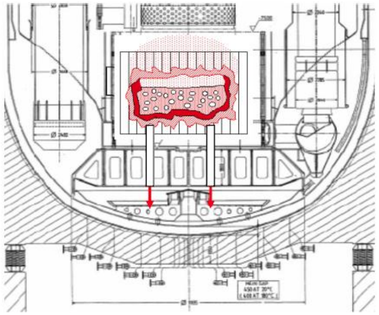
General view of VITI facility

- Synthesis of 2 types of materials based on HfO_2 and $LaAlO_x$ and first tests of compatibility in Na, in **CORRONa**



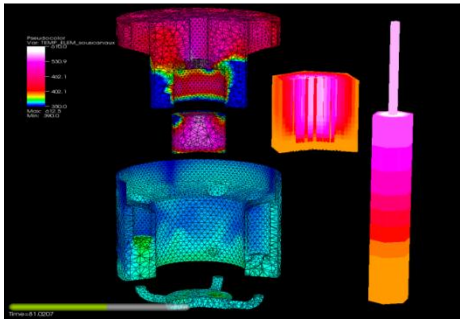
Induction furnace

➔ Studied mixture (≈ 10 g) placed in a protected graphite or tungsten crucible
➔ Inductive heating until **2600°C**
➔ Adjustable atmosphere (2 bars, under argon ≈ 5 L/min)
➔ Measurements during the experiments:
Melting temperature →2 pyrometers
Quantity of the formed gas → measure of pressure and gas flows
➔ Sample analysis after the experiments: identification of different formed products

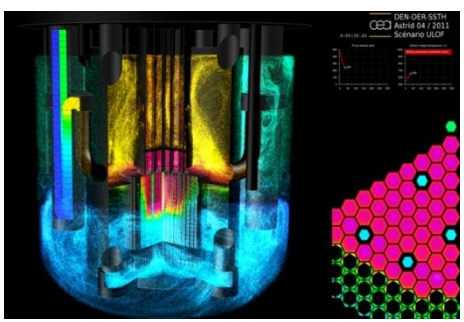


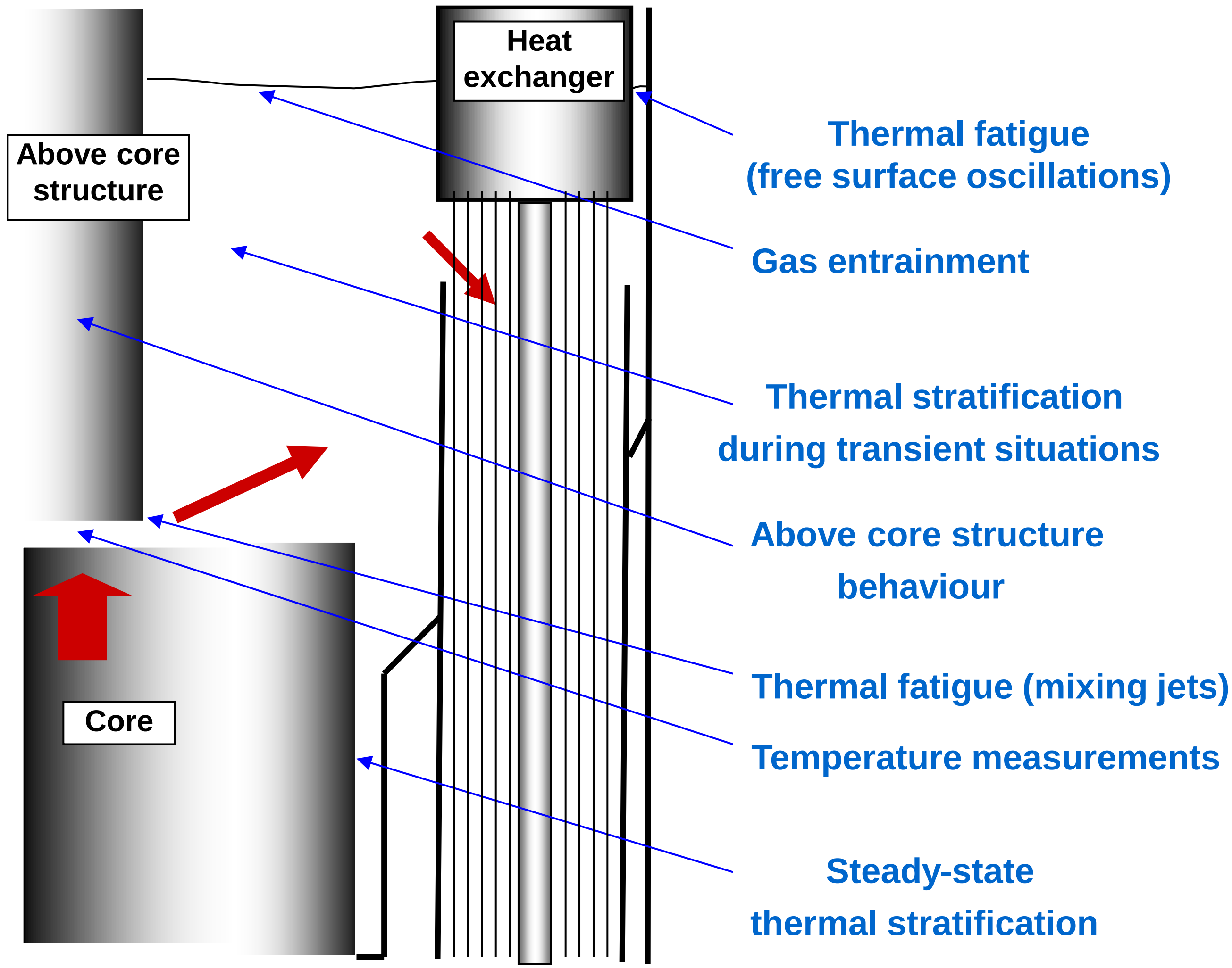
**Recriticality: occurs when corium forms a critical mass producing a sustained nuclear chain reaction ➔ generation of heat leading rapidly to melting and boiling*

Hydraulic and Thermal Hydraulic challenges in hot pool



Asessment of thermal stresses on the structures in:
- steady-state
- transient situations
by computation thanks to optimized system code coupled with CFD and, if required with mockups.





D. Tenchine, « Some thermal hydraulic challenges in sodium cooled fast reactors. », NED 240 (2010) 1195–1217.

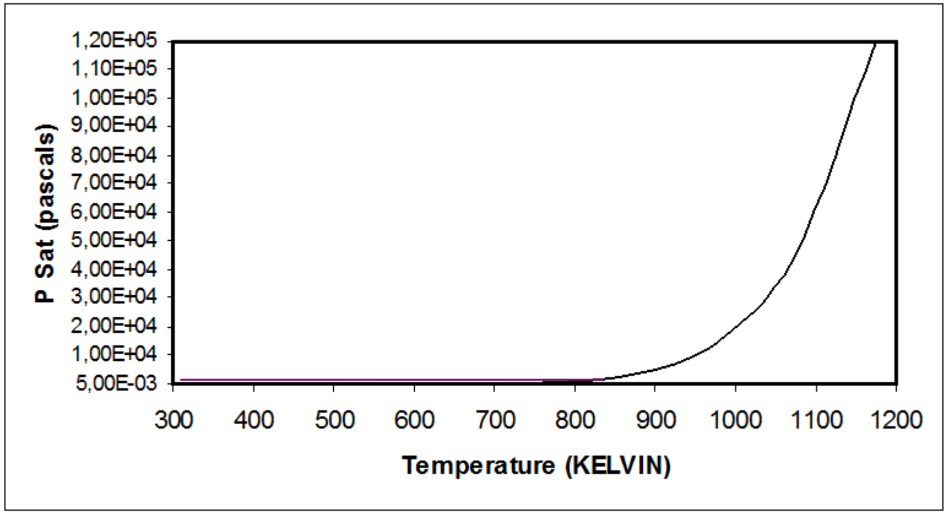
SATURATION VAPOUR PRESSURE

The empirical relationship for the saturation vapour pressure is given by the formula:

$$P_S = \mathrm{Exp}\left[A + \frac{B}{T} + C\,\mathrm{Ln}T + D\,T^E\right]$$

for 371 < T < 2573 K

Where A= 23.99, B= - 12.580, C= - 0.2241, D= 1.712 10^{-22}, E= 6

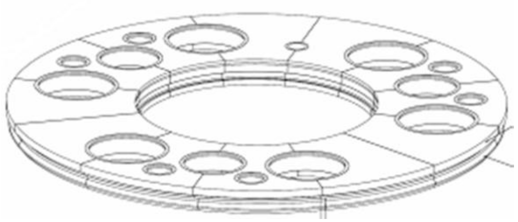


Consequences:

- **very few aerosols and thus low gas phase transfer**
- **very low flames in case of ignition (T> 140°C if in puddle)**
- **vacuum distillation cleaning ineffective ➔ hot gas cleaning used**

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:

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

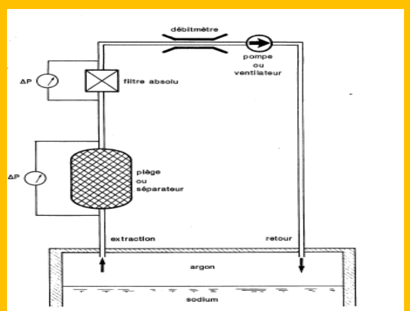
➔ Potential mechanical consequences on handling or rotating systems,…due to Na deposits (condensates):
Difficulties with control rods of PHENIX (one event),
➔ Gradual decrease of magnetic lifting surface; lifting force<rod weight (lifting of the rod impossible)
➔ local cleaning solved the problem

➔ Impact on viewing technologies in cover gas,…

➔ Impact on thermal insulation performances

➔ Impact on contamination and dosimetry (Cs,…)

➔ Impacts on decommissioning …



SCHEMA DE PRINCIPE DU CIRCUIT D'EPURATION DE GAZ DE COUVERTURE

➔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

CONCLUSIONS

Sodium has been selected as a primary coolant due 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, thanks to an efficient coolant purification
- Dosimetry is well mastered (Na and structures can be decontaminated)
- Due to its opacity (a characteristic of liquid metals), In Service Inspection of the reactor is carried out mainly with US systems.
- Thermal stresses on structures are assessed, thanks to improved computations and global hydrodynamics validation, with water mock-ups.
- Temperature of structures in gas plenum is well mastered; production of Na aerosols is limited.

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

Thank you for your kind attention