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Trieste Italy

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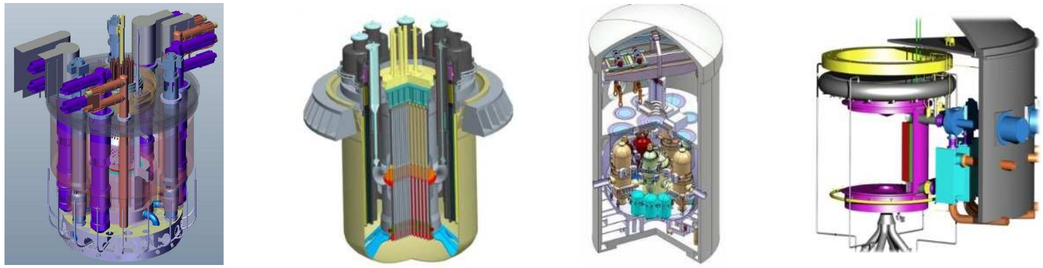

Coolant quality control & Purification

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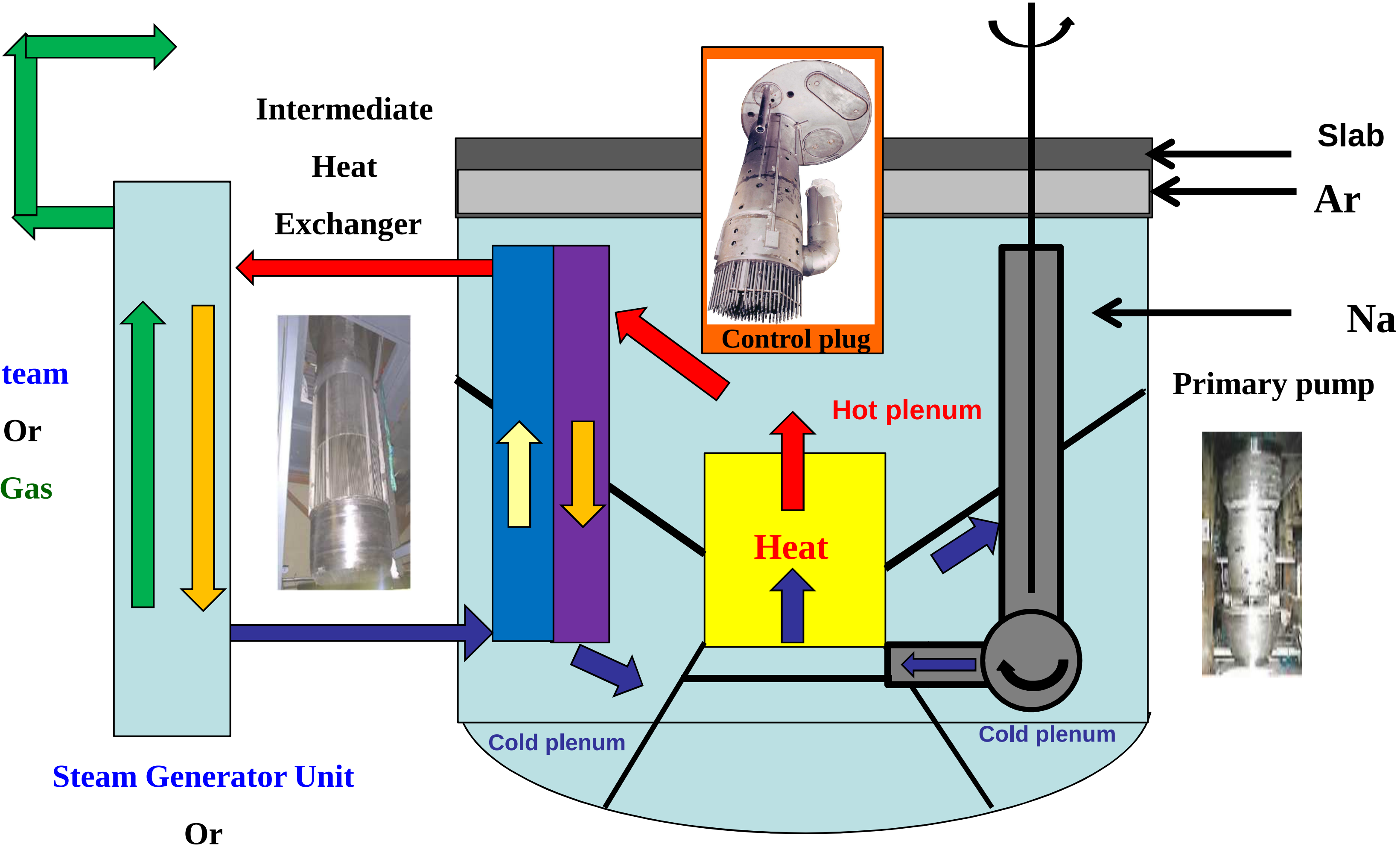
WHY IS IT NECESSARY TO CONTROL QUALITY AND TO PURIFY THE COOLANT IN LIQUID METALS

- **Primary coolant of XFR:**
  - **[O] is a key parameter of corrosion → contamination→dosimetry → necessity to decontaminate (handling, repair, ISI,..): necessity to master [O]**
  - **[O] well mastered can help to maintain oxide layer stable (protection against hard corrosion in heavy liquid metals HLM, enhancement of tribology)**
  - **[O] can induce precipitation of coolant oxide (issue for HLM: PbO due to very low dissolution rate, no problem for Na), and modify composition of binary alloys, Pb-Bi...**
- **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 ingresss in Na (Na-H_2O reaction generates H_2).**
  - **Moreover, Na purification allows to minimize tritium release. (Nota: Tritium release is a common issue for all nuclear systems, including FRs**
- **For all the circuits :**
  - **Control risks of plugging in narrow gaps, tubing, openings, seizing of the rotating parts, reduction of thermal transfer coefficient in IHX (Intermediate Heat Exchanger)…**

➔ to limit the plugging risk, 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℃

SFR

PRIMARY CIRCUIT OF SFR (POOL CONCEPT) 1/2



Intermediate

Heat

Exchanger

Control plug

Slab

Ar

Na

Primary pump

Hot plenum

Heat

Cold plenum

Cold plenum

Steam

Or

Gas

Steam Generator Unit

Or

Heat Exchanger

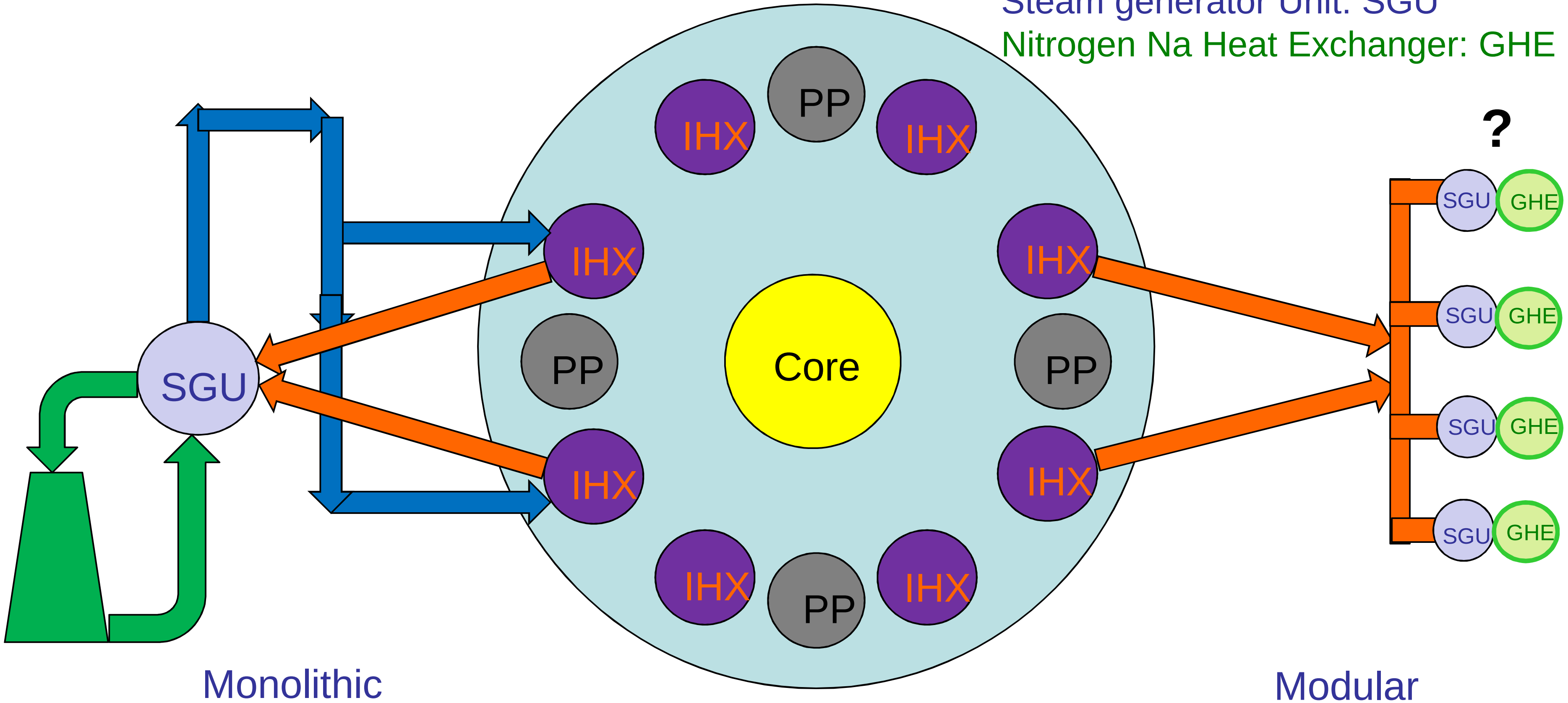
PRIMARY CIRCUIT OF SFR (POOL CONCEPT) 2/2

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

CONTINUOUS OR DISCONTINUOUS INGRESS

Continuous

Diffusion of hydrogen through SGU walls
Impurities in cover gas (Ar)

Discontinuous

Metallic oxides dissolution in Na

Air ingress after repair (air + moisture)

Water ingress in SGU

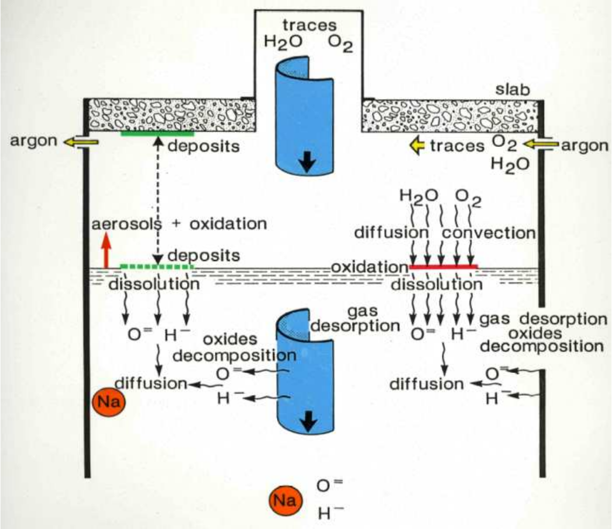
Oil ingress (pumps)

Metallic filling due to maintenance, etc…

Sodium pollution 1/2

➔The development of Sodium Fast Reactors (SFR) is possible thanks to the very attractive properties of Na.

➔ **Nevertheless, this coolant needs to be purified because of a potential accumulation of impurities such as oxygen and hydrogen and their deleterious consequences.** These pollutants can be introduced during the operation of an SFR.



In the primary circuit:

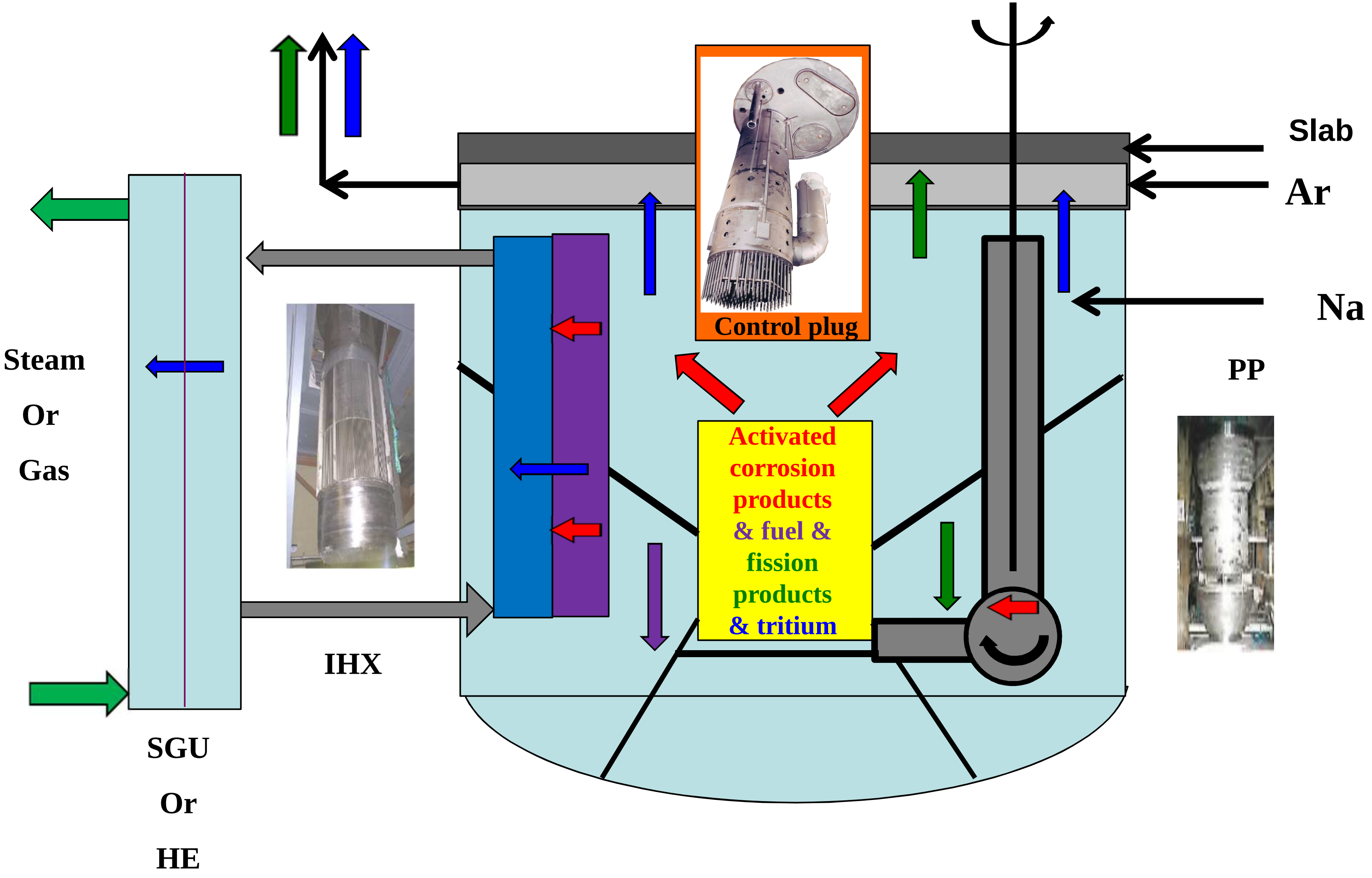
- main discontinuous source of contamination due to **O & H:** adsorbed gas & metallic oxides less stable than Na_2O,
- contribution of O to steel corrosion in core,
- activated corrosion products transported towards the components: Intermediate Heat Exchangers (IHX)…
- contamination (^{60}Co, ^{54}Mn…) & dosimetry during handling and/or repair.

➔ generally considered that an **SFR must be operated with [O]< 3 ppm in normal operation** in order to control the generalized corrosion.

➔ nuclear reactions in fuel and boron carbide : a very small continuous source of tritium in the primary vessel which permeates through the IHX towards the intermediate loops.

➔ Some fission products if fuel cladding failure (^{137}Cs…)

PRIMARY CIRCUIT : CONTAMINATION SOURCES



Slab

Ar

Na

PP

Control plug

Activated corrosion products & fuel & fission products & tritium

Steam

Or

Gas

IHX

SGU

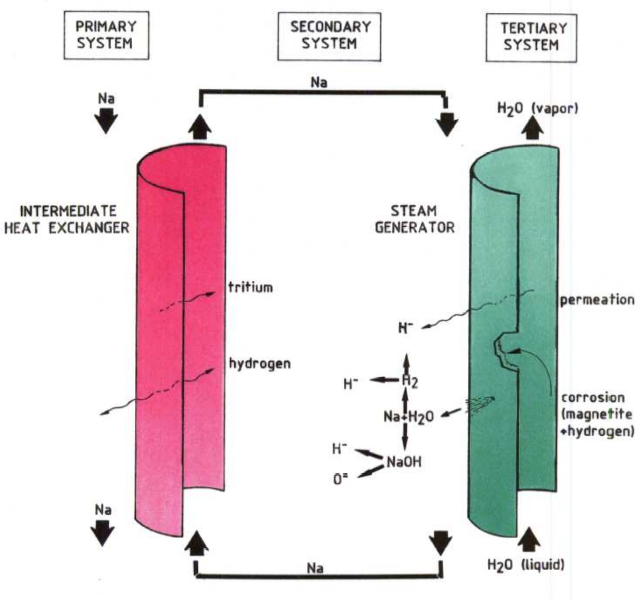
Or

HE

Sodium pollution 2/2

In the intermediate loops:

- **main continuous source: hydrogen** due to hydrogen diffusion in steam generators (SGU) through tube walls, due to aqueous corrosion on the water side and also to the thermal decomposition of hydrazine, used to control the oxygen content in the water.



- **main potential discontinuous sources:**
  - **sodium water reaction** event: H_2, NaOH and potentially Na_2O and NaH crystallized products.

  ➔ strongly exothermic & extremely fast and may be inducing cracks in the neighboring pipes.

  ➔ [H] controlled at a low level (< 0.1 ppm) to detect asap a potential event in SGU producing.

  ➔ Risk of deposits on the cold walls (Na2O & NaH), plugging of narrow sections, reduction of heat transfer coefficient in IHX

  - **contamination of the residual amount of Na by air and moisture**, after draining, prior to handling and/or repair operation, inducing deleterious effects, mainly due to stress corrosion cracking induced by aqueous soda.

In all circuits:

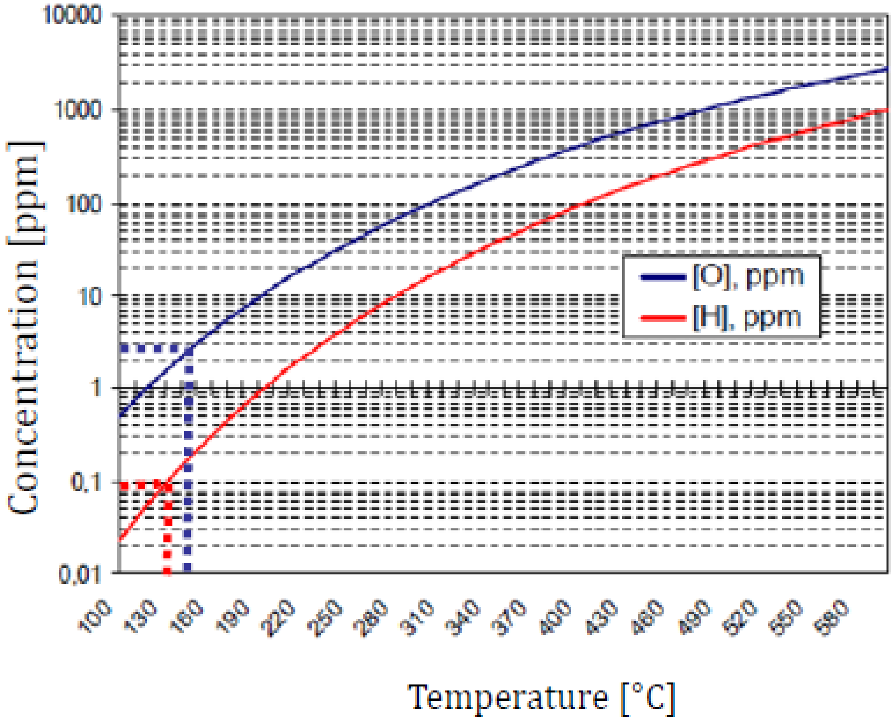
- Potential oil ingress (pumps)
- Metallic filling due to maintenance, etc…

O & H solubilities in liquid Na

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

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

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



Main processes for Na purification

- **Specific methods to obtain nuclear grade sodium**
- **Initial cleaning of loop, components and vessels**
- **Filtering**
- **Cold trapping**
- **Hot trapping**
- **And of course limiting ingress of pollution by appropriate operating rules**

Crystallization methods

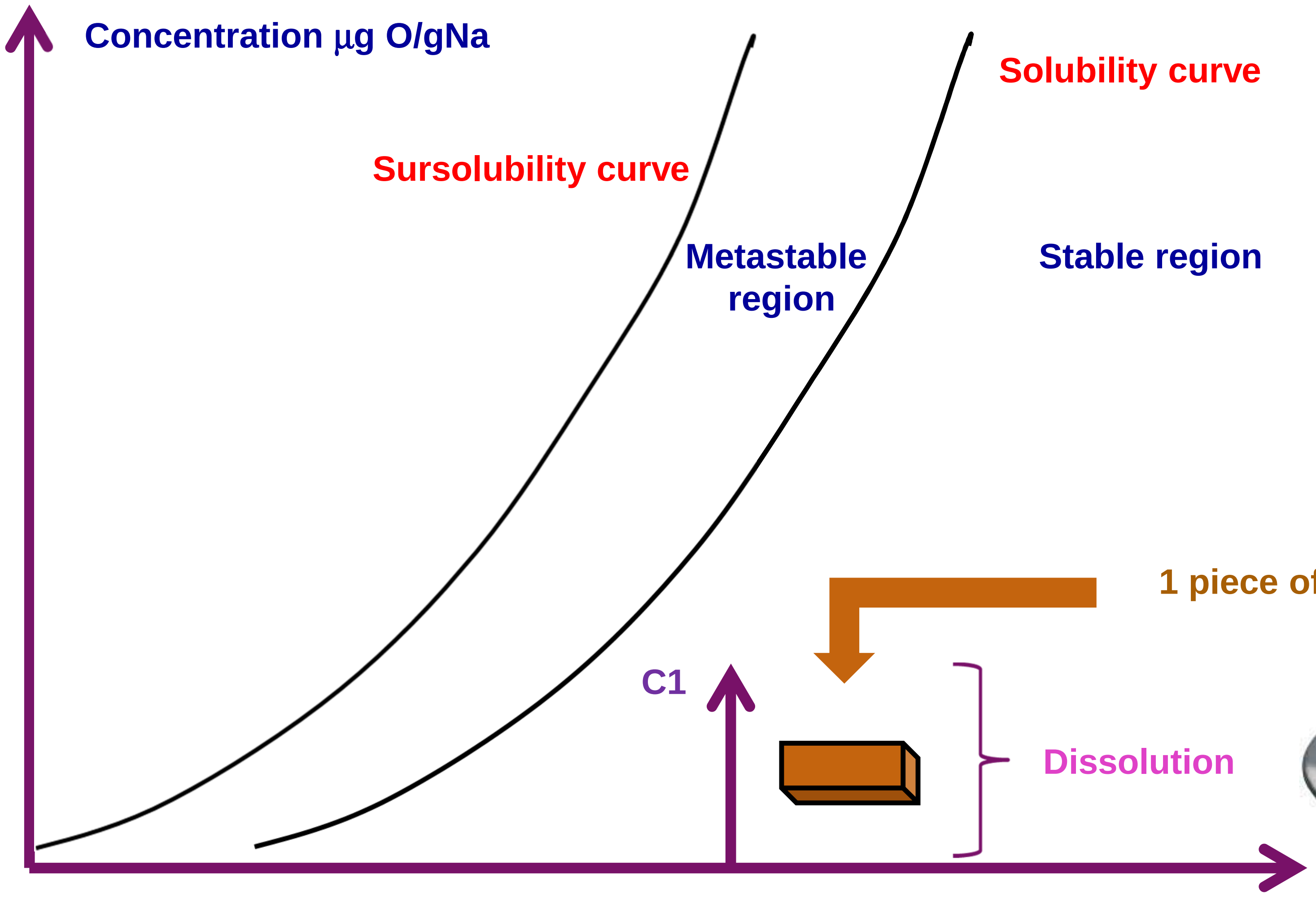
- Liquid evaporation (like salt)
- Reduction of the solubility by adding some additive impurity
- Cooling the liquid below saturation temperature

➔ This last option is the most attractive :

Convenient solubility laws for O and H (reach almost 0 near the Na melting point)

Easy implementation : cooling and solid retention

CONCENTRATION-TEMPERATURE DIAGRAM



Concentration μg O/gNa

Solubility curve

Sursolubility curve

Metastable region

Stable region

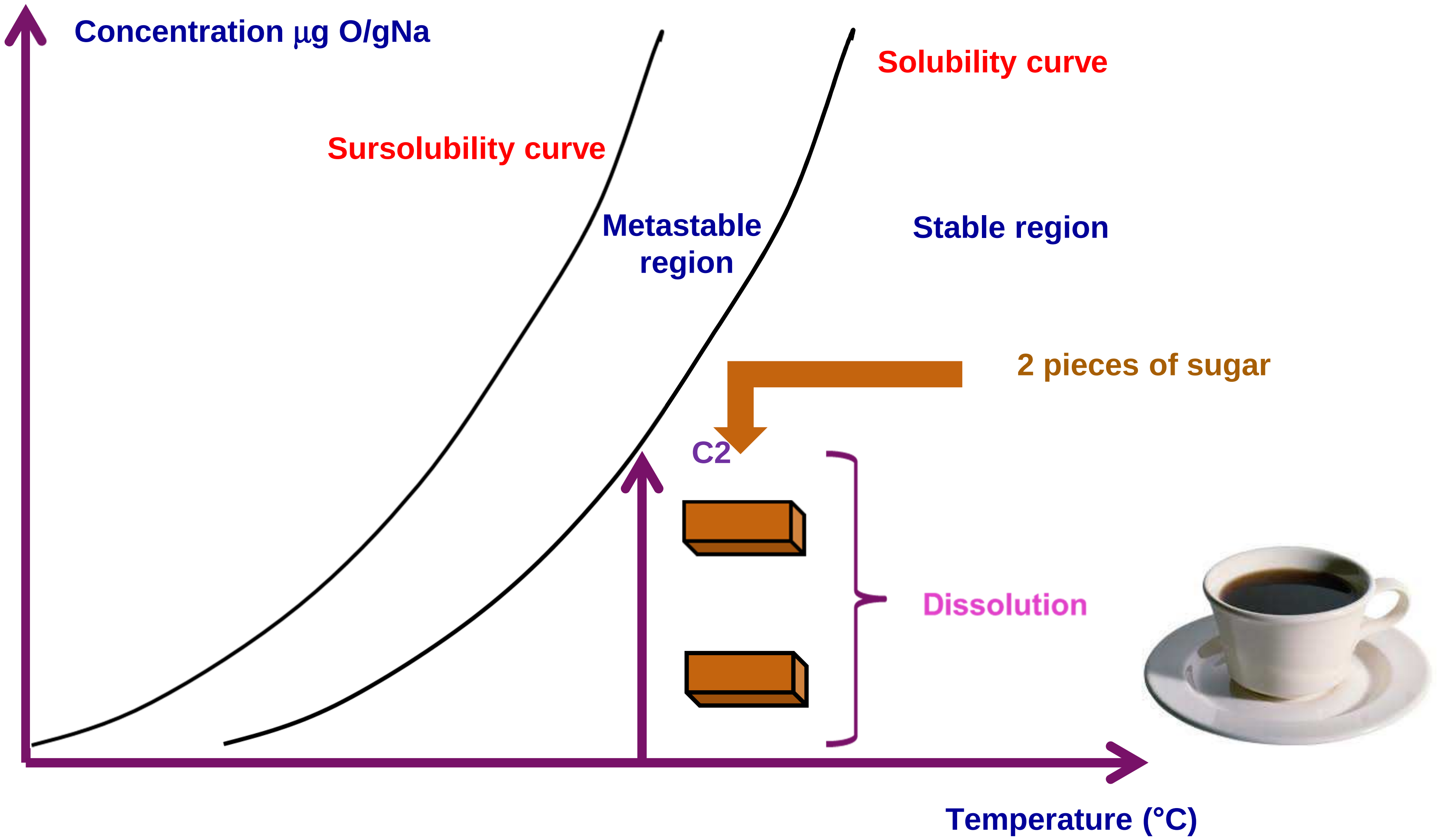
1 piece of sugar

C1

Dissolution

Temperature (°C)

CONCENTRATION-TEMPERATURE DIAGRAM



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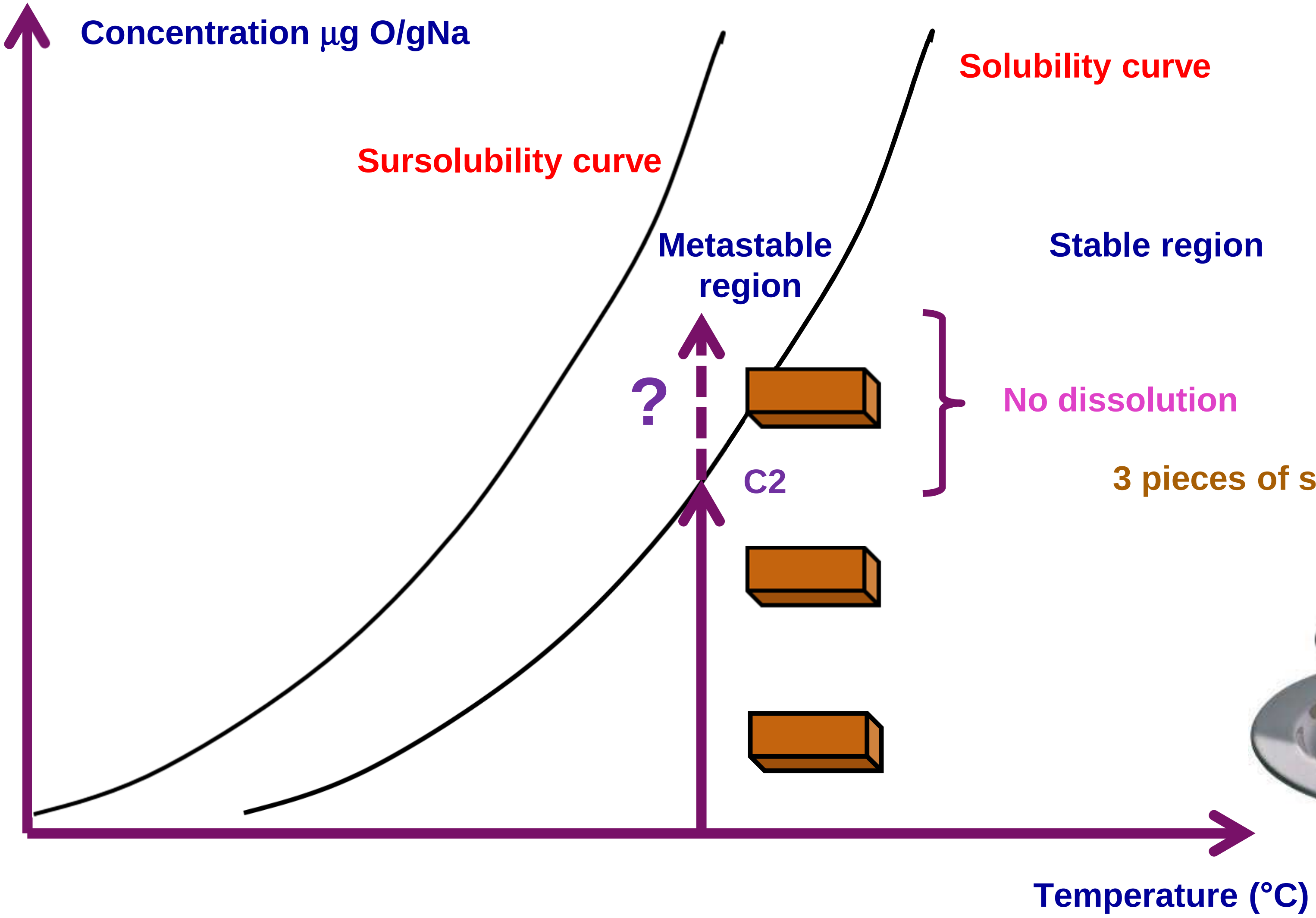

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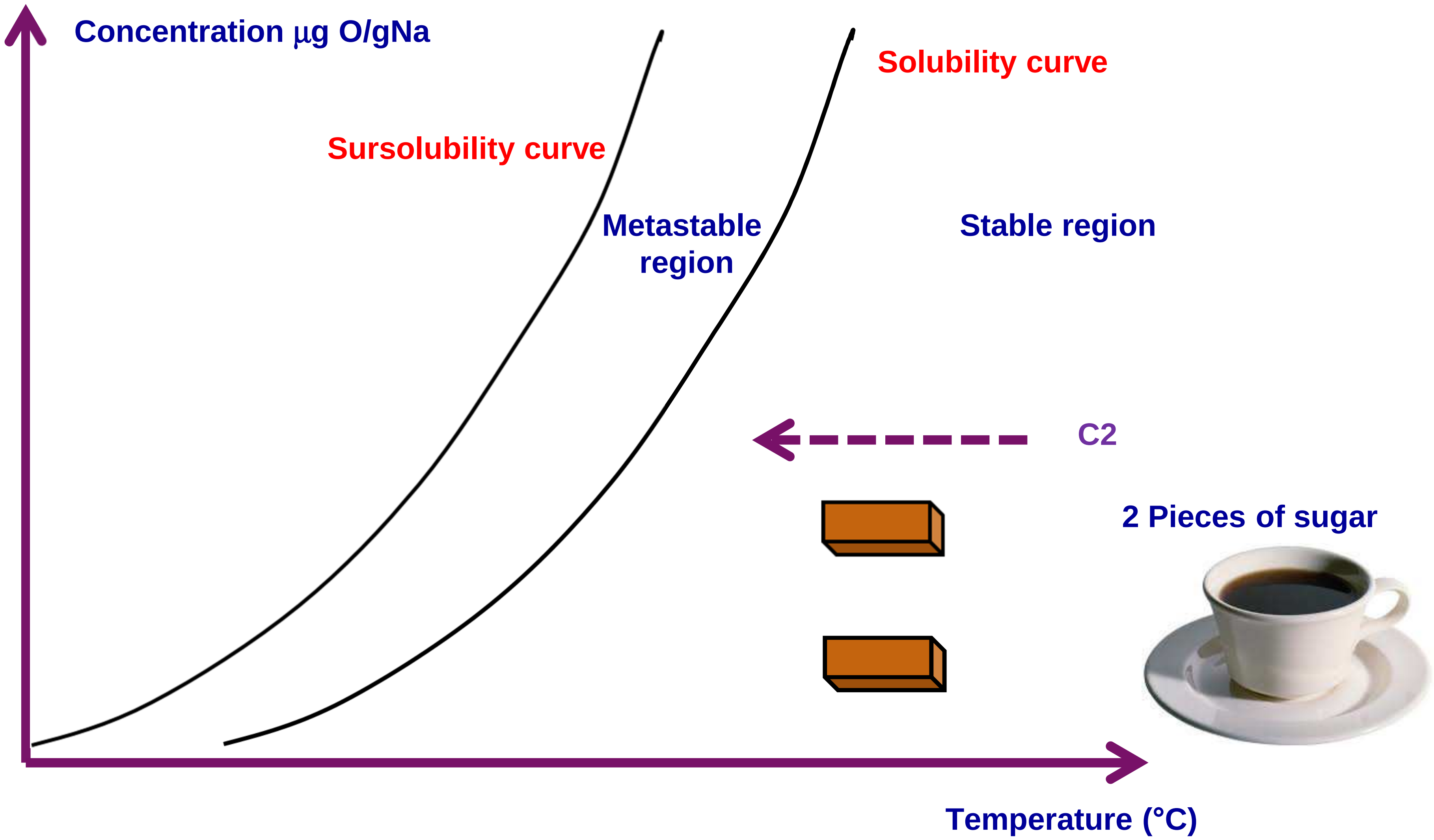


Concentration µg O/gNa

Solubility curve

Sursolubility curve

Metastable region

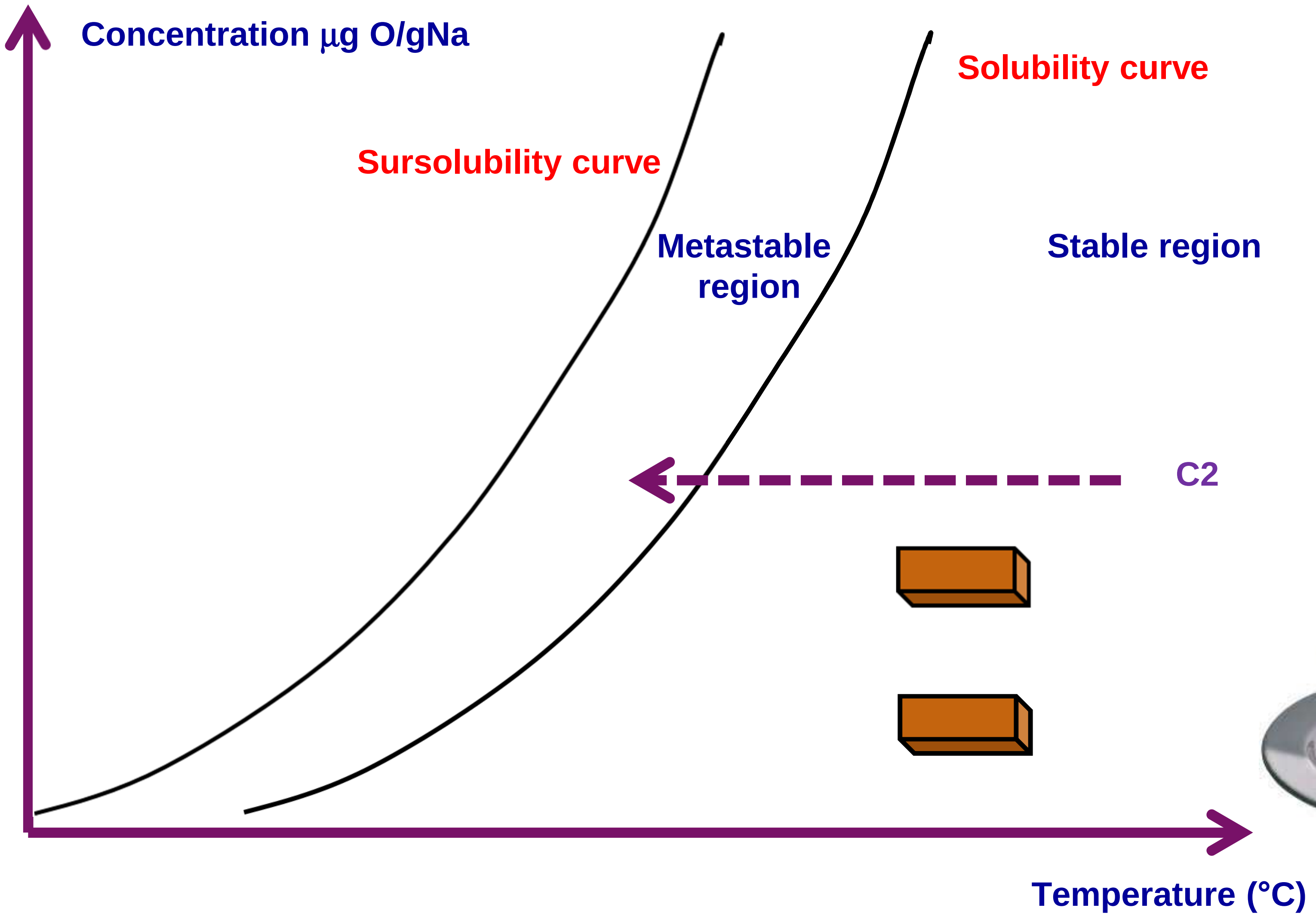
Stable region

C2

2 Pieces of sugar

Temperature (°C)

CONCENTRATION-TEMPERATURE DIAGRAM



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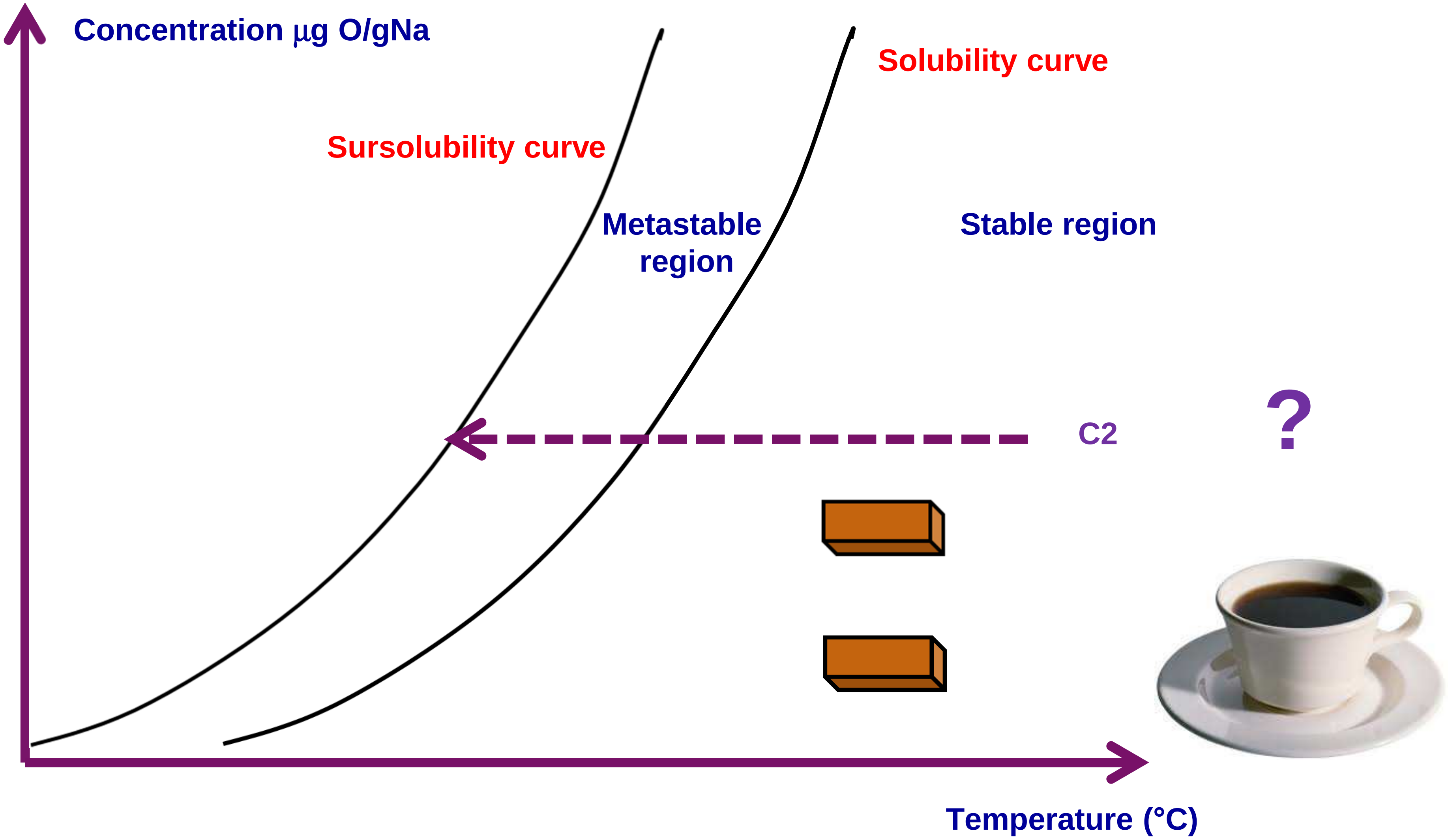

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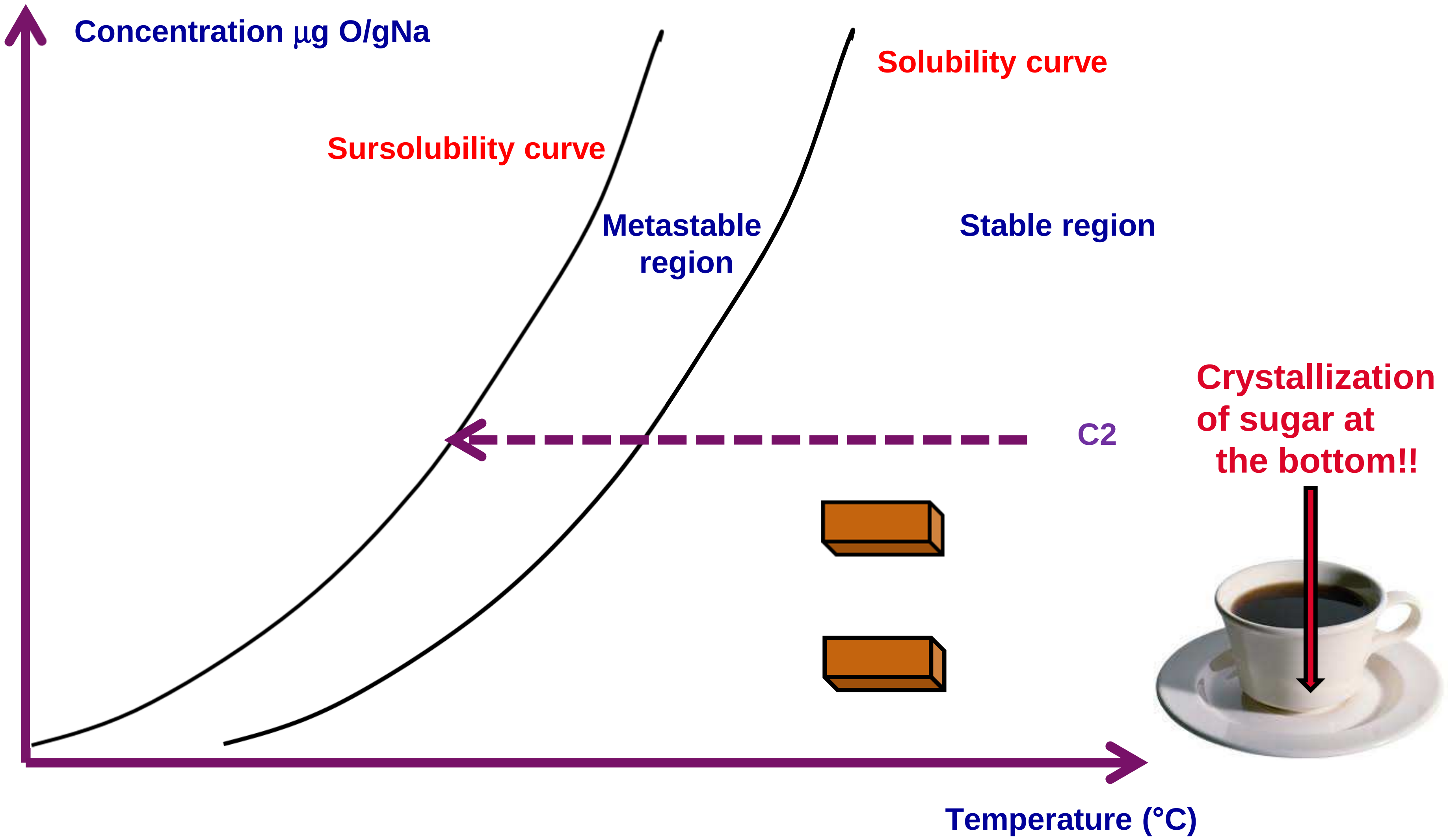


Concentration µg O/gNa

Sursolubility curve

Solubility curve

Metastable region

Stable region

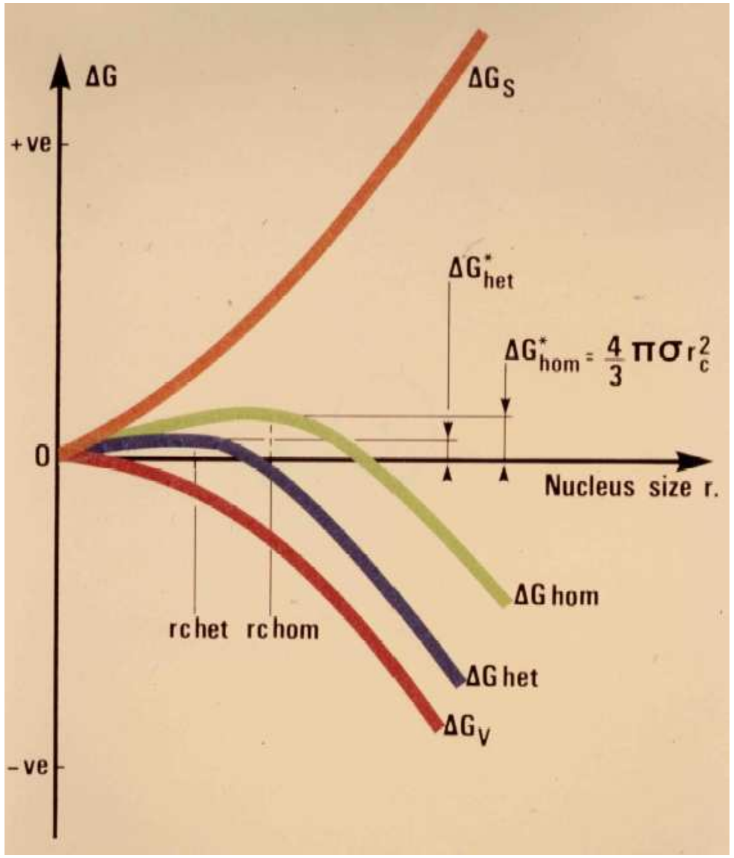
C2

Crystallization of sugar at the bottom!!

Temperature (°C)

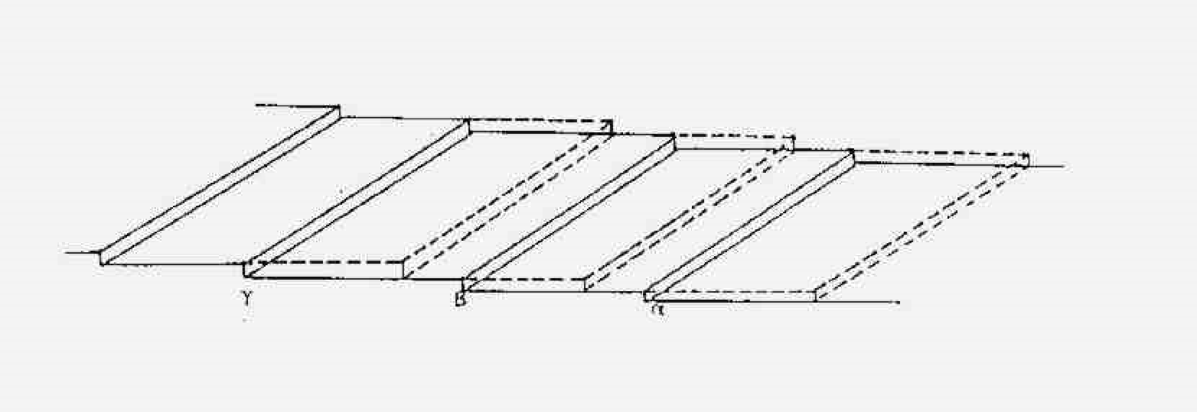
Nucleation phenomena

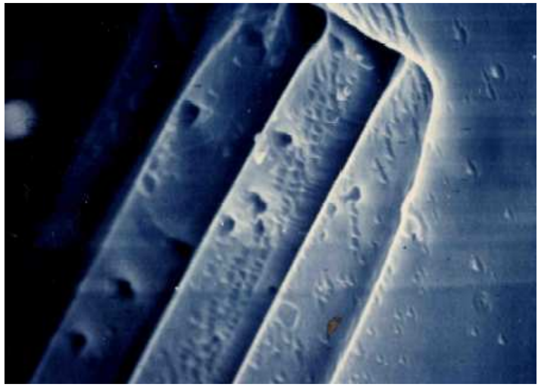
- If sodium is supersaturated, presence of agglomerates
- These agglomerates can turn into nuclei if free enthalpy of the system reaches a limit value (primary nucleation)
- Nevertheless some existing crystals can produce some small particles by attrition (secondary nucleation)
- The primary nucleation can be homogeneous (if it occurs in the sodium bulk) or heterogeneous if it occurs on metallic surfaces. Wetting characteristics have a large influence on heterogeneous nucleation



Growth phenomena

- **Model of the kinematic wave (Franck-Vermilyea) : explain the formation of steps**





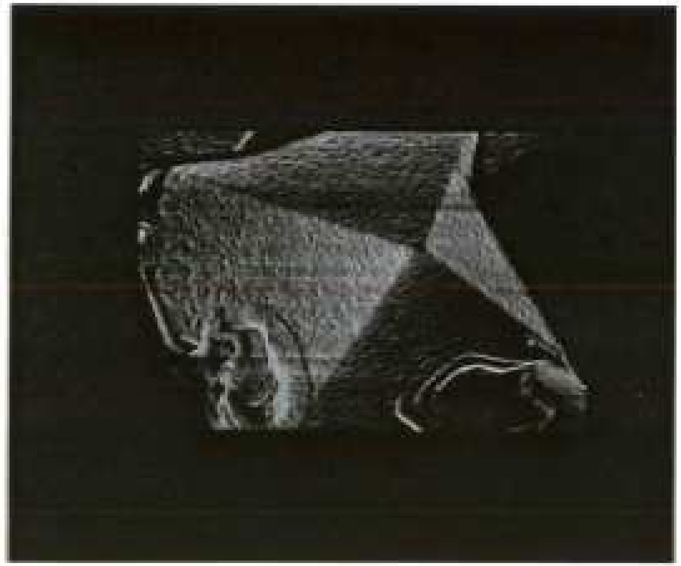
Crystal growth (Na_2O)

Crystal growth (NaCl)

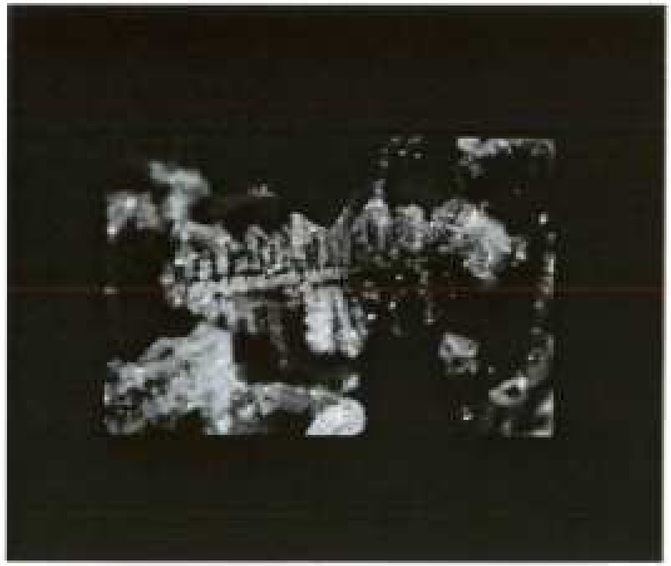
Growth phenomena

Two growth phenomena for Na_2O:

- **low supersaturation : regular growth**
- **high supersaturation : dendritic growth**

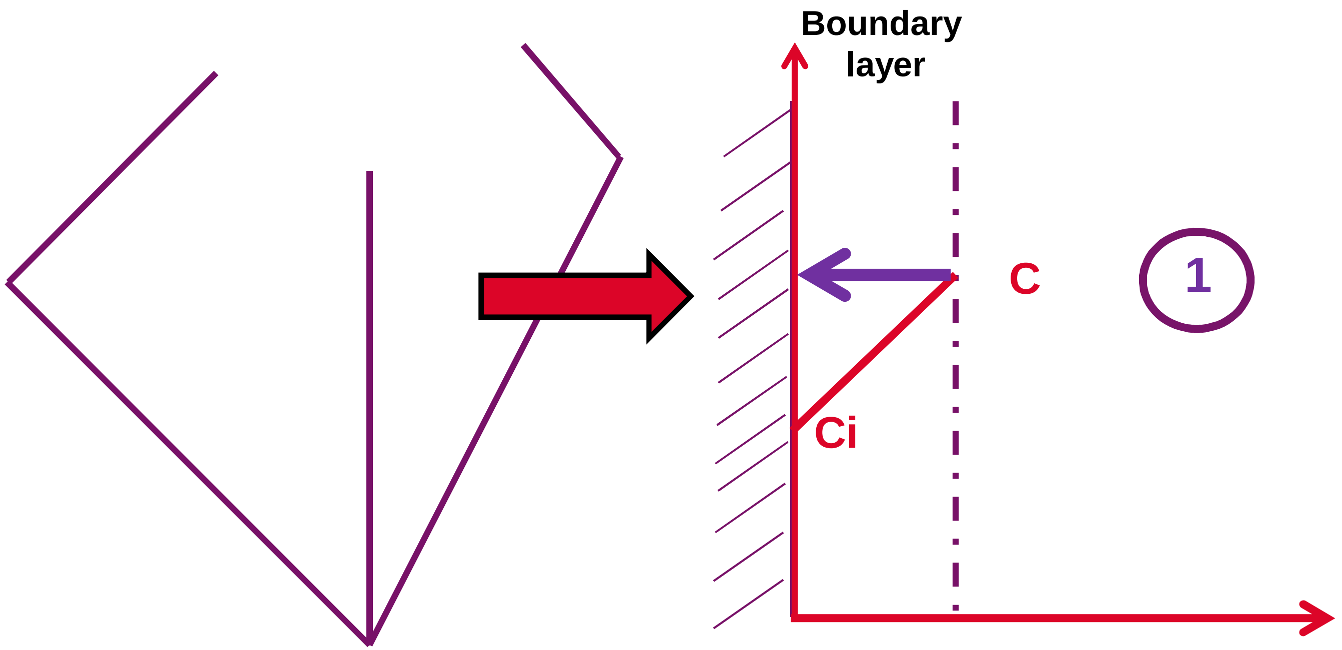


REGULAR GROWTH (X500)



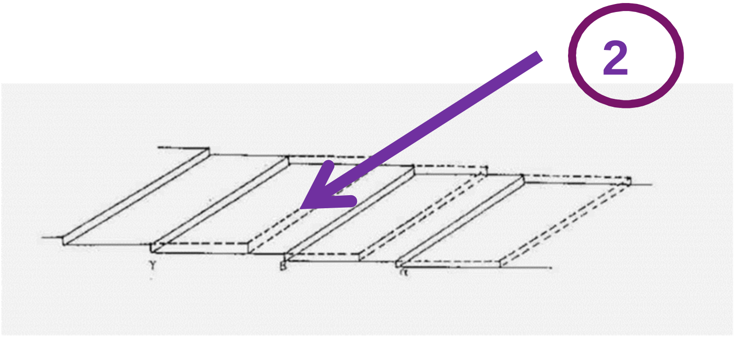
DENDRITIC GROWTH (X20)

Growth phenomena



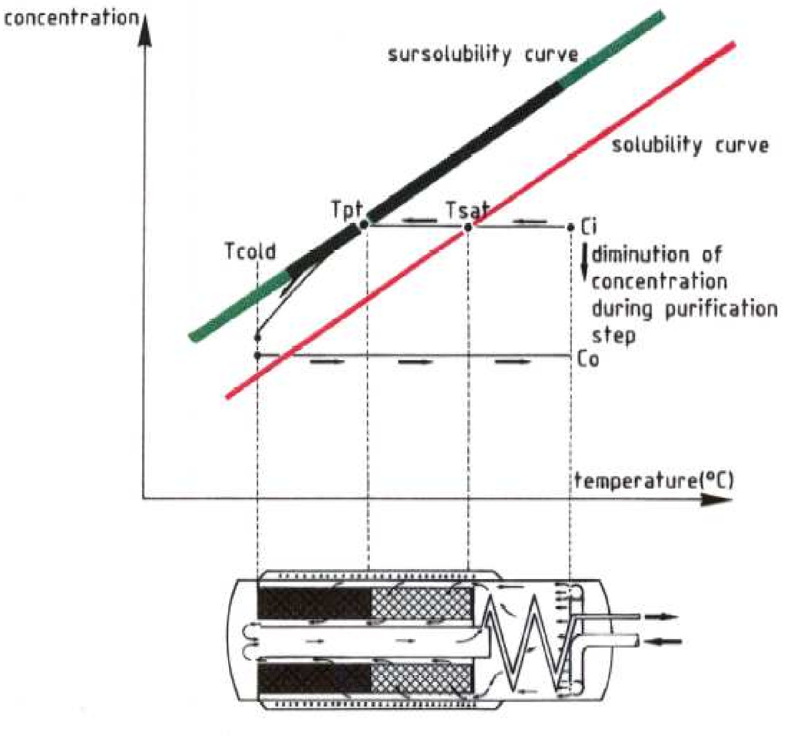
Step 1: Diffusion through the boundary layer

Step 2: Integration in the crystal lattice



➔ Kinetics of the overall phenomena = kinetics of the slowest step

Cold trap principle

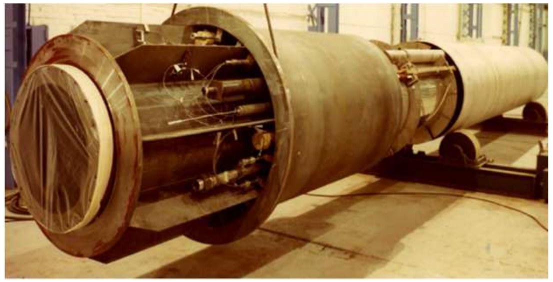


Crystallization kinetics, given for one impurity O or H,]:
in [kgNa2O/s] or [kgNaH/s]

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

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

Experiments carried out on Na_2O and NaH

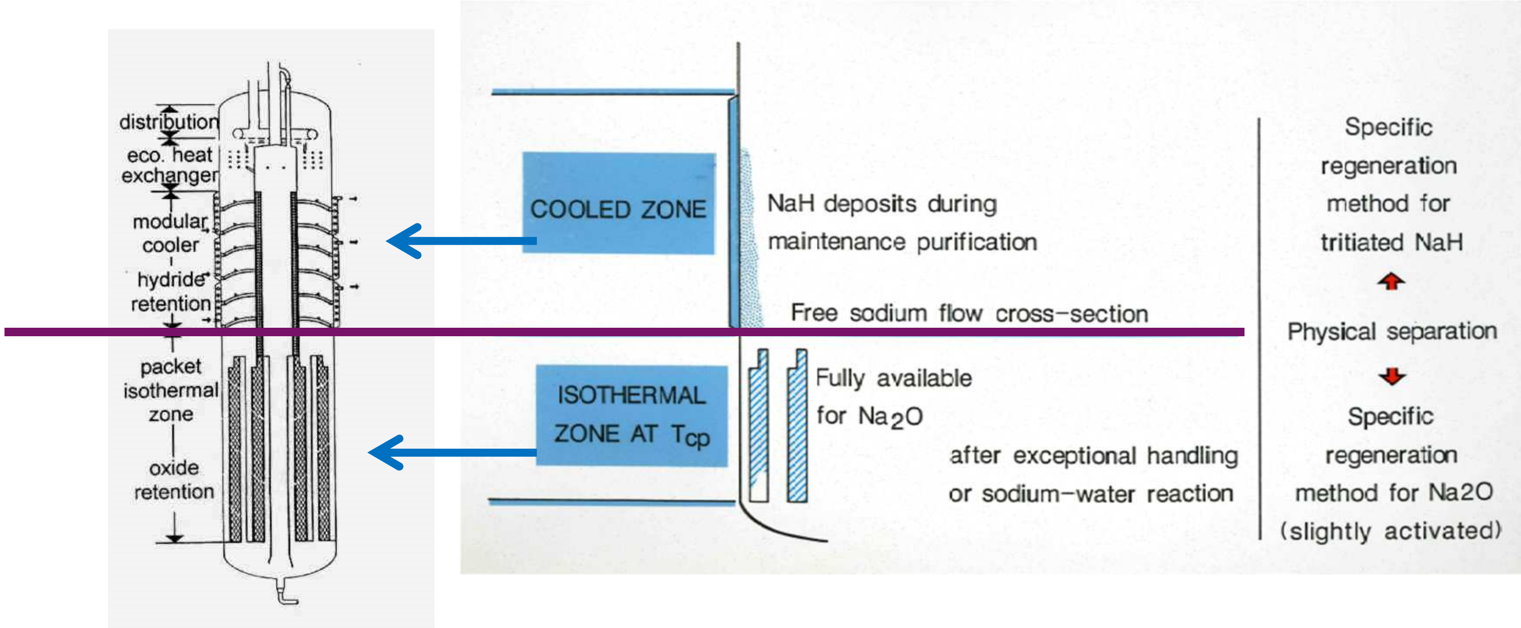
For a cold trap designed with an upper packless cold zone:

➔ **Na_2O crystallization only on wire mesh packing**

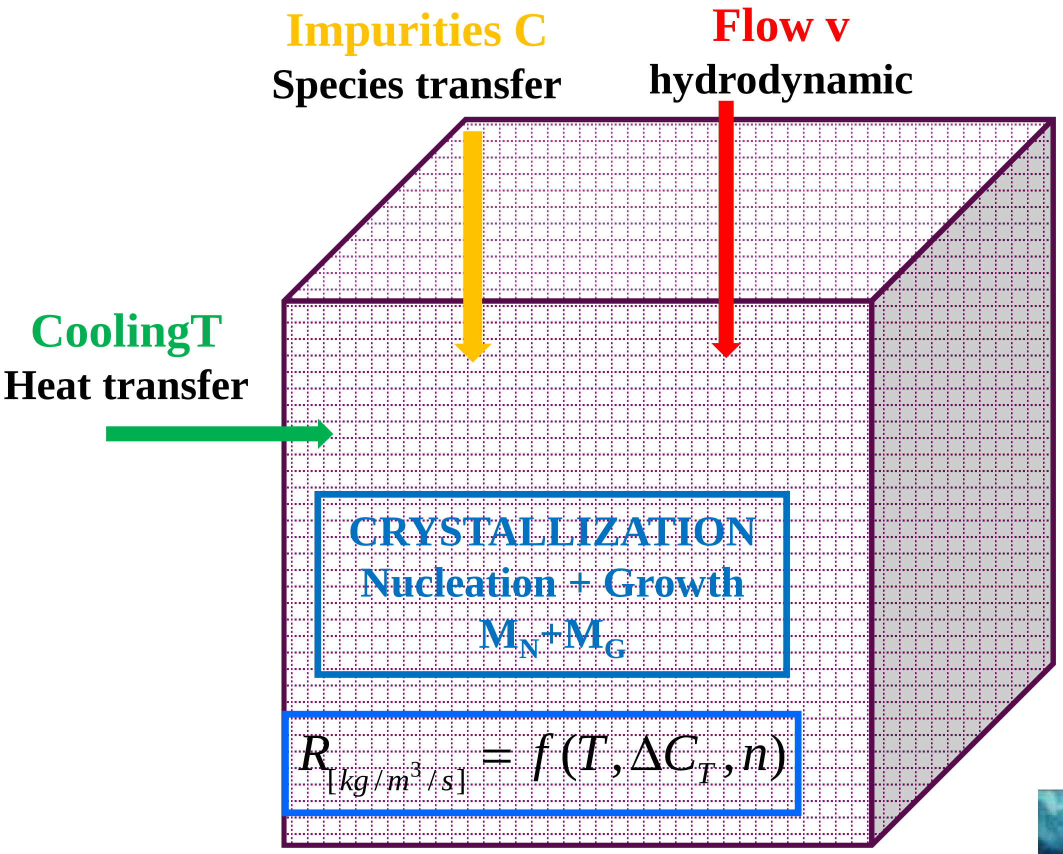
➔ **NaH crystallization essentially on cold walls of the system, (if thermal flux is enough)**

However, in case of a non-optimized packless cold zone, hydride might as well crystallize on wire mesh packing. Thus, co-crystallization occurs between sodium hydride and sodium oxide.

➔ **Hypothesis:** kinetics parameters for NaH crystallization on cold walls identical to those on wire mesh packing.



Transport Phenomena Coupling



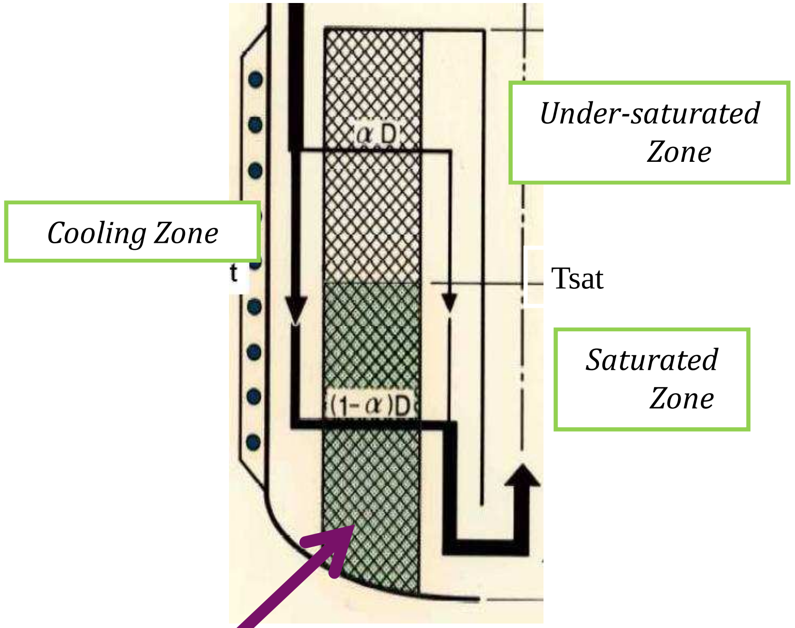
Impurities C
Species transfer

Flow v
hydrodynamic

CoolingT
Heat transfer

CRYSTALLIZATION
Nucleation + Growth
M_N+M_G

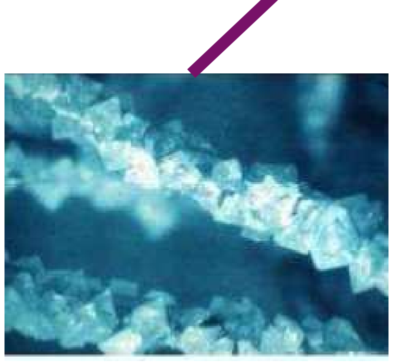
$$R_{[kg/m^3/s]} = f(T, \Delta C_T, n)$$



Under-saturated Zone

Cooling Zone

Saturated Zone



Main characteristics of the model:

Two types of crystallization behavior:

➔ **Two different modeling approaches** (on cold walls or on mesh).

Crystallization	Wire mesh packing	Cold walls (packless zone)
Impurities	- Na_2O - NaH	**- NaH**
Models	- Porous medium densification	**- Porous medium densification** **- Interface tracking**
Surface to crystallize	**- Wire mesh** **- Oxide and/or hydride crystals**	**- Hydride crystals**

➔ **For both approaches:**

System : a porous media with a porosity ϕ referring to the void fraction of the liquid phase.

Porosity is initially:

- equal to 1 with deposit on walls (NaH),

- equal to the void fraction of the mesh packing if the deposit occurs on wire mesh (Na_2O).

Mixture of crystal and liquid sodium in which void fraction changes with time and space, as well as its physical parameters such as permeability, diffusion or thermal conductivity…

Fluid assumed to be incompressible and each infinitesimal volume assumed isothermal.

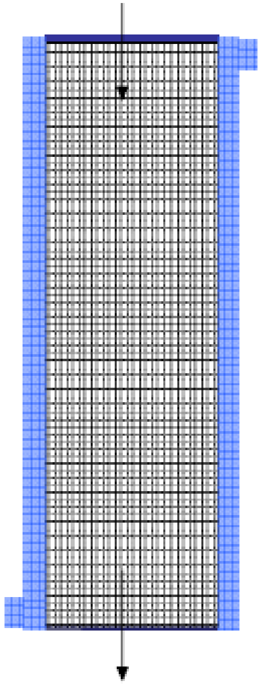
➔**The model takes into account hydrodynamics in porous media, heat transfer, mass transfer, and nucleation and growth kinetics**

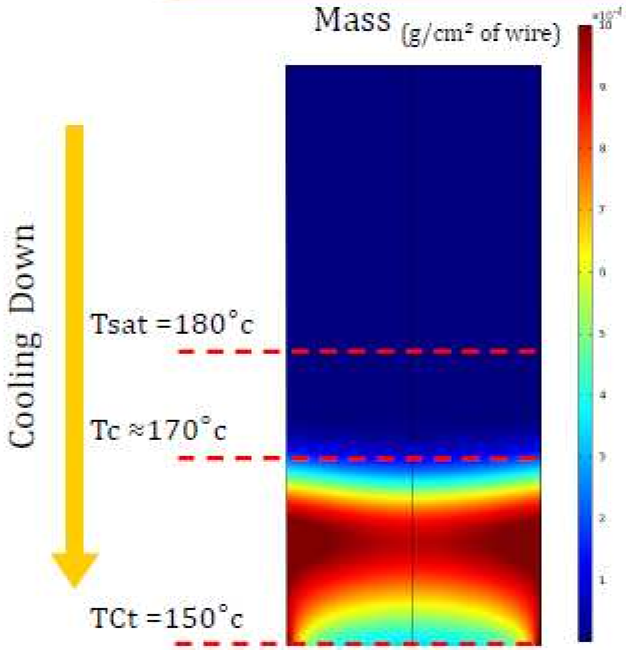
➔ **Numerical model solved by finite element method in Comsol Multiphysics®** software.

Na_2O crystallization modeling

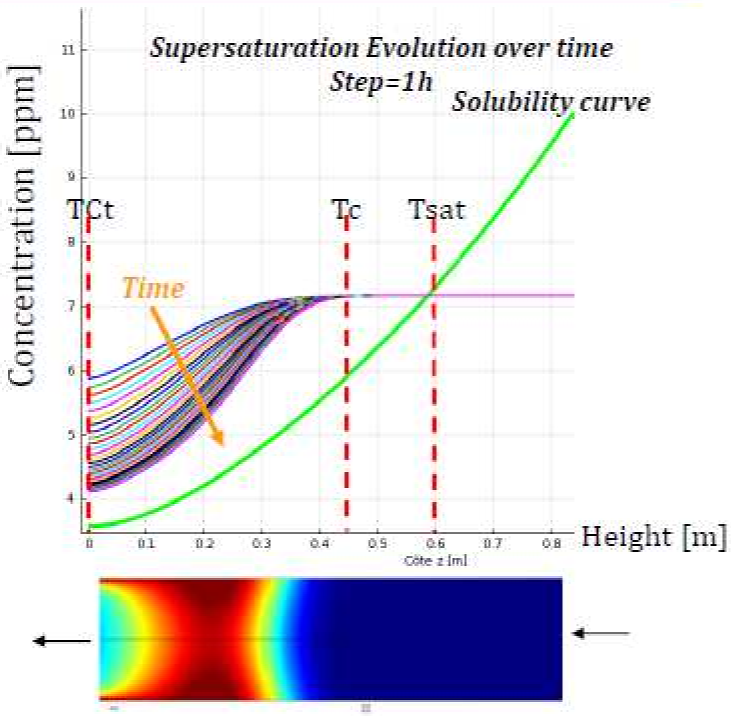
Oxide Trapping on packing: *Supersaturation Evolution*

Inlet Concentration [O]=7,2µg/gNa





Localization of Mass of Na_2O on wire mesh $[g/cm^2$ of wire]

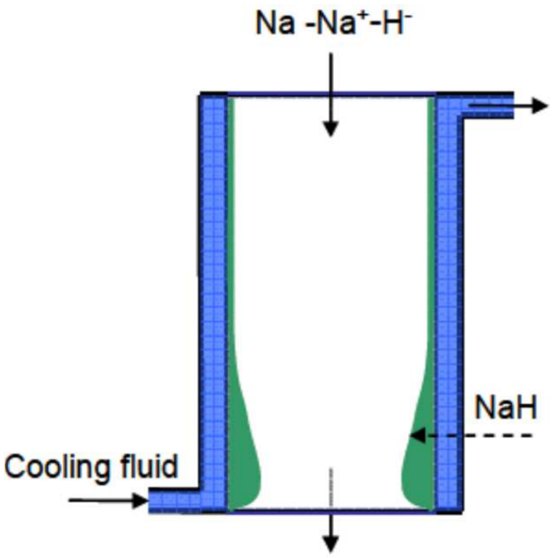


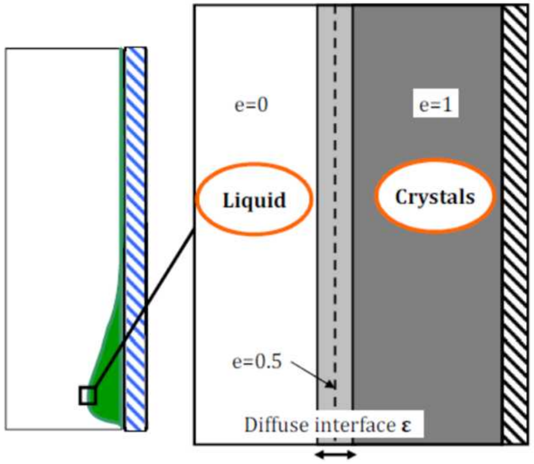
Front propagation tracking for NaH crystallization

➔ Density of NaH deposit experimentally estimated to be around 0.5

➔ Crystal growth on cold walls can be seen as a phenomenon involving a moving interface, with propagation of a deposit front.

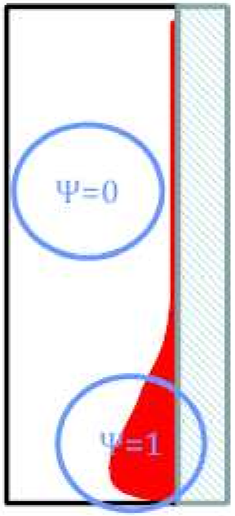
➔ Tracking Moving Interface is a key element of the model



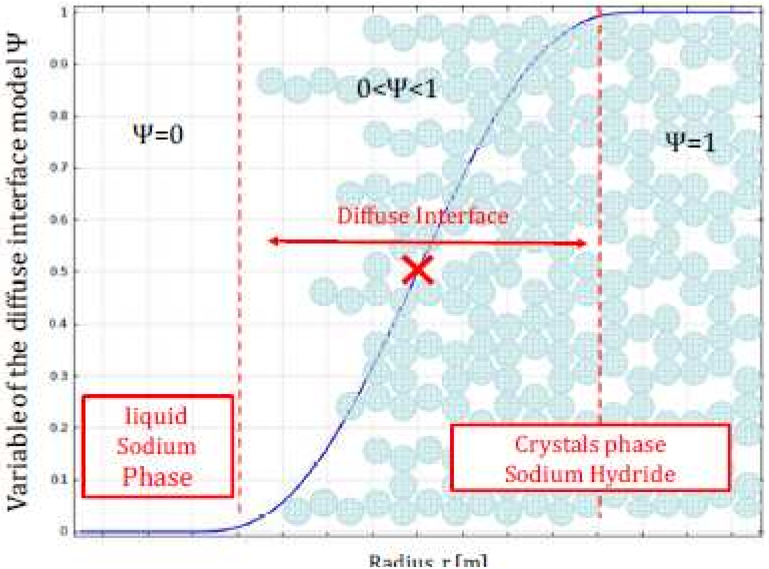


NaH deposits on cold wall (EPINAR experiment)

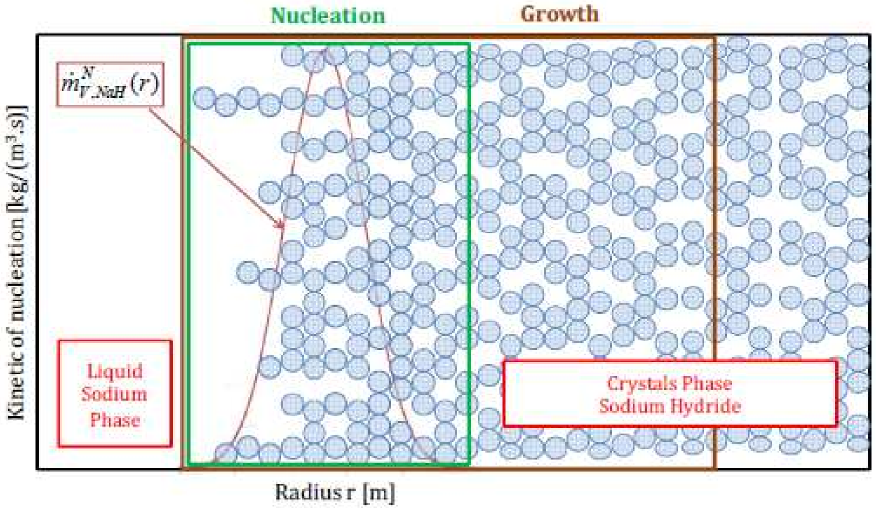
Interface tracking model for NaH crystallization on cold walls



Phases localization with occurring rate variable Ψ



: Occurring rate Ψ through diffuse interface

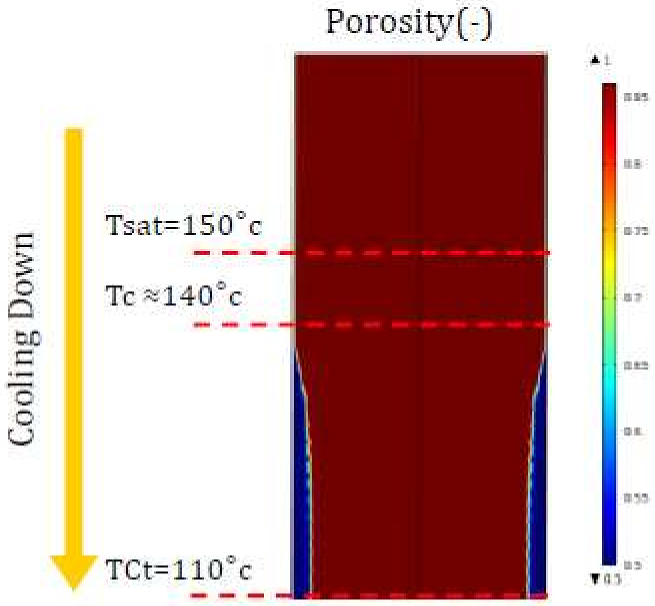


Location of the nucleation process

NaH crystallization modeling

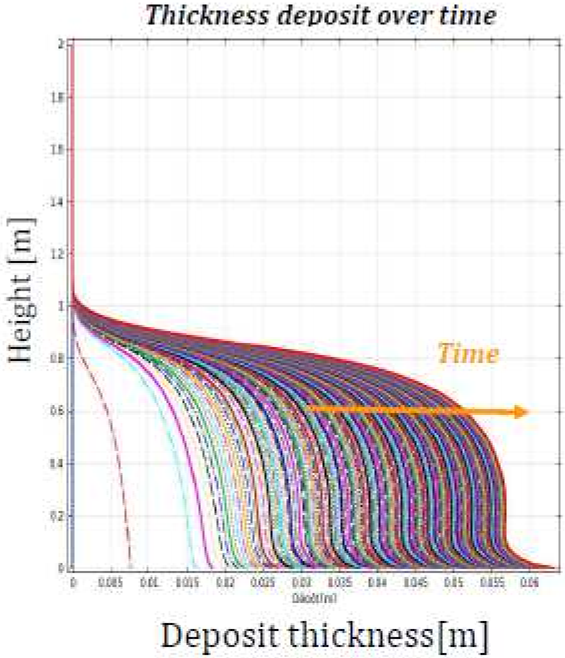
Hydride Deposit on Cold Walls

Inlet Concentration [H]=2µg/gNa



Porosity profile

Hydride Localization on walls



Purification system design methodology

- **Identification of the impurities to be removed** from the Na: mainly oxygen and moisture, potentially NaOH in case of very large sodium-water reaction.
- **Assessment of their sources and their production rate** (continuous & discontinuous)

i.e. Na-H2O reaction considered as instantaneous: necessity to define a Na leak scenario and a probability of occurrence. Then, it is possible to estimate the amount of water reacted and consequently the amount of products to be trapped.

- **Assessment of their potential sinks** i.e. corrosion of structural material, deposition in the coldest points of the circuits.

➔ **induces specifications on the removal rate** to be obtained in order to prevent any deleterious effects, (exceptional corrosion due to large air ingress, stress corrosion cracking due to residual aqueous soda in remote locations…).

- **Evaluation of the amount of impurities to be removed from the Na circuits, vessels**, during the cold trap(s) operation over a given period depending on the strategy selected for the purification systems

  ➔ **induces specifications on the loading capacity**

- **Selection of several trapping zones** (cold trap: generally a combination of 2 zones):

  Zone 1-A: Cooling zone, equipped with stainless steel mesh,

  Zone 1-B: Cooling zone, without mesh, with cooled walls, designed to trap or not NaH,

  Zone 2: Isothermal zone, located downstream from the cooling zone, after reaching the coldest point of the cold trap, equipped with stainless steel mesh.

Four main design criteria

Four main criteria generally considered for cold trap design:

Efficiency: $$\varepsilon = \frac{C_i - C_o}{C_i - C_{Tcp\_sat}}$$

➔ recommended to get an efficiency of 1 for each trapping zone. (efficiency depends on the crystallization kinetics, residence time, local conditions….)

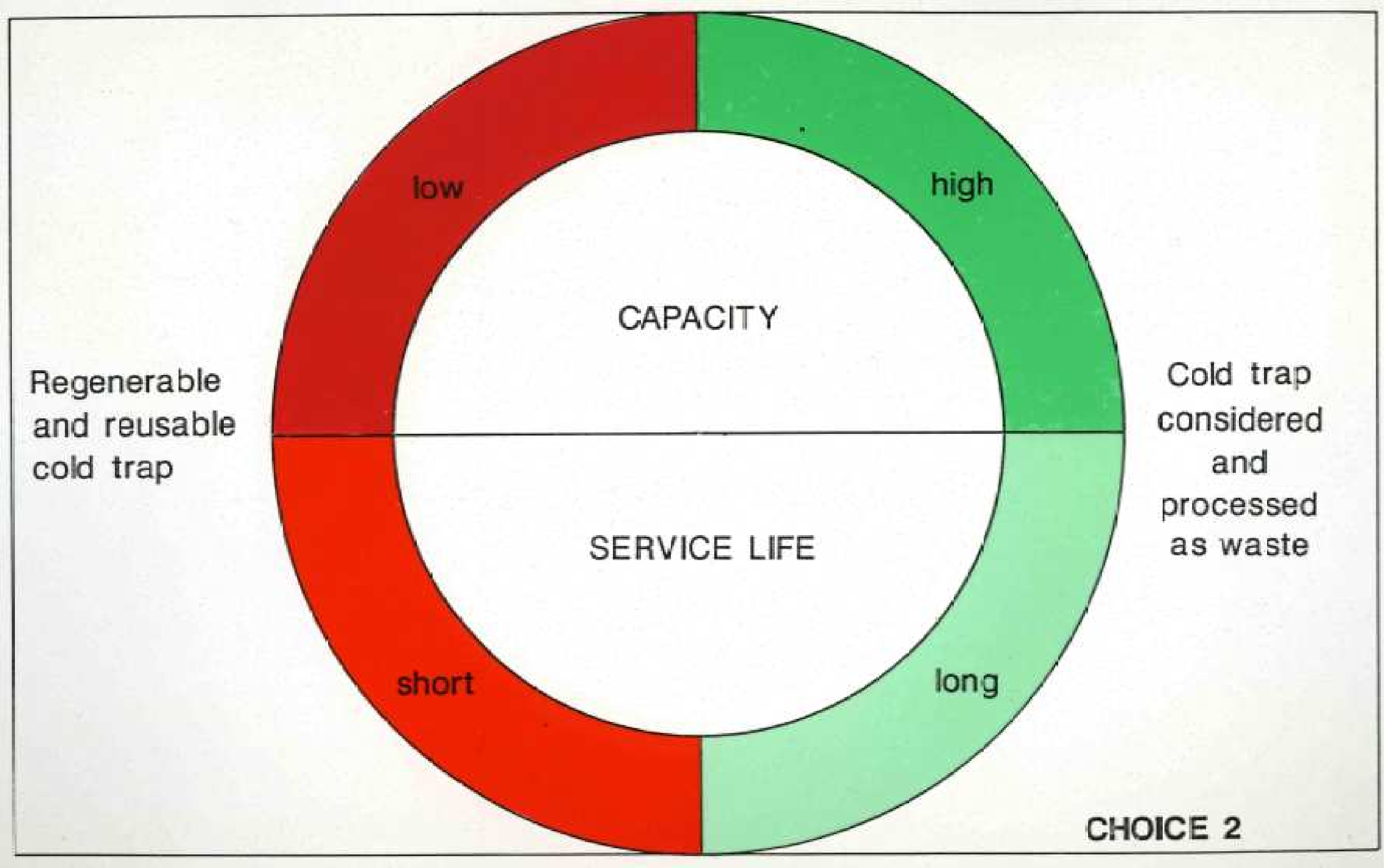
Purification rate: $Rp = \varepsilon \cdot D_{na} \cdot (Ci - C_{Tcp\text{-}sat})$

➔ duration of a purification campaign determined by the initial impurities content in Na and Rp

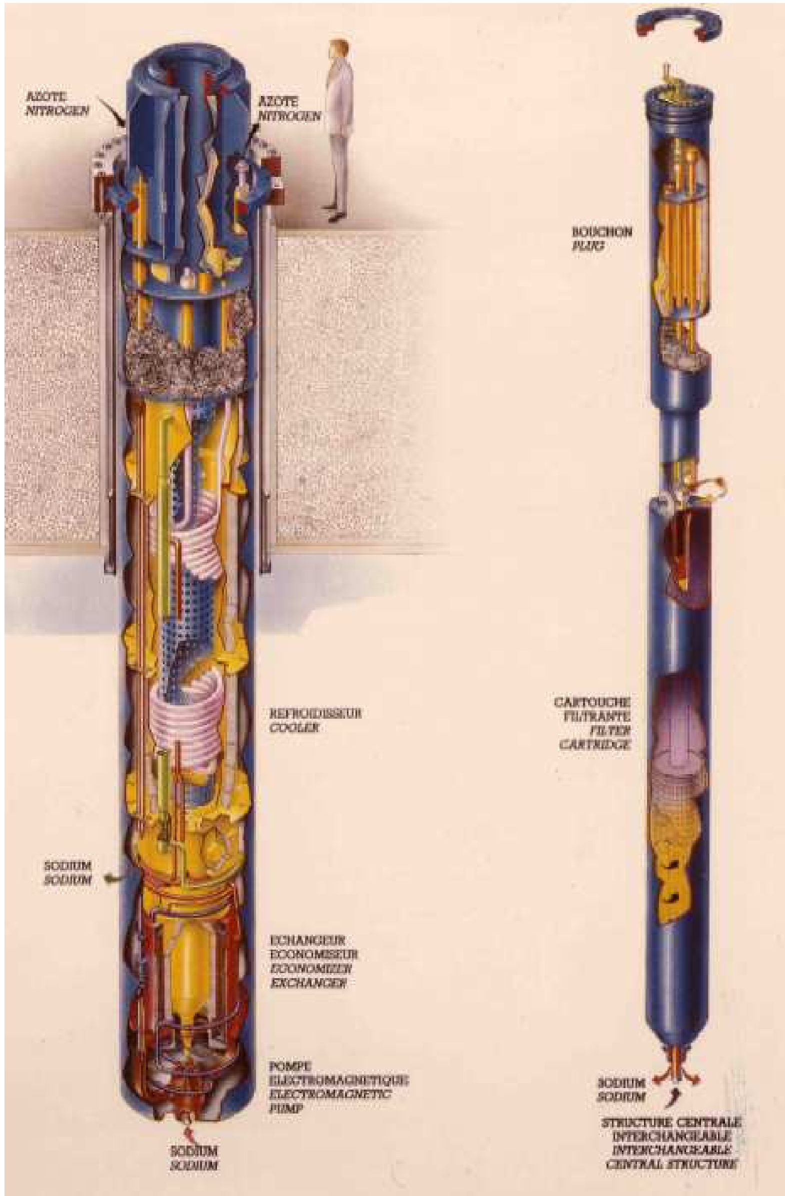
Capacity: total amount of impurities (mass or volume) accumulated in the cold trap over the entire time of operation, defined by the designer.

Compactness: ratio between the volume of impurities trapped in the cold trap and the overall internal volume of the cold trap.

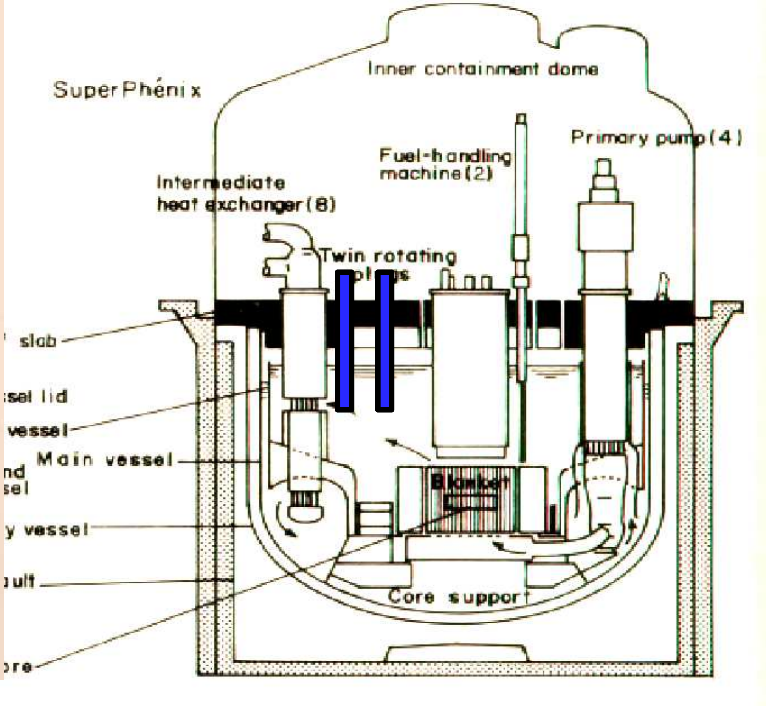
Basic choice for purification system



INTEGRATED PURIFICATION SYSTEM (SPX)



Primary Integrated Purification



Performance criteria for cold traps

Instantaneous efficiency: $E = (Ci-Co)/(Ci-C^*)$ $0<E<1$

Ci: concentration at the cold trap inlet
Co: concentration at the cold trap outlet
C*: concentration at equilibrium (solubility)

Purification rate: $Vp = E.(Ci-C^*).F_{Na}$

F_{Na}: Na flow-rate

Capacity: $Cap = \Sigma\, \tau r.Ed$ **(in unit of volume)**

where τr = filling rate
and Ed = deposited element concerned (area, volume)

Compactness: $Comp = V1/V2$

V1 = Maximum volume of the impurities retained in the trap
V2 = Internal volume of the trap in which the deposit zones are located

Qualification strategy for SFR cold traps

In the eighties:

- **Definition of the main requirements**: pollution sources, purification rate, capacity, compactness)

- **Design of the scale-one cold trap for the reactor,** i.e. type of cold trap, cooling fluid, maximum allowable temperature, trapping zones to be implemented, …

- **Identification of similitude rules** (heat transfer, residence time in each zone, mesh density, loading capacity…) **and down-scaling of the mockup**

- **Manufacturing of the mockup** and implementation of dedicated chemical instrumentation (O-meter, H-meter) on the facility used for qualification tests

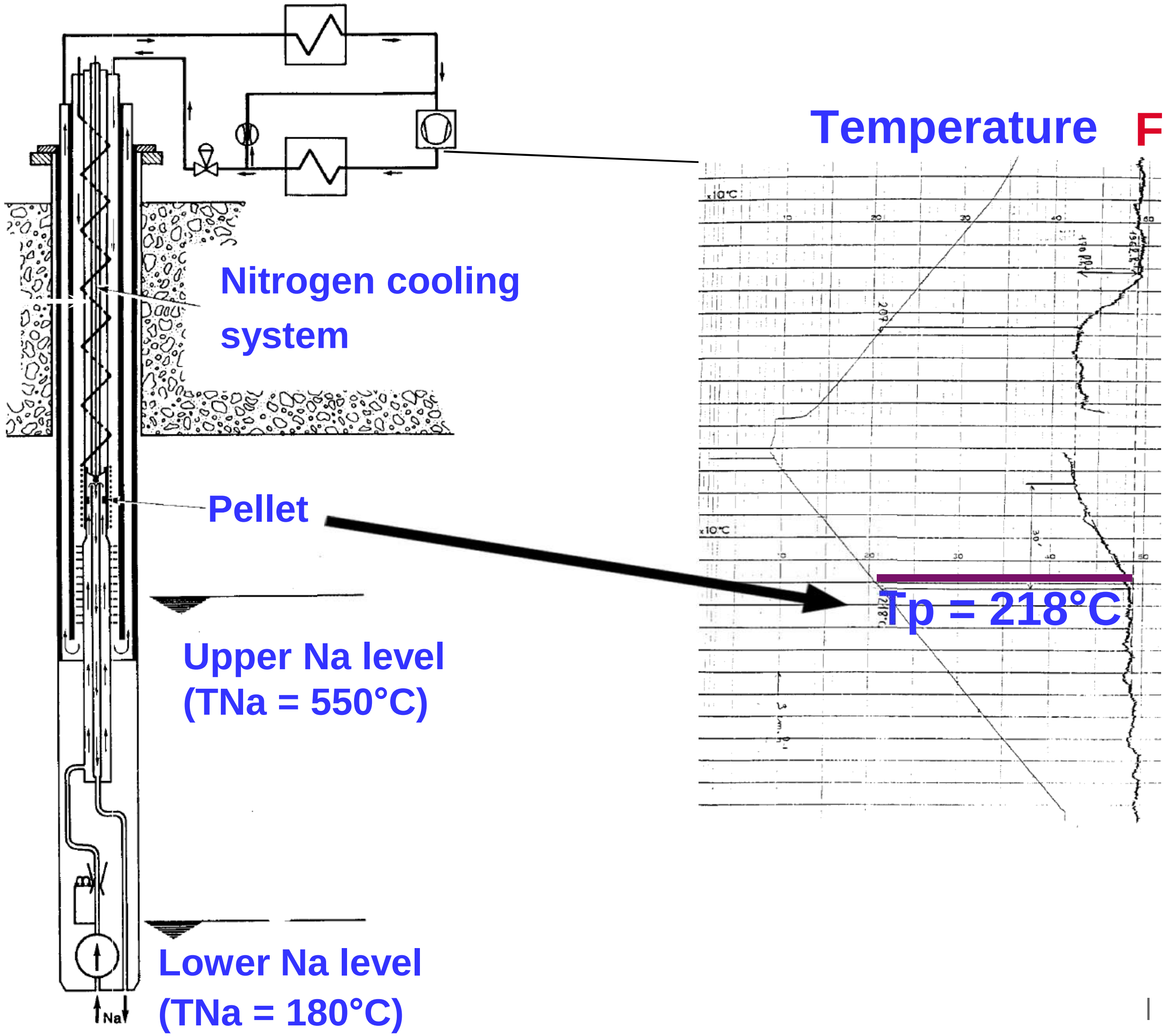
- **Loading of the ancillary cold trap, used as a polluting device**, with Na_2O or NaH or both

- **Operating the cold trap in various conditions** in order to assess the allocated performances (efficiency, purification rate and capacity) and to confirm the operating rules.

Today:

- **Use of the new CEA code** described here, validated using the previous experimental results, allows for a quite efficient design procedure, based on sequential calculations, avoiding long and very expensive experimental tests.

SuperPhenix Integrated plugging-meter (50 l/h)



Temperature

Flow-rate

Integrated heat exchanger

Nitrogen cooling system

Pellet

Tp = 218°C

Upper Na level
(TNa = 550°C)

EM Pump

Lower Na level
(TNa = 180°C)

H-meter for detection of Sodium-water reaction

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

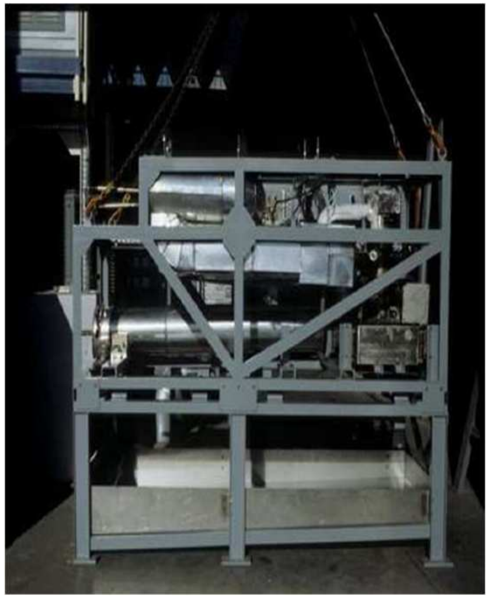
; nevertheless tracks for improvement:

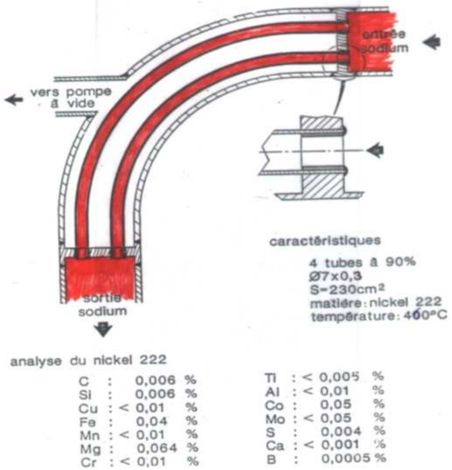
Reduction of Na transit time

Signal processing

Other complementary solutions developped:

(Acoustic detection, electrochemical H-meter,…)





analyse du nickel 222

C : 0,006 %		Ti : < 0,005 %	
Si : 0,006 %		Al : < 0,01 %	
Cu : < 0,01 %		Co : 0,05 %	
Fe : 0,04 %		Mo : < 0,05 %	
Mn : < 0,01 %		S : 0,004 %	
Mg : 0,064 %		Ca : < 0,001 %	
Cr : < 0,01 %		B : 0,0005 %	

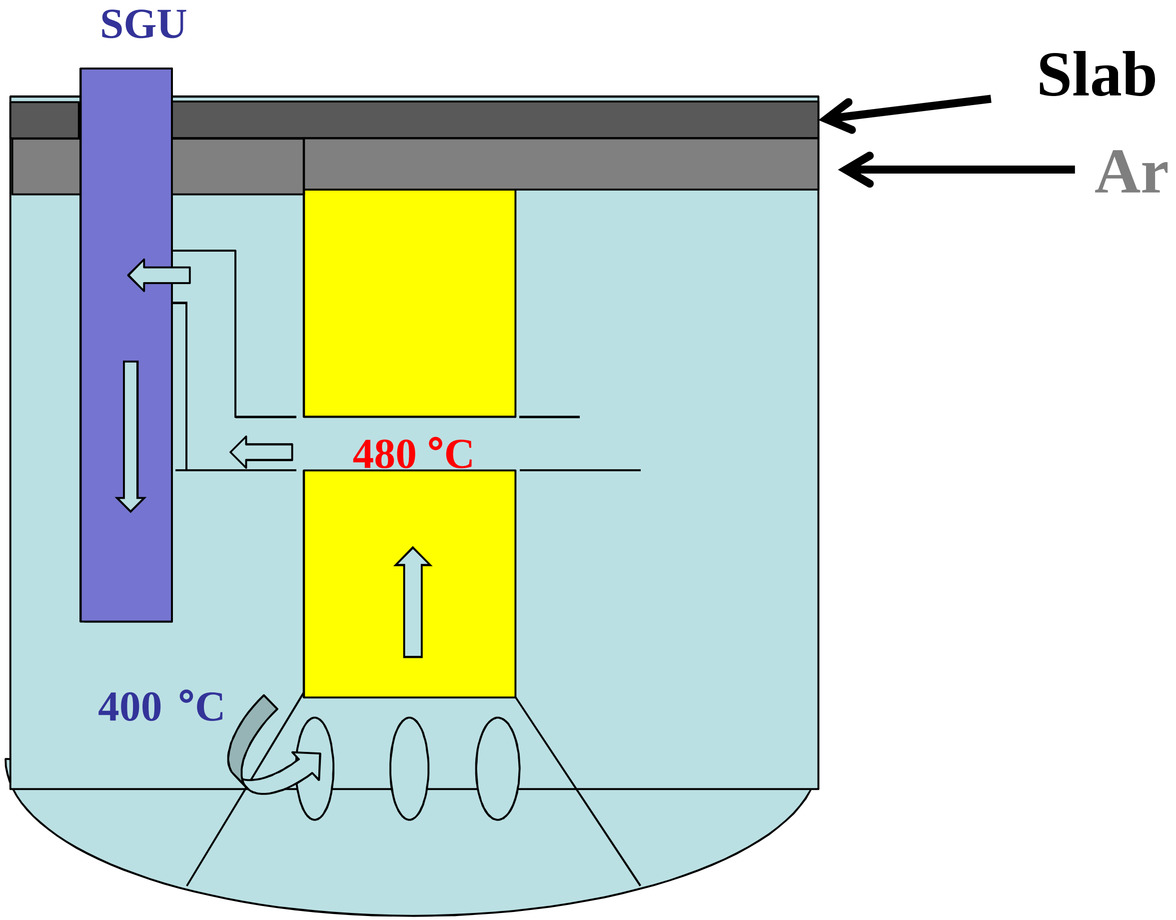
CAPTEUR D'HYDROGENE DANS LE SODIUM

Electro-chemical H-meter

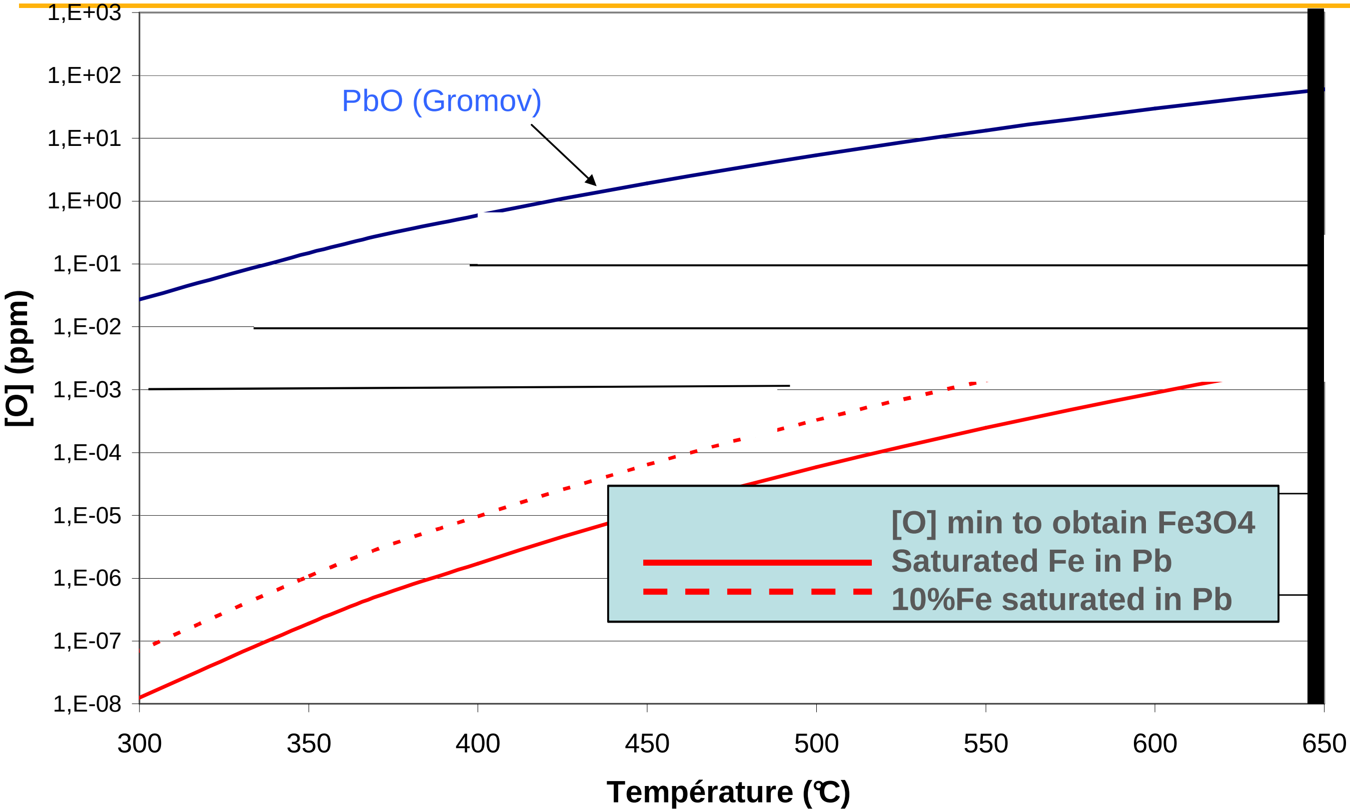
(Courtesy of IGCAR)

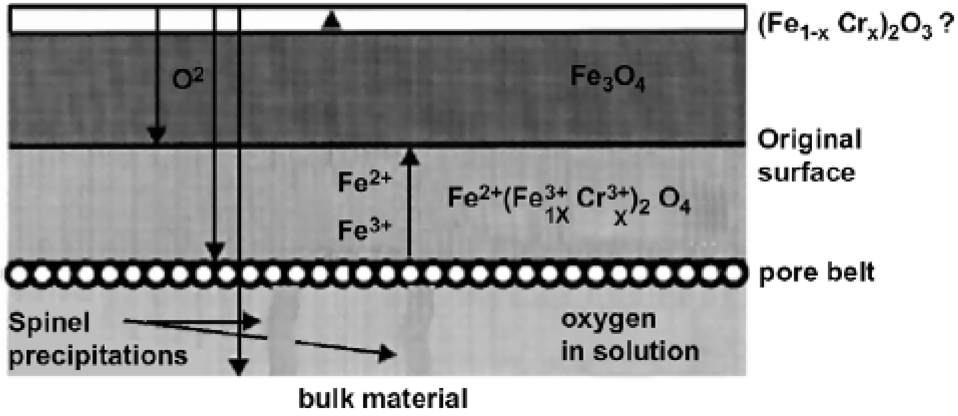
LFR

Hot and cold plenum



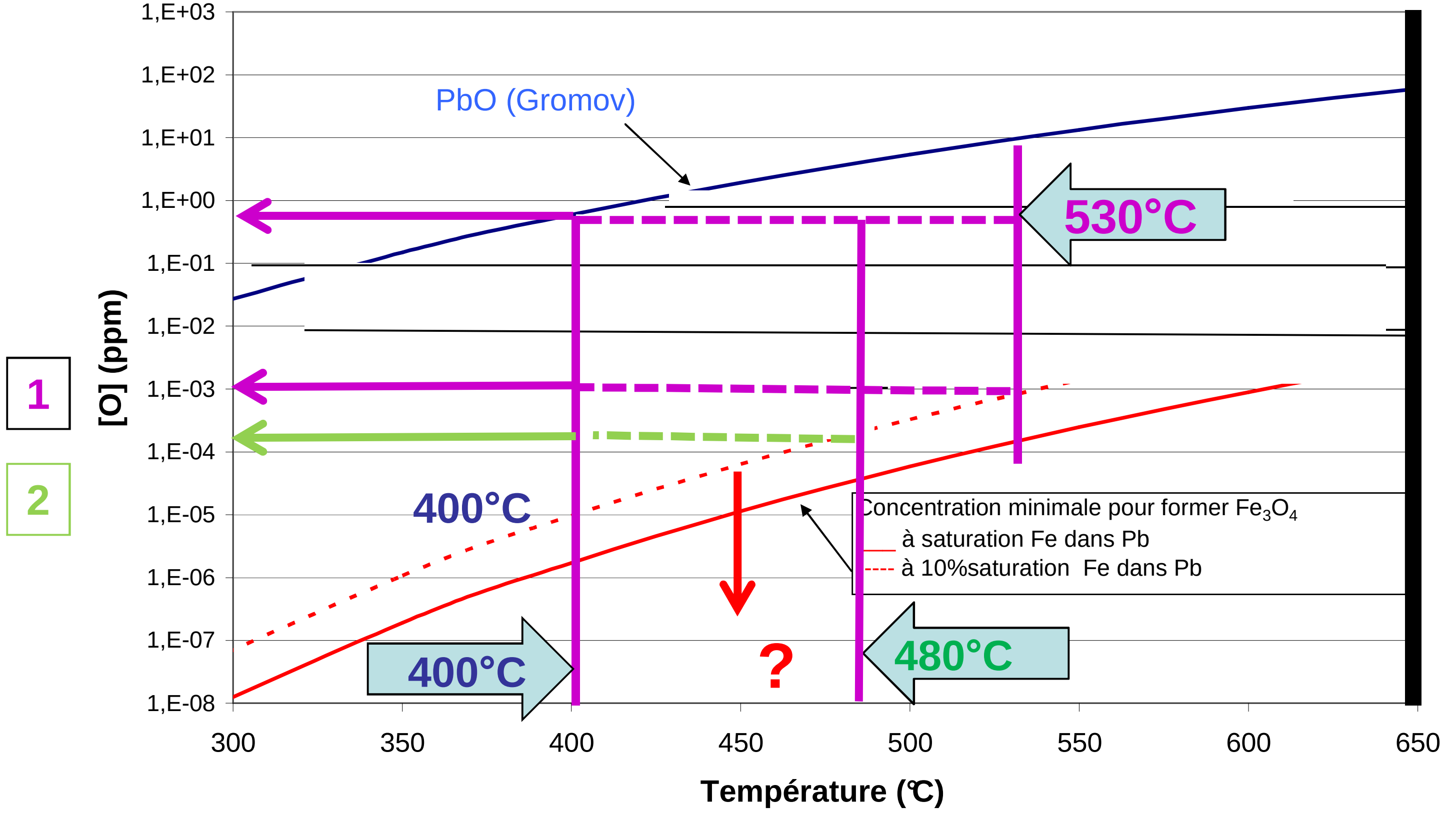
O Thermodynamic diagram





Thermodynamic diagram (from 400℃ to 530℃)

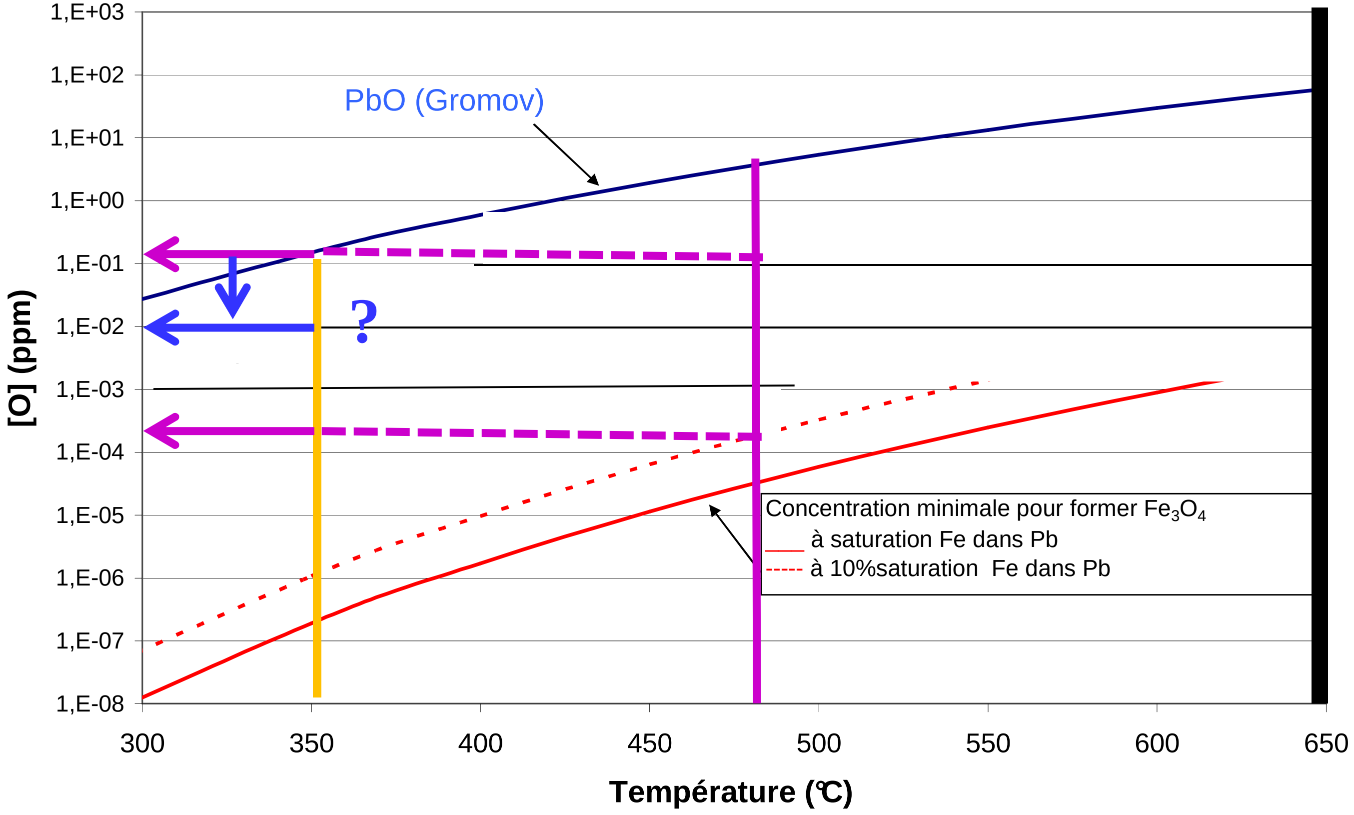
Hypothesis: T= 530°C Cladding temperature



?: possibility to decrease depends on coating properties

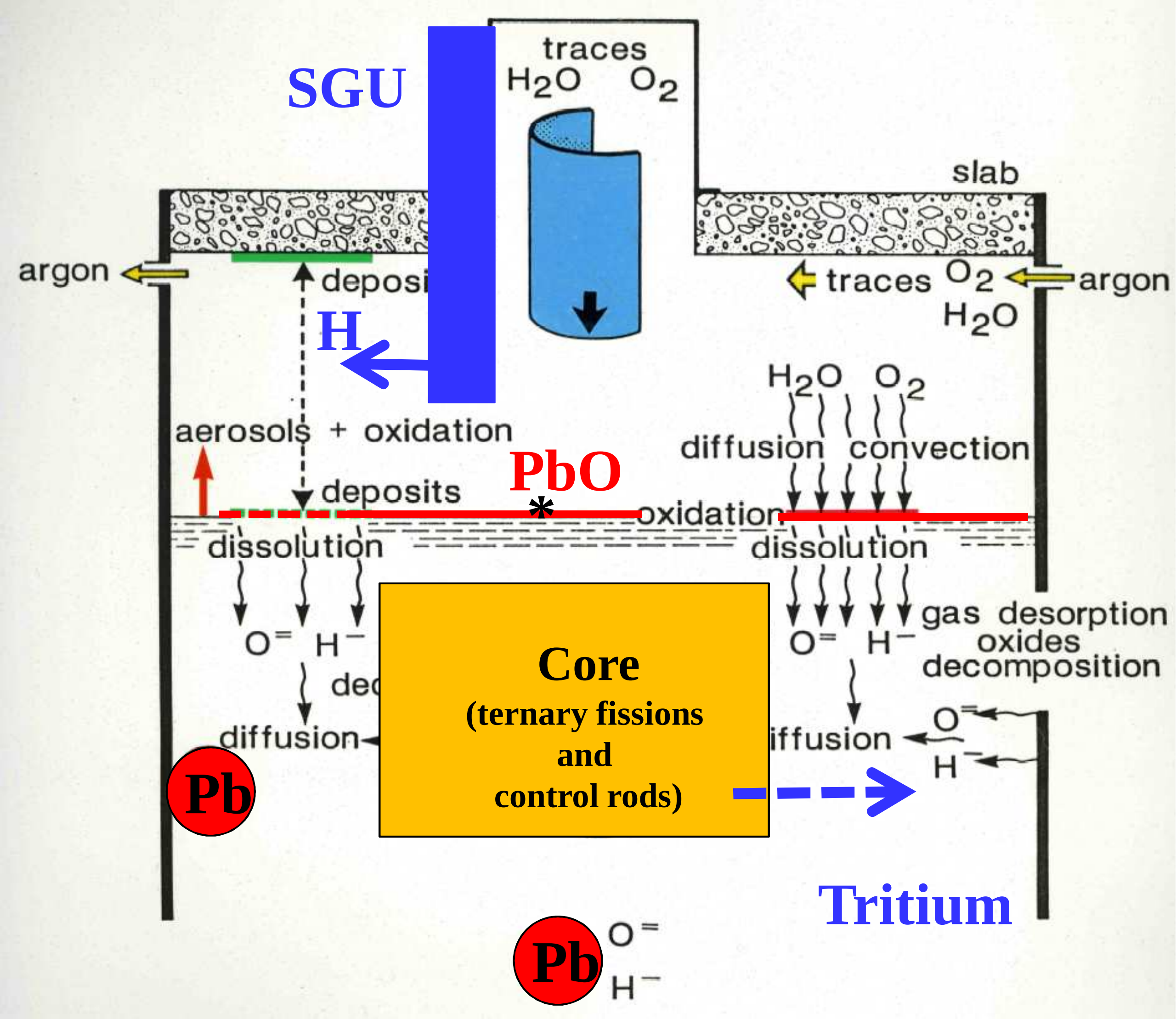
2: if cladding are protected against dissolution (but not hot leg and SGU)

Diagram showing optimal working area



? With margin?

Pb ways of pollution in Primary Vessel 2/2



Core
(ternary fissions
and
control rods)

Consequences of main potential events:

If air ingress, PbO is produced on Pb bulk surface, but very slow dissolution rate on surface, and risks of entrainment if vortices…

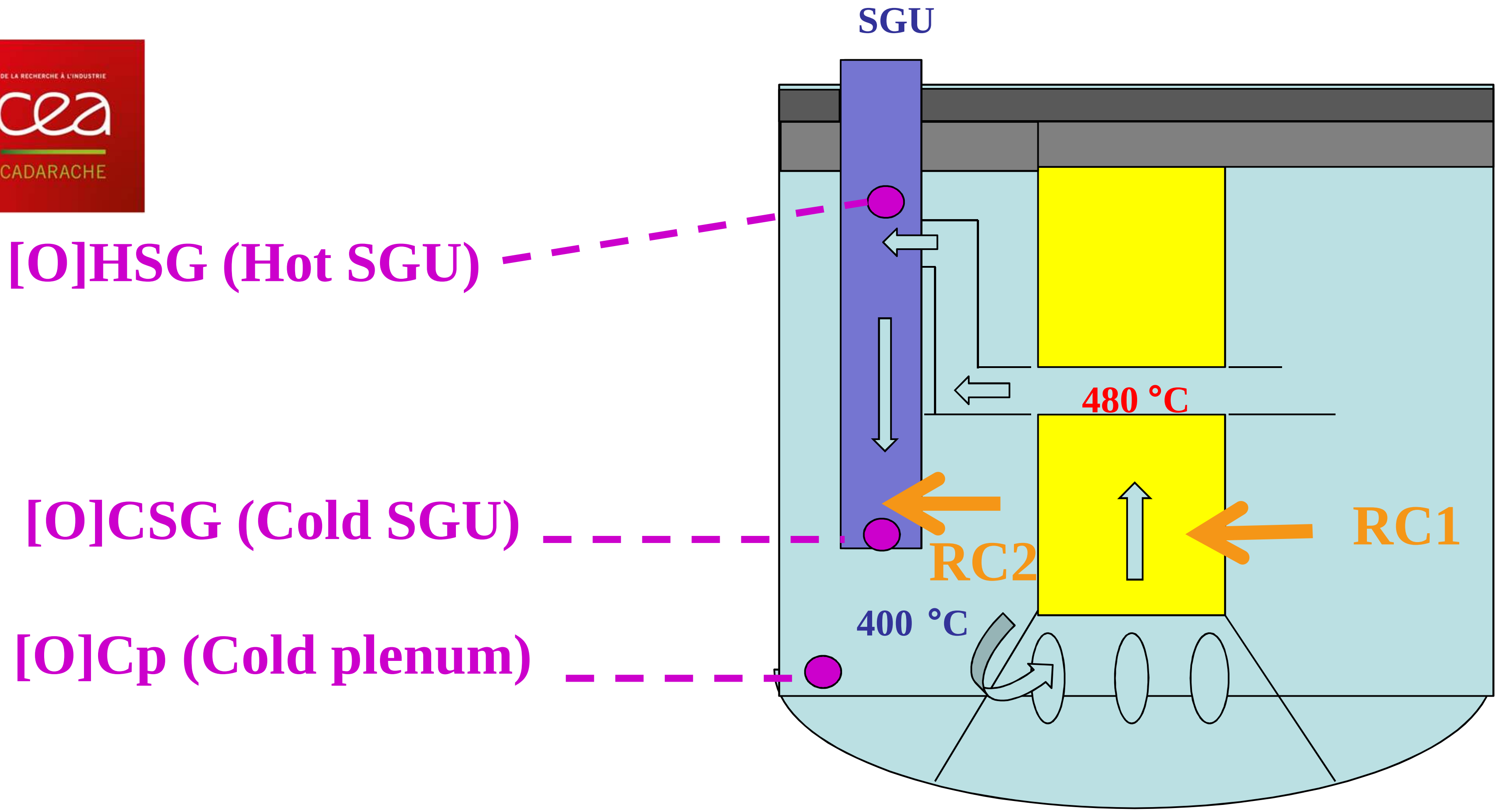
- Detection in cover gas (N_2 or O_2) by MS or gas chromatography
- Confirmation in Pb by O-meter

- **If water ingress, very small amont of PbO produced continuously**
  - Detection by O-meter and more probably by H-meter in gas plenum or water by SM or IR spectroscopy (to be investigated)

➔**Then, in both cases, purification by:**

- filtration,
- H_2 reduction or
- overflooding and collection in dedicated vessel.

[O] control strategy in hot and cold plenum



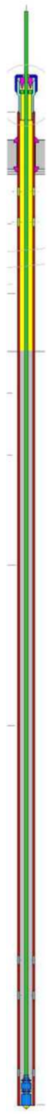
[O]HSG (Hot SGU)

[O]CSG (Cold SGU)

[O]Cp (Cold plenum)

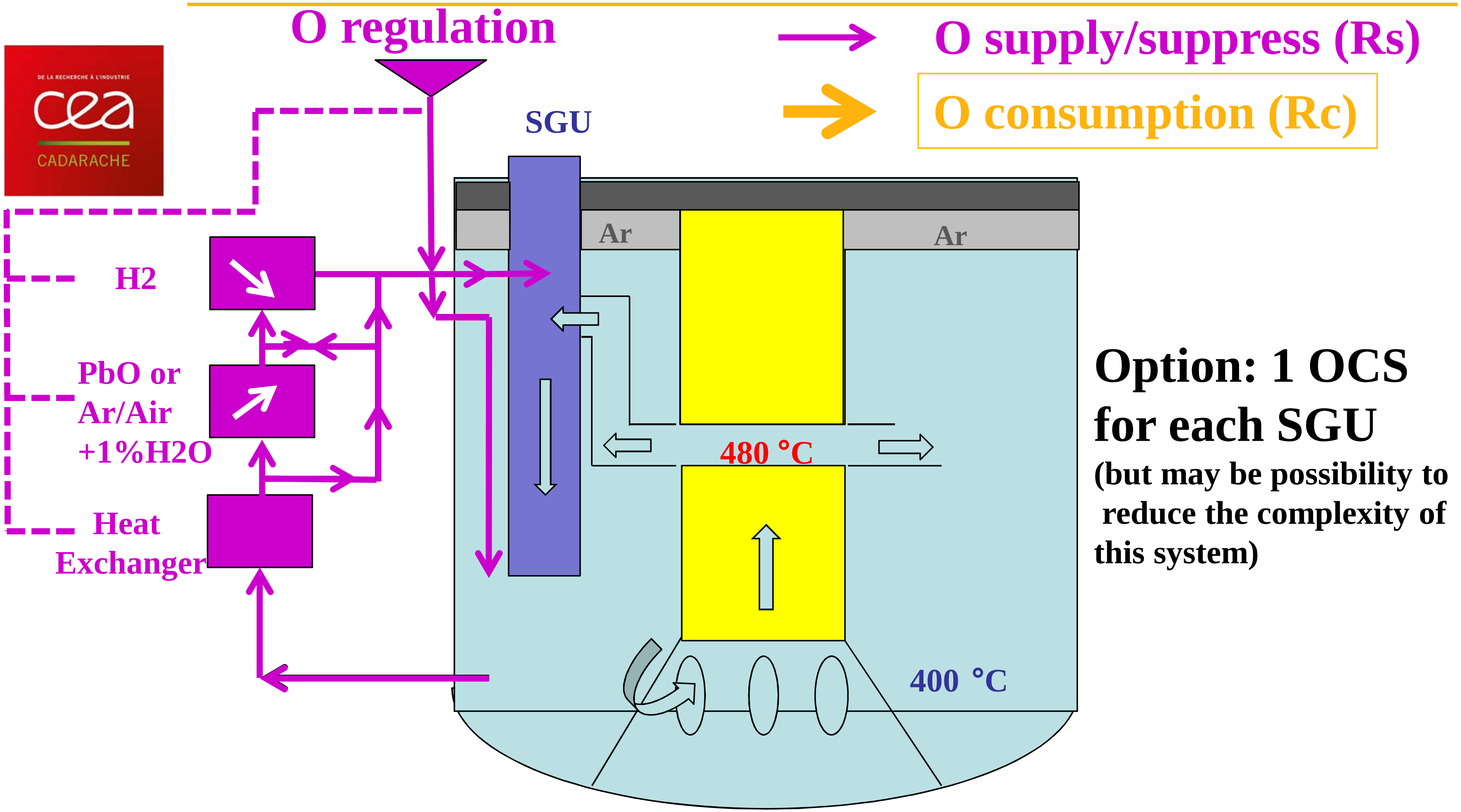
[O]HSG depends on oxidation/corrosion in core ➔ RC1 (Rate of oxygen consumption in core)

[O]CSG depends on oxidation/corrosion in SGU and possible PbO precipitation➔ RC2 (Rate of oxygen consumption in core)



O-meter

Possible O control strategy (OCS) (to be validated)



Option: 1 OCS for each SGU

(but may be possibility to reduce the complexity of this system)

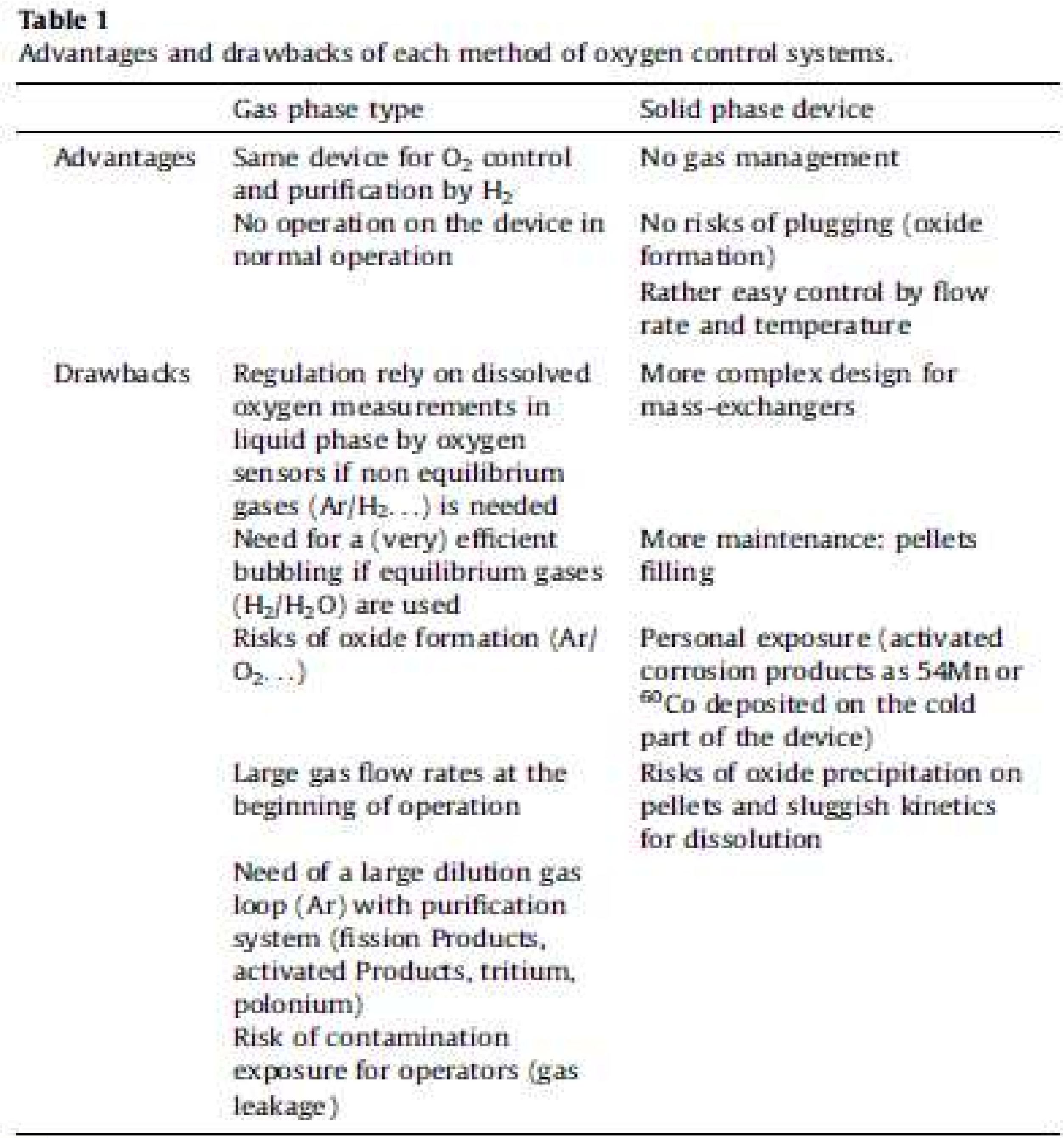
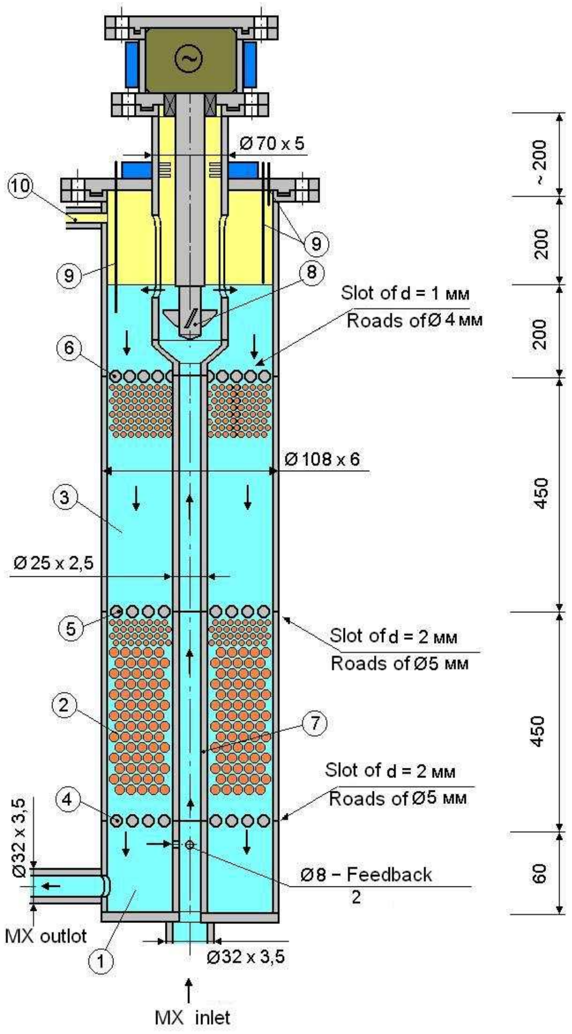


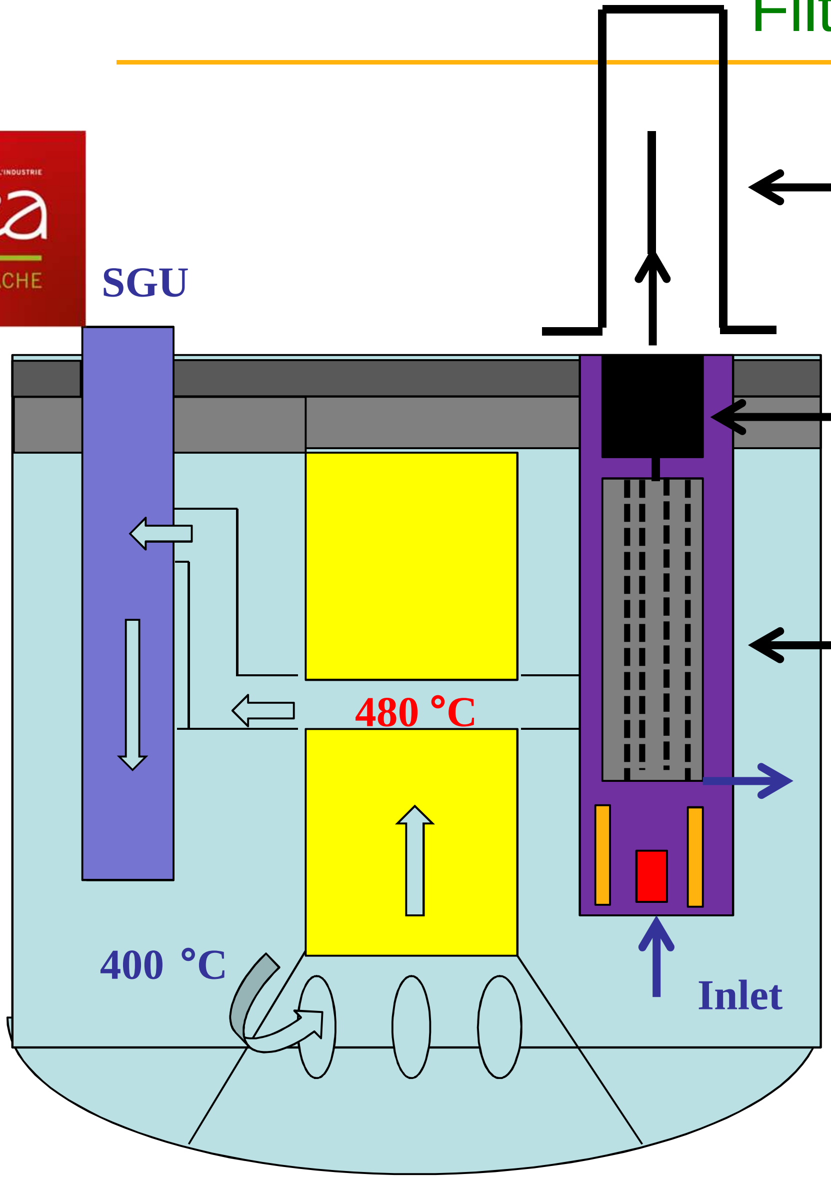
Table 1
Advantages and drawbacks of each method of oxygen control systems.

	Gas phase type	Solid phase device
Advantages	Same device for O_2 control and purification by H_2	No gas management
	No operation on the device in normal operation	No risks of plugging (oxide formation)
		Rather easy control by flow rate and temperature
Drawbacks	Regulation rely on dissolved oxygen measurements in liquid phase by oxygen sensors if non equilibrium gases (Ar/H_2…) is needed	More complex design for mass-exchangers
	Need for a (very) efficient bubbling if equilibrium gases (H_2/H_2O) are used	More maintenance: pellets filling
	Risks of oxide formation (Ar/O_2…)	Personal exposure (activated corrosion products as 54Mn or ^{60}Co deposited on the cold part of the device)
	Large gas flow rates at the beginning of operation	Risks of oxide precipitation on pellets and sluggish kinetics for dissolution
	Need of a large dilution gas loop (Ar) with purification system (fission Products, activated Products, tritium, polonium)	
	Risk of contamination exposure for operators (gas leakage)	

PbO oxygen Control system (Russia)



Filtration unit (Integrated option)



SGU

480 °C

400 °C

Handling cask (for filter)

Internal Plug

Filter (PbO, Activated corrosion products, fission products and fuel (if pin rupture)

Outlet

EMP

Heat Exchanger (if required)

Inlet

Pb filtration

Several types of liquid filters tested (for Pb-Bi)

- Metallic mesh ; dynalloy, Poral (CEA)
- Filtration efficiency depends on :
  - Liquid metal properties (viscosity, density,..)
  - Particles : nature, form, size, concentration
  - Temperature
  - Hydrodynamics
  - Filters medium characteristics (geometry, porosity, pressure drop...)
  - Its location in system

Temperature max : 400℃

Flow velocity : ≈ 0.5 m/s, but filtration rate 0.2 cm/s (related to filter area, <2 cm/s recommended by manufacturers)

- Far from elbows…
- Need of a auxiliary « loop » or cartridge to have flow rate compatible with filters characteristics

➔ how to replace the filters (when loaded with impurities), in presence of high contamination and dosimetry ?

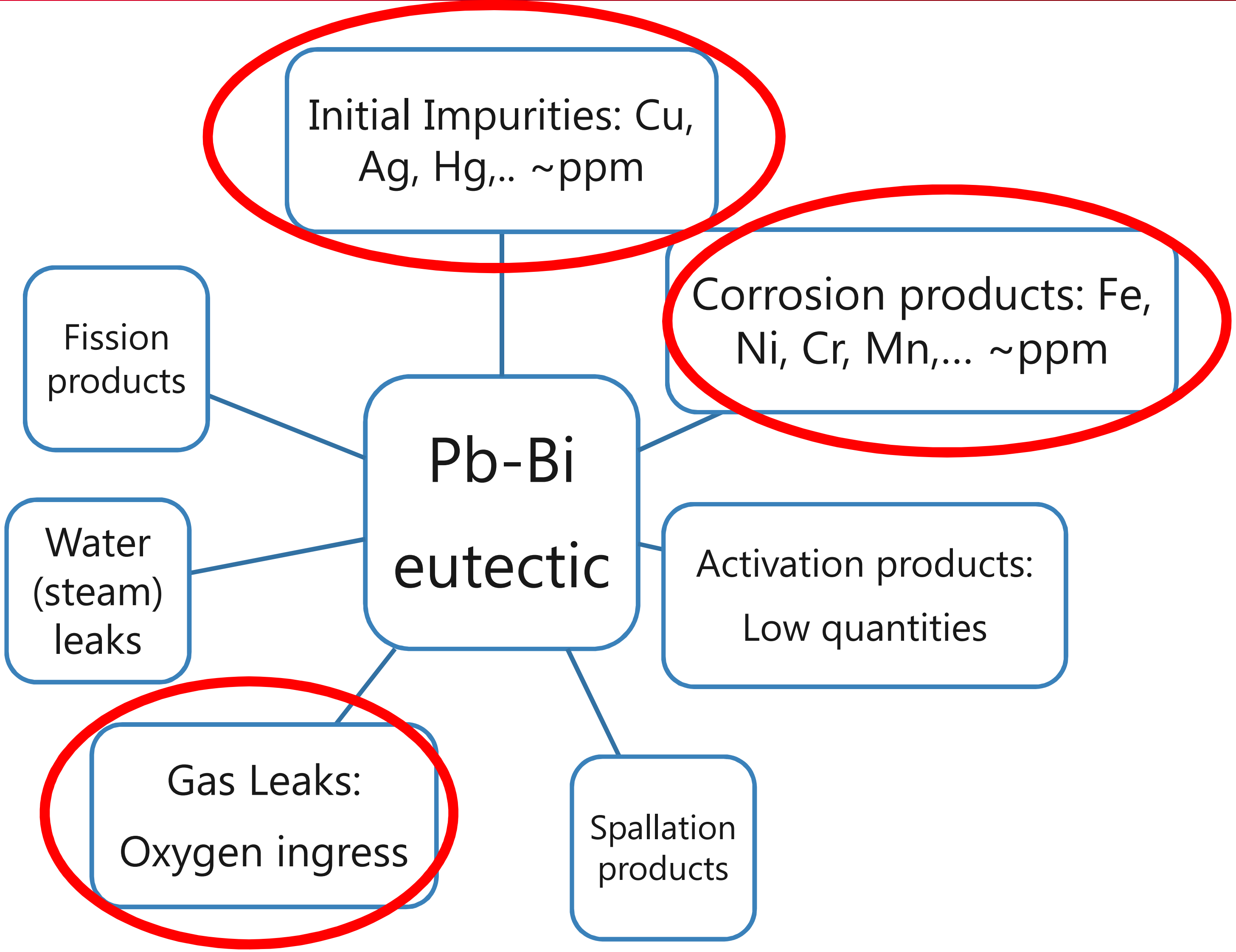
➔ Necessity to perform CFD calculations to confirm the best locations for implementation of the filters

Poral

Dynalloy

Pall cartridge

Impurities in LBE



Initial Impurities: Cu, Ag, Hg,.. ~ppm

Corrosion products: Fe, Ni, Cr, Mn,… ~ppm

Fission products

Pb-Bi eutectic

Water (steam) leaks

Activation products:

Low quantities

Gas Leaks:

Oxygen ingress

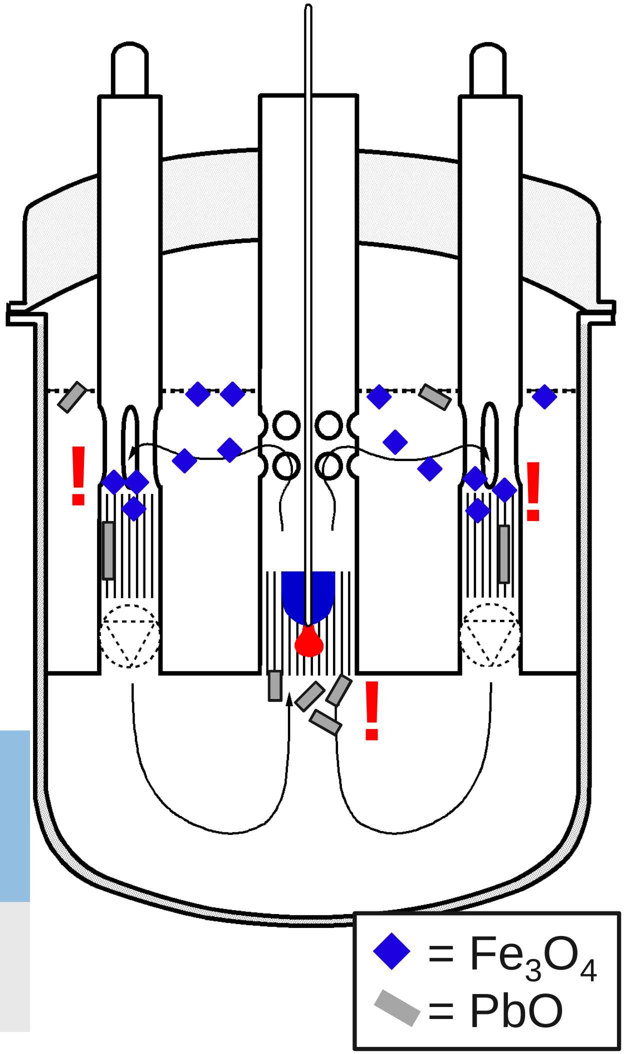
Spallation products

Courtesy K Gladinek SCK_Mol ESNII+ Summer School

SOLID PARTICLE FORMATION IN LBE

- Plugging risk
  - By solids (particles, deposits) in HEX, core
  - Only by abundant elements
  - Mainly due to reactions with oxygen:
    - Pb (LBE) + O (LBE) → PbO (s)
    - Corrosion products (Fe, Cr, Ni) (*e.g.* magnetite, Fe_3O_4)
- Corrosion products*
  - Largest contribution

	Duration	Ni (kg)	Cr (kg)	Fe (kg)	Mn (kg)	Total (kg)
EOL MYRRHA	40 years	460	320	230	90	**1100**



*A. Weisenburger (KIT), SEARCH deliverable 3.2 (2014)
Courtesy of K. Gladinek SCK-CEN Mol ESNII+ Summer School PISA 2016

MODEL (COURTESY K GLADINEK SCK-CEN U-GENT)

Modeling of nucleation and growth of oxides in LBE by CFD (K Kristof Gladinez PhD student U.Gent) :

➔ **Goal:** define deposition and precipitation of oxides in LBE to identify a filtering strategy

➔ **Strategy:**

- **Develop kinetic model for particle formation & growth**
- **Couple with CFD calculations**
  - Dissolved impurity concentration mapping
  - Particle formation dependent on local conditions:
    T, concentrations and residence time
- **Model the particle – flow interaction**
  - Particle accumulation, flotation,…
  - Oxide particle distribution important to define the correct filtering method (non relevant for Na coolant)

➔ **Kinetic model: Classical (homogeneous) Nucleation Theory (including nucleation barrier)**

Particles are extremely small: diameter~2E-9m ➔ Follow the flow perfectly

- Assumption of mass transfer limited growth and dissolution ((**in Na:** growth limited by mass transfer through boundary layer for Na_2O, or by integration to crystal lattice for NaH)

➔Mass transfer to micro-particles in agitated systems (**in Na:** heterogeneous nucleation on mesh packing or cooled walls)

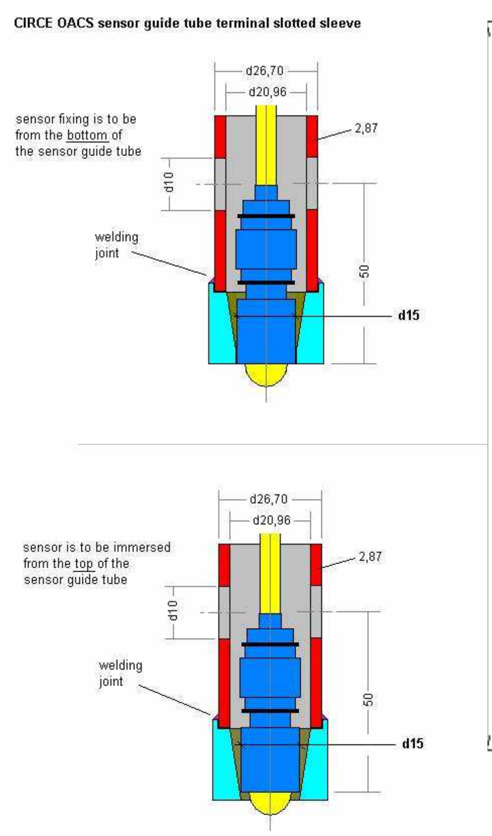
$$Sh = 2 + 0.52\, Re^{0.52}\, Sc^{\frac{1}{3}} \quad Re = \left(\frac{\varepsilon\, d^4}{\sigma^3}\right)^{\frac{1}{3}}$$, σ = kinematic viscosity

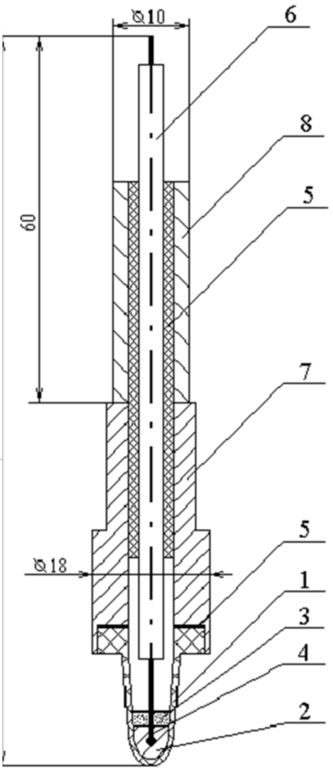
➔ **Necessity to perform experimental studies in MEXICO chemistry loop**

Ref: Armenante, P. M. & Kirwan, D. J. Mass transfer to microparticles in agitated systems *Chemical Engineering Science, Elsevier,* **1989**, *44*, 2781-2796)

Ref: Gladinez, K., Rosseel, K., Lim, J., Marino, A., Heynderickx, G., & Aerts, A. (2017). Nucleation and growth of lead oxide particles in liquid lead-bismuth eutectic. *Physical Chemistry Chemical Physics*, *19*(40), 27593-27602.

Sensors (O-meters) for large HLM facilities and industrial-scale reactors (DEMETRA Project)





Characteristics

- ❑ Electrolyte thimble
  - Seal between electrolyte and housing immersed in the liquid metal
  - Glass ceramic sealant developed for compatibility with YSZ and steel (thermal), and with liquid Pb alloys (chemical)
- ❑ Reference electrodes:
  - Bi/Bi_2O_3
- ❑ 3-YSZ with optimized mechanical properties
- ❑ Prototype for oxygen measurement in a depth of ~5 m below the surface of a liquid-metal pool

(based on R&D by IPPE)

Hydrogen & tritium transfer from SGU in LFR

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 :

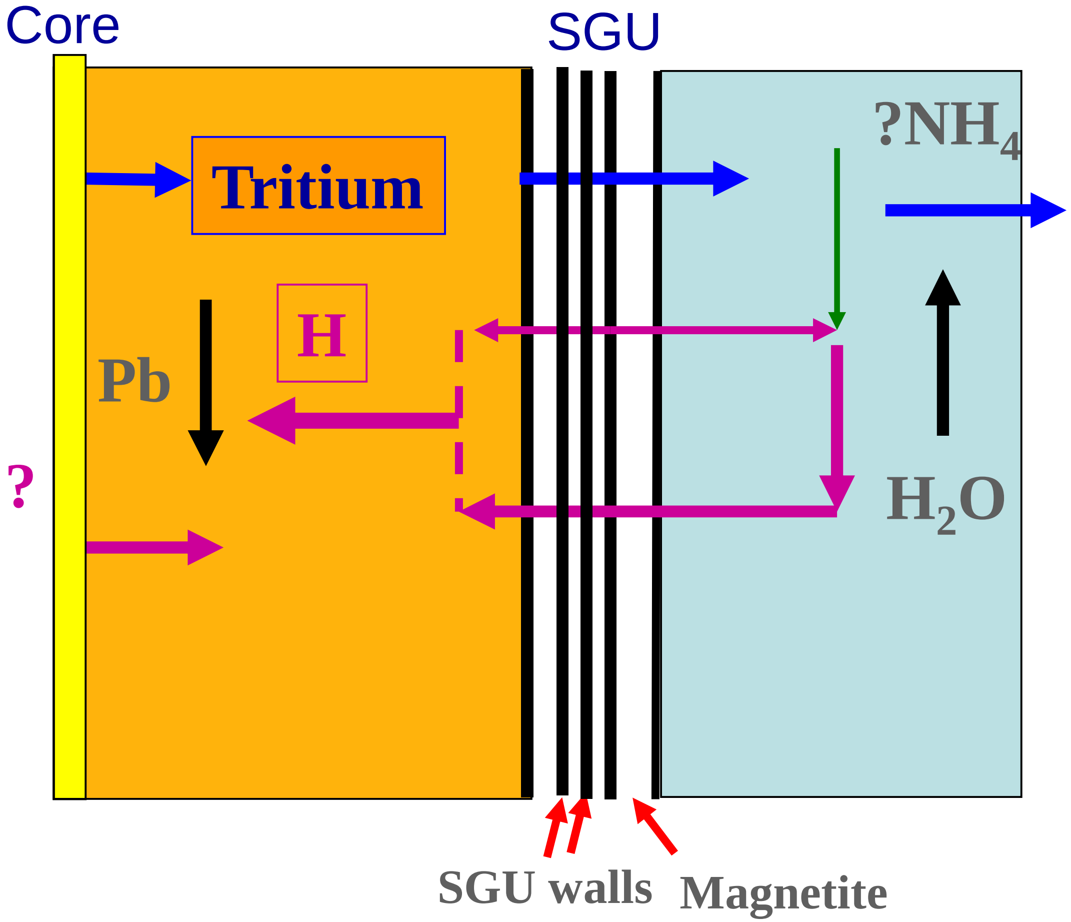
Assess tritium releases to the environment (gaseous and aqueous)

- 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,…) and Tritium build-up in purification units



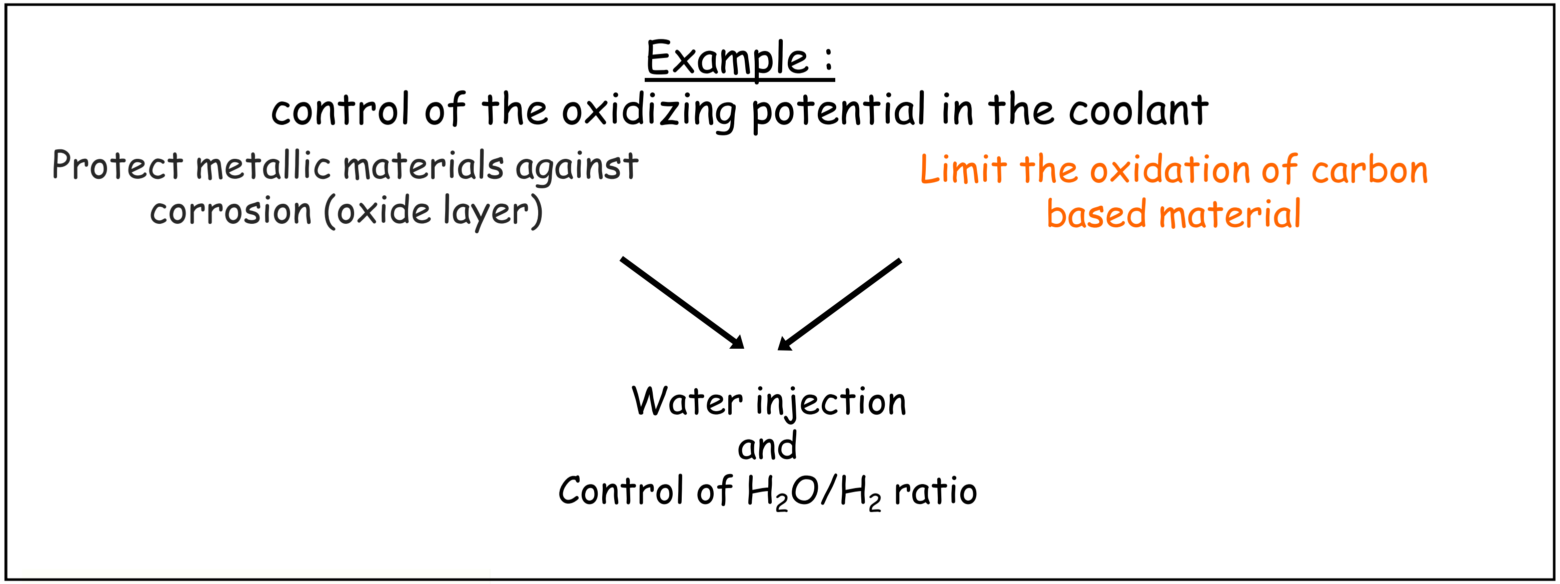
GFR

Purpose of Helium chemistry control

- Ensure safety during operation and in case of accident : limit the inventory of particles, fission products and activated species,

- Increase service life : minimize the interactions between gas and structures

Specification for Primary Coolant Chemistry



Example :

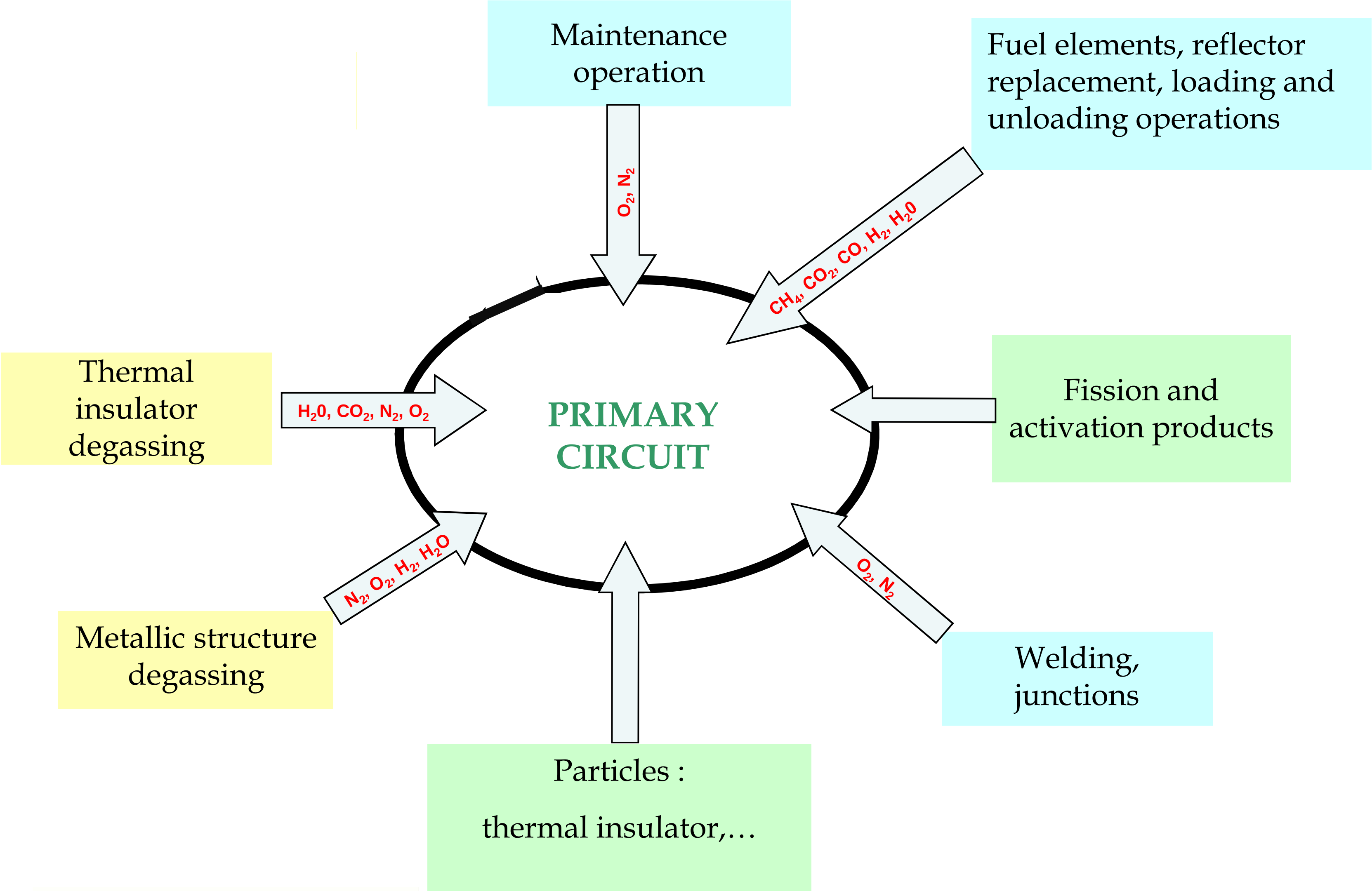
control of the oxidizing potential in the coolant

Protect metallic materials against corrosion (oxide layer)

Limit the oxidation of carbon based material

Water injection
and
Control of H_2O/H_2 ratio

Source of impurities in primary coolant



PRIMARY CIRCUIT

Maintenance operation

O_2, N_2

Fuel elements, reflector replacement, loading and unloading operations

$CH_4, CO_2, CO, H_2, H_20$

Fission and activation products

Welding, junctions

O_2, N_2

Particles :

thermal insulator,…

Metallic structure degassing

N_2, O_2, H_2, H_2O

Thermal insulator degassing

H_20, CO_2, N_2, O_2

Background on He Purification

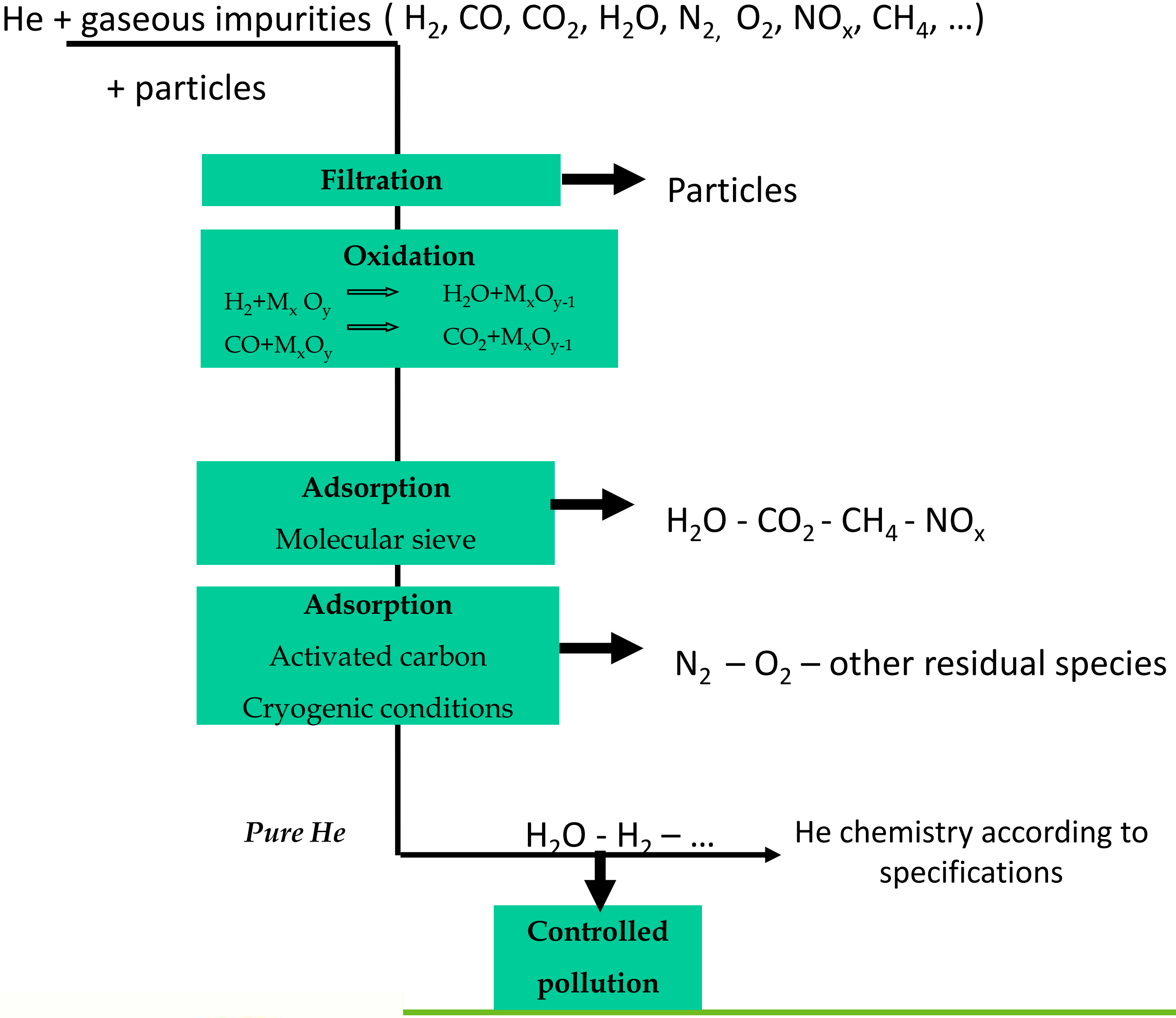
- **Chemical Impurities:** H_2O,CO,N_2,H_2, CH_4, CO_2, O_2 (tritiated species will behave as H_2, H_2O and CH_4)
- **Helium chemistry specifications** depend on operating conditions

Possible Recommendations (for VHTR; to be up dated for GFR)

Partial Pressure (µbar or ratio)	Temperature < 950°C	Temperature < 1000°C
H_2O/H_2	$> 10^{-3}$	$> 10^{-2}$
H_2O	< 10 µbar	< 10 µbar
CO	> [130 – 450] µbar	> [500 – 1570] µbar
CH_4/H_2O	<< 100	<< 100
N_2	< 5 µbar	< 5 µbar

- **Continuous process with operating conditions**:
  - Pressure = Primary circuit pressure
  - Flowrate = [5%-10%] of primary circuit flowrate or 5% of He inventory per hour
- **Purification system principles:**
  - Filtration
  - Oxydation of hydrogen into water
  - Adsorption of impurities on one or several fixed beds

Reference process for Helium purification



He + gaseous impurities (H_2, CO, CO_2, H_2O, N_2, O_2, NO_x, CH_4, …)

+ particles

Filtration → Particles

Oxidation

$H_2 + M_x O_y \Longrightarrow H_2O + M_xO_{y-1}$

$CO + M_xO_y \Longrightarrow CO_2 + M_xO_{y-1}$

Adsorption

Molecular sieve

→ H_2O - CO_2 - CH_4 - NO_x

Adsorption

Activated carbon

Cryogenic conditions

→ N_2 – O_2 – other residual species

Pure He

H_2O - H_2 – …

He chemistry according to specifications

Controlled pollution

Alternative purification systems

- Membranes,
- Getters,
- He Cryogenic traps

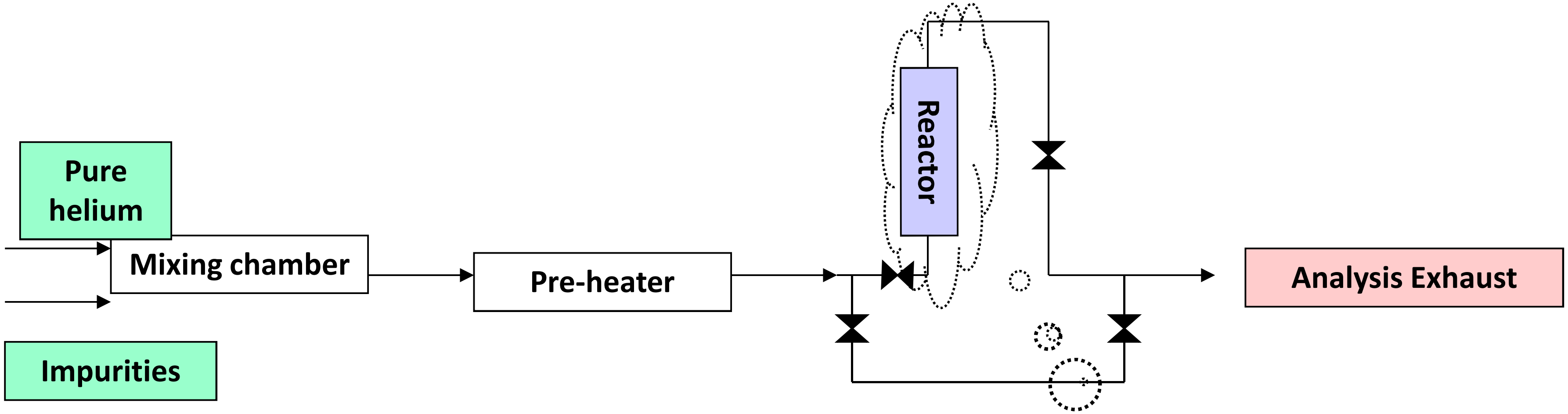
Studies on Helium purification and control at CEA

1.Improve the knowledge for Helium purification using standard processes through the development of a loop dedicated to Helium chemistry control and monitoring (HPC)

- Operating on a stand-alone basis
- Connected to a loop representative of Helium Primary Circuit

2.Evaluate new materials (alternative metal oxide, molecular sieve, activated carbons)

CIGNE – the facility



Pure helium

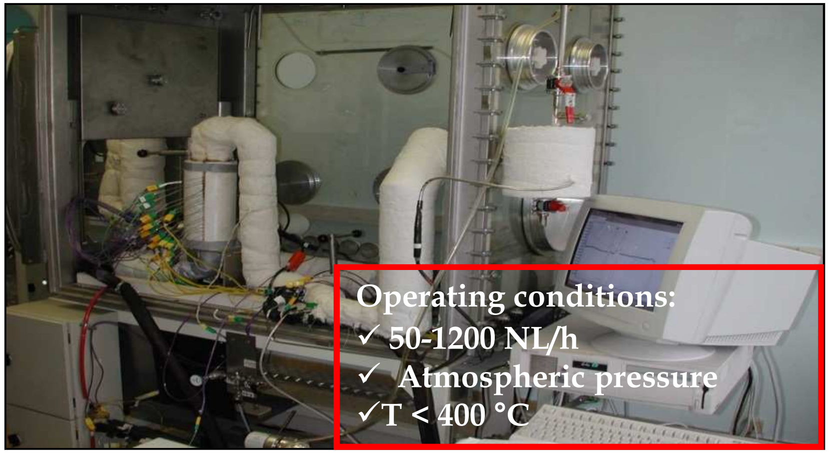
Impurities

Mixing chamber

Pre-heater

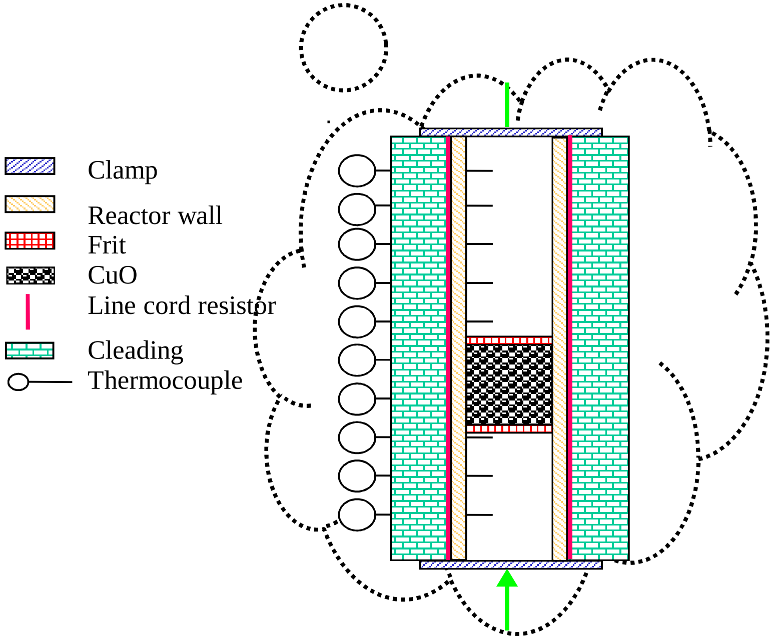
Reactor

Analysis Exhaust



Operating conditions:

- ✓ 50-1200 NL/h
- ✓ Atmospheric pressure
- ✓T < 400 °C



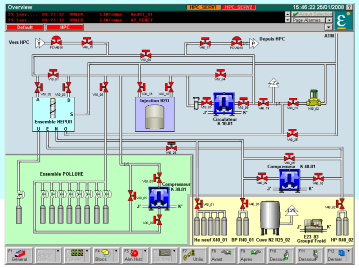
▨ Clamp
▨ Reactor wall
▦ Frit
▩ CuO
| Line cord resistor
▦ Cleading
○— Thermocouple

HPC – Main characteristics

	Flow rate (g/s)	Pressure (bars abs.)	Temperature (℃)	Volume (L)
Oxidation (CuO)	5 - 20	25 - 80	300 Regeneration: 350℃	10
Molecular sieve	5 – 20	25 – 80	25 Regeneration: 250℃	50 (x 2)
Activated carbon	5 – 20	25 – 80	-180 Regeneration: 150℃	20

For inlet impurities concentration of 40ppmV, regeneration frequency

- Oxidation column : 5 days
- Molecular sieve column : 12 hours
- Activated carbon column: 24 hours


```
25 janv.... 09:23:32 UNACK LINComms And01_41
25 janv.... 09:23:32 UNACK LINComms AT_FONCT
```

Thank you for your kind attention !

Commissariat à l'énergie atomique et aux énergies alternatives
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