

**NATO Advanced Study Institute MATGEN 2007**  
**Materials for Generation IV Nuclear Reactors**



**Chemistry control in Sodium Fast Reactors: feedback from Phenix,  
Superphenix and other Liquid Metal Fast Breeder Reactors**

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# Content

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- **Main coolants for nuclear applications**
- **quality control for Sodium :**
  - **crystallization phenomena involved in Na**
  - **Cold traps : design and operation**
  - **Impurities measurement in Na**
  - **Needs for future SFR**
- **Others liquid metal coolants : chemistry control in large installations**

# Main coolants for Nuclear applications

- Fission :

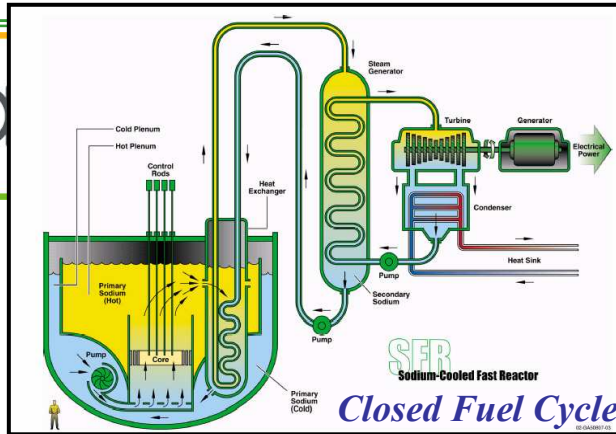


- Sodium for sodium-cooled fast reactor (SFR)
- Lead for lead (alloy) cooled fast reactor (LFR) or Accelerated Driven Systems (ADS)
- Lead-bismuth eutectic for ADS spallation targets, intermediate loops of SFR
- Molten-salts for molten salt reactors (MSR) or intermediate loops of SFR
- Gas : He for Very High Temperature Reactor (VHTR), gas-cooled fast reactor (GFR), He-N<sub>2</sub> for Energy conversion systems of SFR,
- Water as primary coolant for Pressurized water reactors (PWR), super-critical water-cooled reactor (SCWR),...and Steam Generator Units (SGU) for Energy conversion systems of SFR, LFR,...
- Fusion :
- Lead-Lithium eutectic for Fusion breeding blankets
- Lithium as material for International Fusion Materials Irradiation Facility (IFMIF)

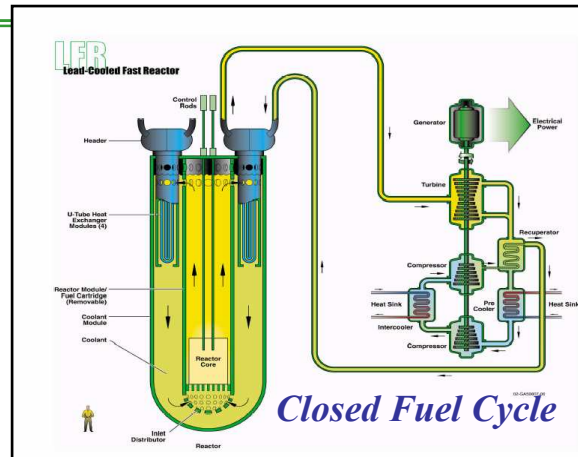
→ Nota :

- in spallation targets Lead Bismuth Eutectic acts also as a neutron generator,
- In fusion, lithium acts also as tritium or neutron generator.

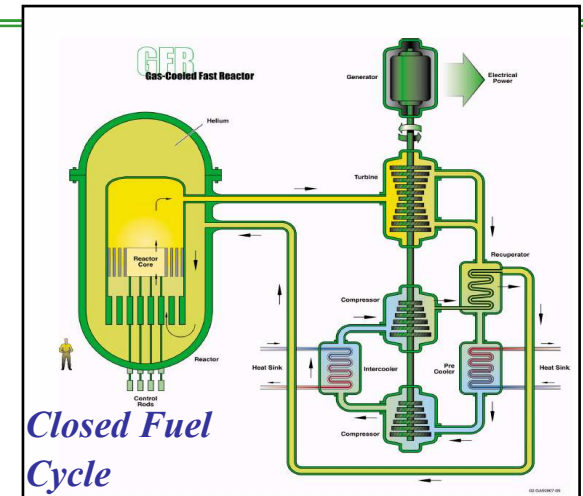
# 6 Innovative concepts with technological breakthroughs



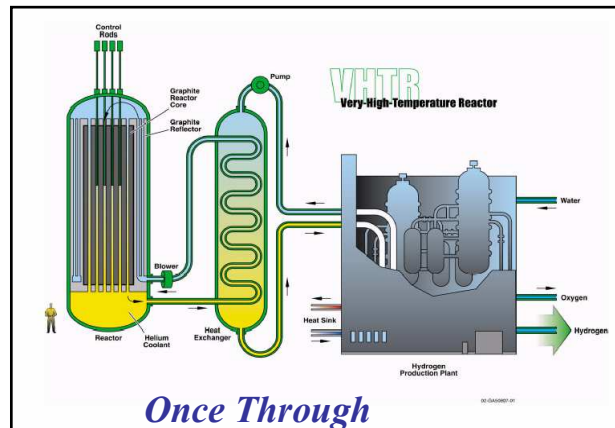
*Sodium Fast reactor*



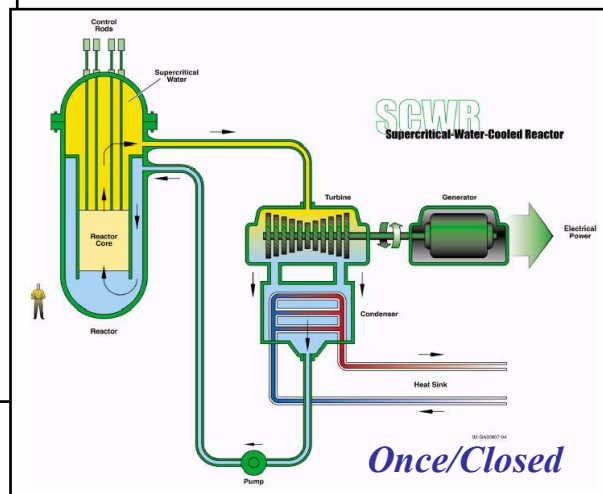
*Lead Fast Reactor*



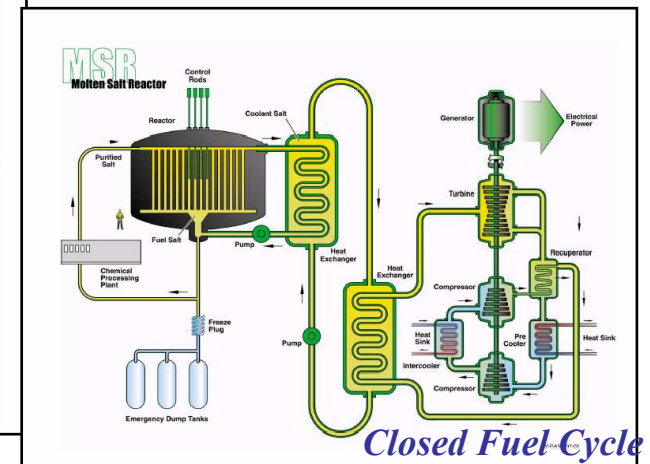
*Gas Fast Reactor*



*Very High Temperature Reactor*



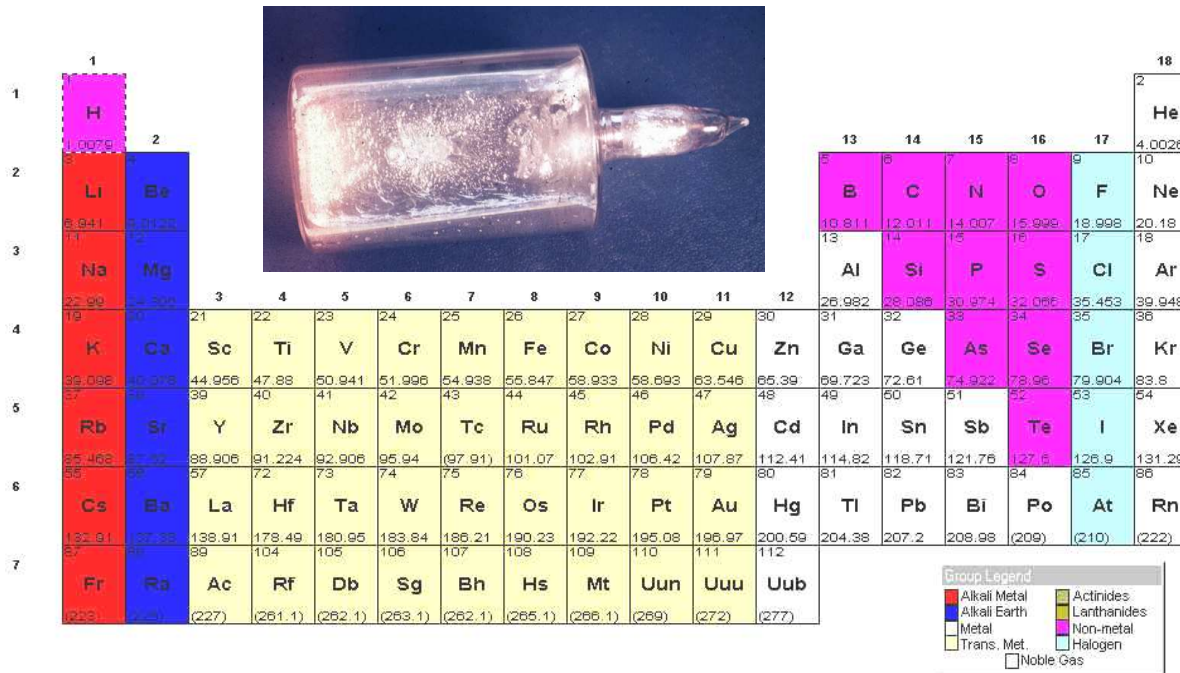
*Supercritical Water Reactor*



*Molten Salt Reactor*

## ced

فَقَلَّوْیَ



Lanthanide Series	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinide Series	140.12	140.91	144.24	(144.9)	150.36	151.97	157.25	158.93	162.5	164.93	167.26	168.93	173.04	174.97
	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	232.04	231.04	238.03	(237)	(244.1)	(243.1)	(247.1)	(247.1)	(261.1)	(252.1)	(257.1)	(268.1)	(269.1)	(262.1)



# Sodium properties



- Na a very attractive coolant for Fast Neutron Reactors :

- Very good thermal conductivity.
- High thermal capacity.
- Liquid between 97.8 up to 880°C
- at dynamic pressure below 4 bars,
- Compatible neutron-physical properties.
- Viscosity comparable to that of water.
- Compatibility with metallic materials fairly satisfactory.
- No toxicity
- Low cost,...

**But high reactivity**



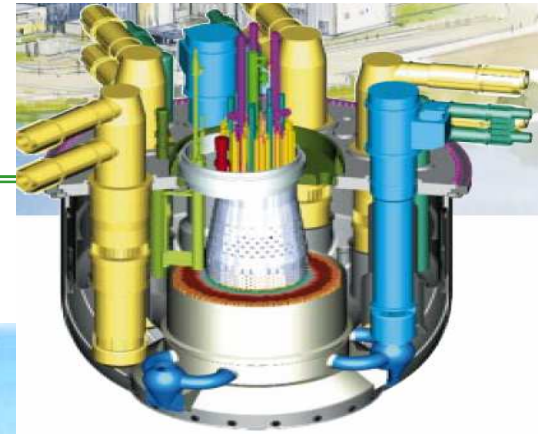
**From RGN  
September 2007**

RÉACTEURS RAPIDES DANS LE MONDE 2007				
Réacteur (pays)	Puissance thermique (et électrique) MW	Première divergence	Arrêt définitif	Nombre d'années de fonctionnement
EBR-I (USA)	1.4 (0.2)	1951	1963	12
BR-5/BR-10 (Russie)	8 (0)	1958	2002	44
DFR (UK)	60 (15)	1959	1977	18
EBR-II (USA)	62.5 (20)	1961	1991	30
EFFBR (USA)	200 (61)	1963	1972	9
Rapsodie (France)	40 (0)	1967	1983	16
BOR-60 (Russie)	55 (12)	1968		39
SEFOR (USA)	20 (0)	1969	1972	3
BN-350 (Kazakhstan)	750 (130)	1972	1999	27
Phenix (France)	563 (250)	1973		34
PFR (UK)	650 (250)	1974	1994	20
JOYO (Japon)	50-75/100 (0)	1977		30
KNK-II (Allemagne)	58 (20)	1977	1991	14
FFTF (USA)	400 (0)	1980	1993	13
BN-600 (Russie)	1470 (600)	1980		24
SuperPhenix (France)	3000 (1240)	1985	1997	12
FBTR (Inde)	40 (13)	1985		22
MONJU (Japon)	714 (280)	1994		13
CEFR (Chine)	65 (25)	En construction (2009)		
PFBR (Inde)	1250 (500)	En construction (2010)		
BN-800 (Russie)	2100 (880)	En construction (2012)		
Total				385

# From Rapsodie to EFR



**Superphenix**



**EFR**



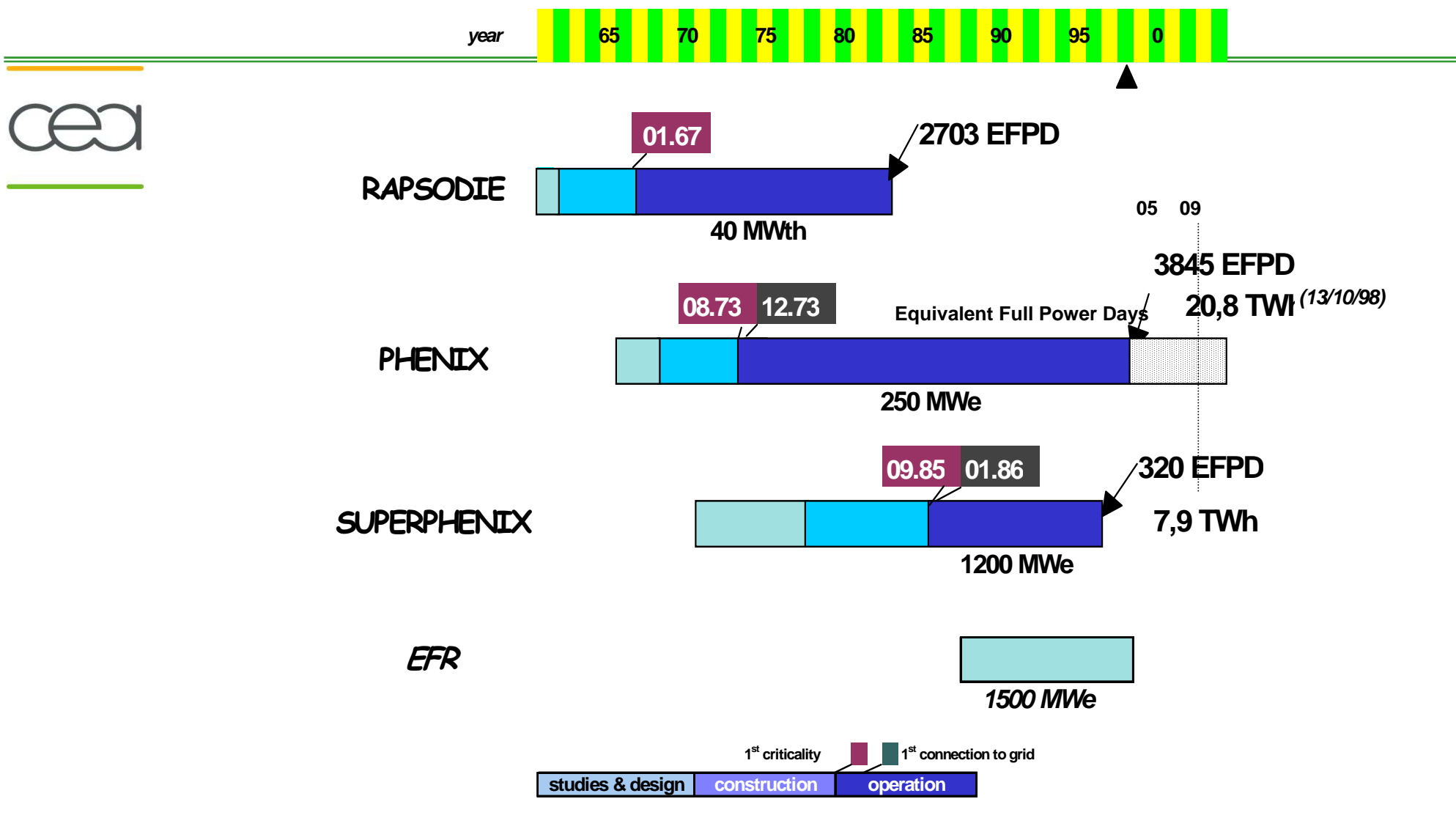
**Phenix**



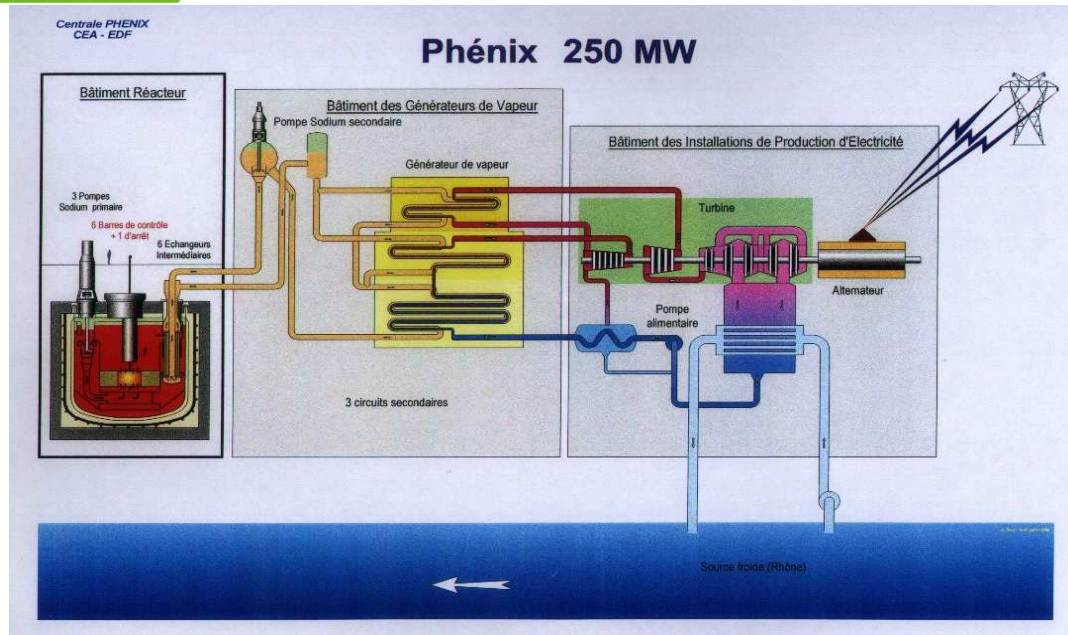
**Rapsodie**



# Fast reactors in France - Main data and milestones



# General design of the plant (ex : PHENIX)

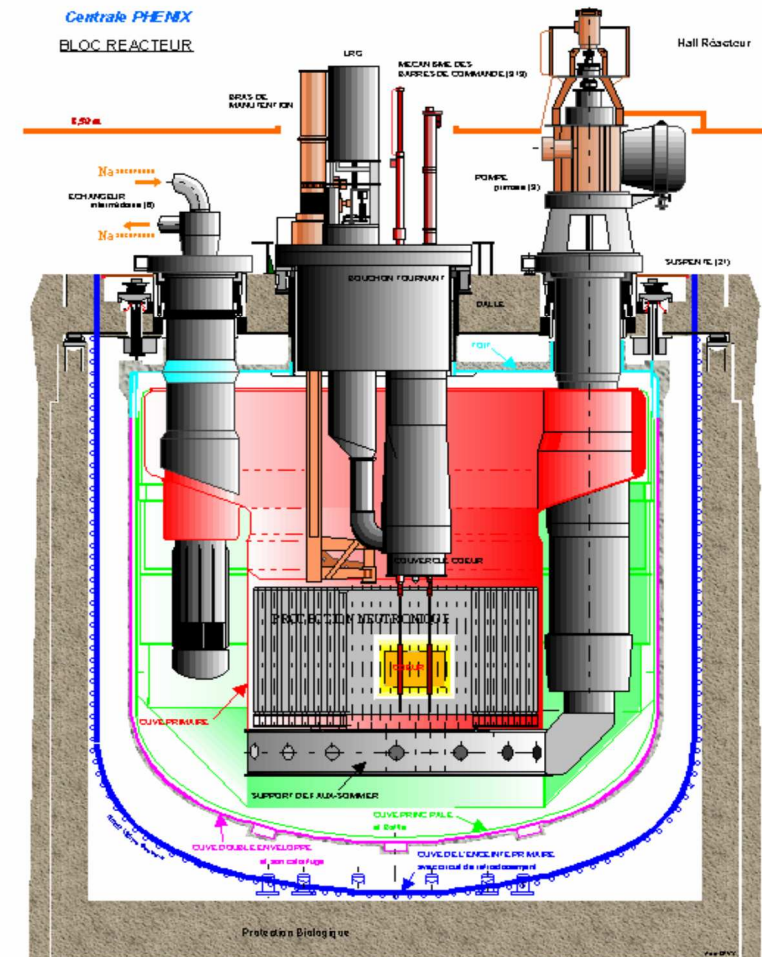


Pool type primary circuit

3 primary pumps

6 intermediate heat exchangers

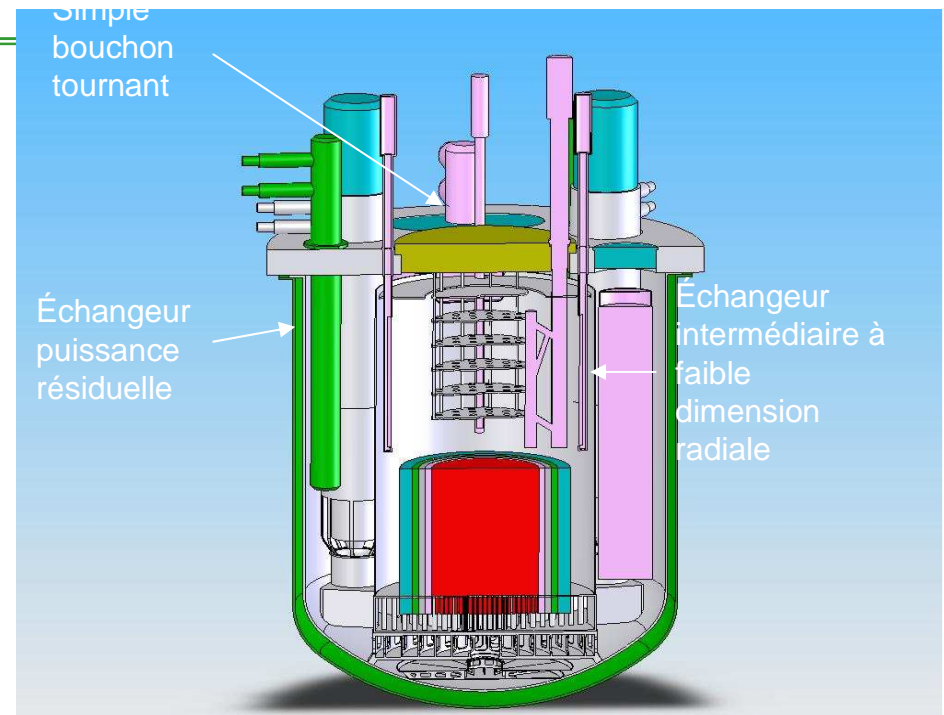
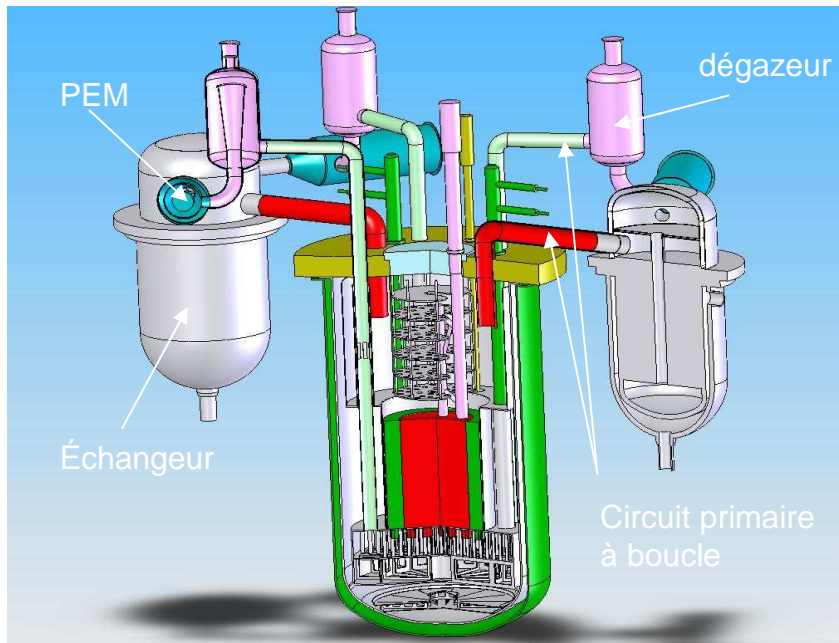
temperatures : 400 - 560°C



# Innovative SFR Sketches

cea Large pool type

1500 MWe optimized size



Modular concept with gas conversion system

# Pollution sources at reactor start-up

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- **Impurities coming from nuclear grade sodium (Ag, Li, ....)**
- **Dissolved hydrogen and oxygen :**
  - Liquid sodium hold H and O at concentrations corresponding to the transfer temperature for the initial filling (maximum value)
- **Inerting gas and cover gas : residual traces in volumes**
  - Reduced to a minimum by evacuation procedures and inerting gas purification (argon gas sweeping at  $T_{\text{ambient}}$  then at 200°C, possibly vacuum)
- **Various compounds present on steel**
  - Metallic oxides,
  - Gases :  $O_2$ ,  $H_2O$ , adsorbed on surface and  $H_2$  dissolved in structural material (structural material of fuel assemblies)
  - Iron cuttings, filings, oil traces,
  - A careful cleaning before sodium filling reduce the quantity to a minimum achievable

# Impurity level guaranteed for « nuclear grade » Na



Argent	< 5	Activation
Baryum	< 5	Plugging
Bore	< 5	Nuclear reactions
Calcium	5	Plugging
Carbone (total)	10	Mechanical properties
Chlore + Brome	15	Corrosion
Lithium	< 5	Tritium
Soufre	20	Corrosion
Uranium	< 0,1	Nuclear reactions
Aluminium	< 5	.....
Chrome	< 3	
Cuivre	< 3	
Etain	< 2	
Magnésium	< 2	
Manganèse	< 2	
Molybdène	< 5	
Nickel	1	
Plomb	< 2	
Potassium	~ 300	cover gas activity
Titane	< 5	
Vanadium	< 3	
Zinc	< 2	

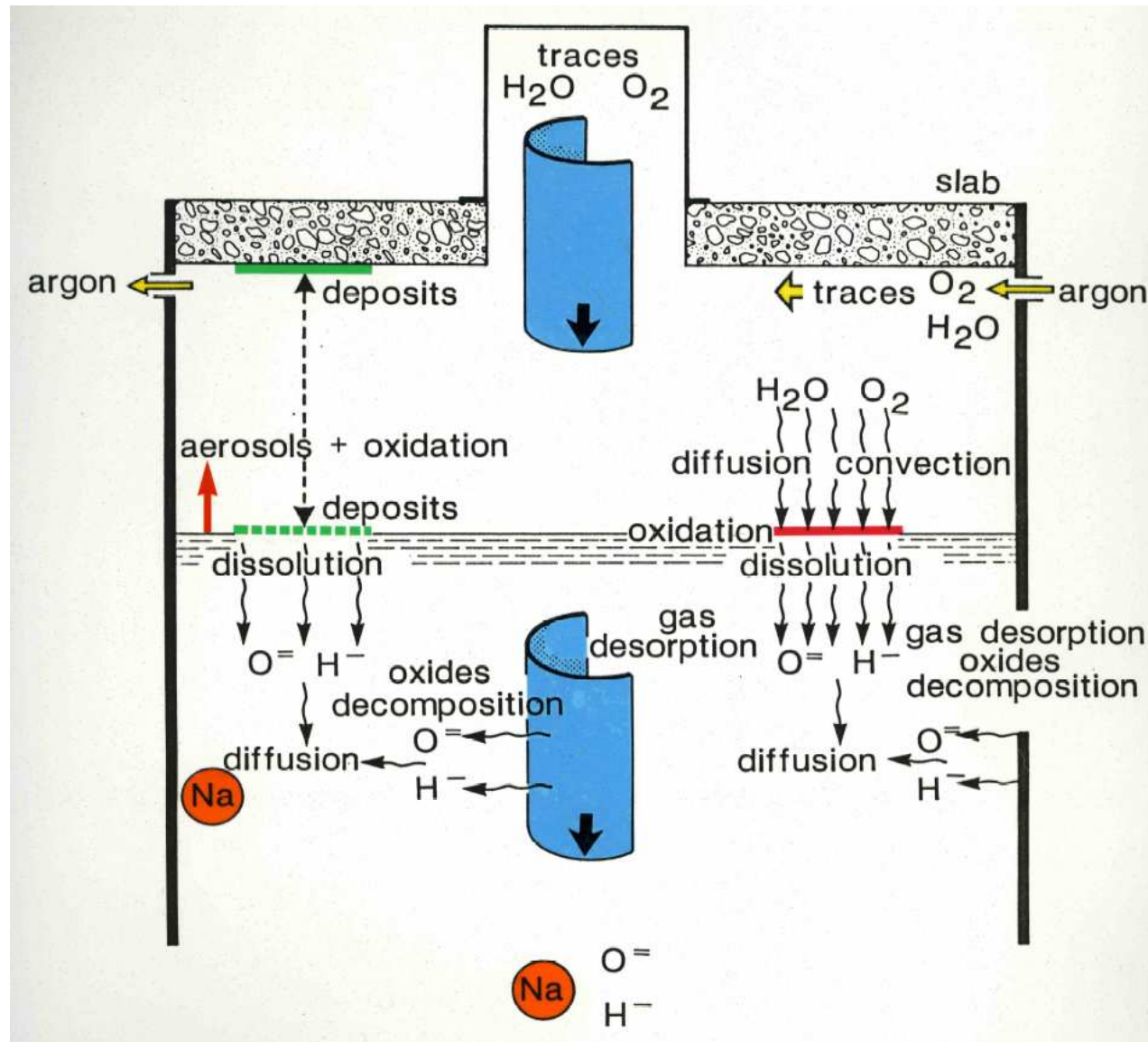
# Continuous or discontinuous pollution ingress in operation

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- Continuous
  - Diffusion of hydrogen through SGU walls (from aqueous corrosion and hydrazine thermal decomposition)
  - Impurities in cover gas (Ar) (oxygen, moisture)
- Discontinuous
  - Oxide dissolution in Na
  - Air ingress after repair (air + moisture)
  - Water ingress in SGU
  - Oil ingress (pumps)
  - Metallic filling due to maintenance, etc...

# O and H contamination during handling operations



# General corrosion



Dissolution of the steel elements (Fe, Cr, Ni, Mn, C) of the surface in contact with the sodium then transfer and a deposition on the reactor structures → contamination.

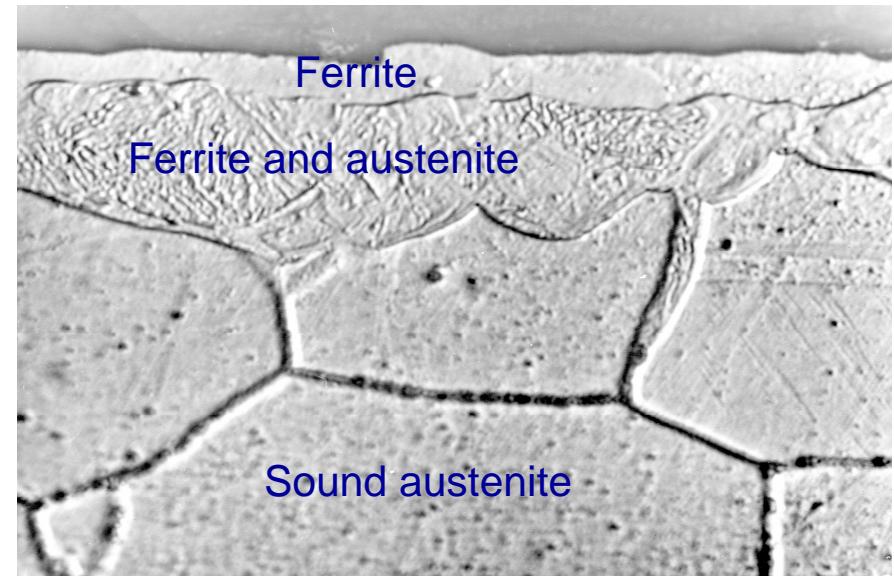
## **Four successive stages :**

Stage 1: surface cleaning. (oxide dissolution)

Stage 2: austenite dissolution in Na. ( $T > 570^{\circ}\text{C}$ ) and diffusion of the steel elements .

Stage 3: formation of a ferrite layer. At  $T > 590^{\circ}\text{C}$ , diffusion of elements from the external austenite layer → ferritization of the steel. This layer then dissolves and the steel elements diffuse to the surface.

Stage 4: steady state behavior : Limit value of the ferrite layer (dissolution and diffusion of elements to the sodium equivalent to stoichiometric corrosion of the basic austenite).



General corrosion : formation of a ferrite film at the surface

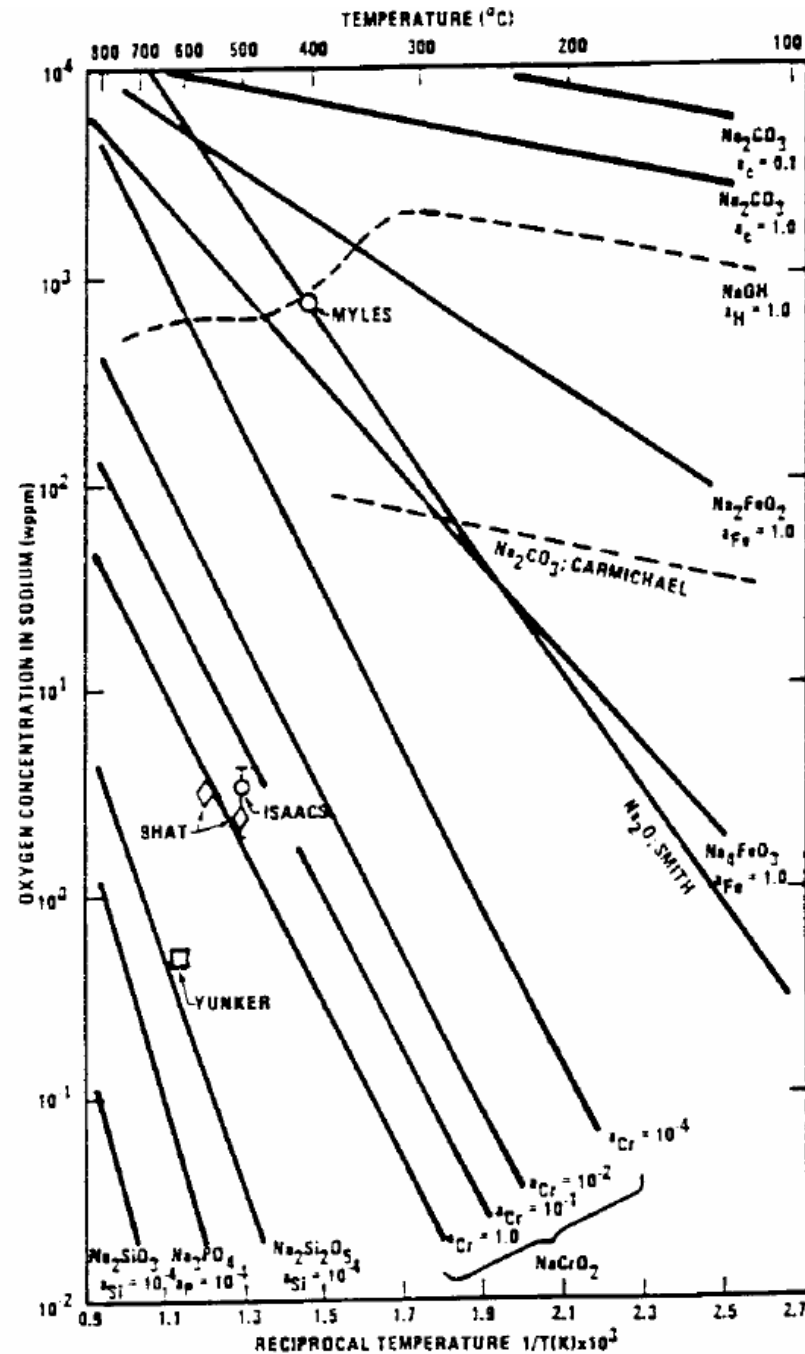
# Main Parameters affecting general corrosion

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- temperature affects the corrosion, mainly over 570°C → structural cladding material in the core.
- change of corrosion process when  $[O] > \text{about } 5\text{ppm}$  (Dissolution then displaced by oxidation reactions inducing complexes)
- critical sodium flow-rate beyond which the corrosion rate does not increase. (phenomenon explained by the disappearance of the laminar layer)
- negligible downstream effect due to the positive temperature gradient along the fuel cladding.

# Solubilities of various ternary oxides in liquid Na



Calculated Solubilities of Various Ternary Oxides in Liquid Sodium.

# Corrosion models used in France :



## [O] below 5ppm, Baque's model used :

$$R = 0 \quad (T < 817,13 \text{ K})$$

$$R = a \cdot V^{0.435} \cdot [O] \cdot \exp(-150.5/(T-817,13))$$

where : R = rate of metal loss in kg.m<sup>-2</sup> for one year

a = coefficient function of the alloy

V = sodium velocity (m.s<sup>-1</sup>) (below 10 m.s<sup>-1</sup>)

[O]= oxygen content in ppm (Eichelberger law)

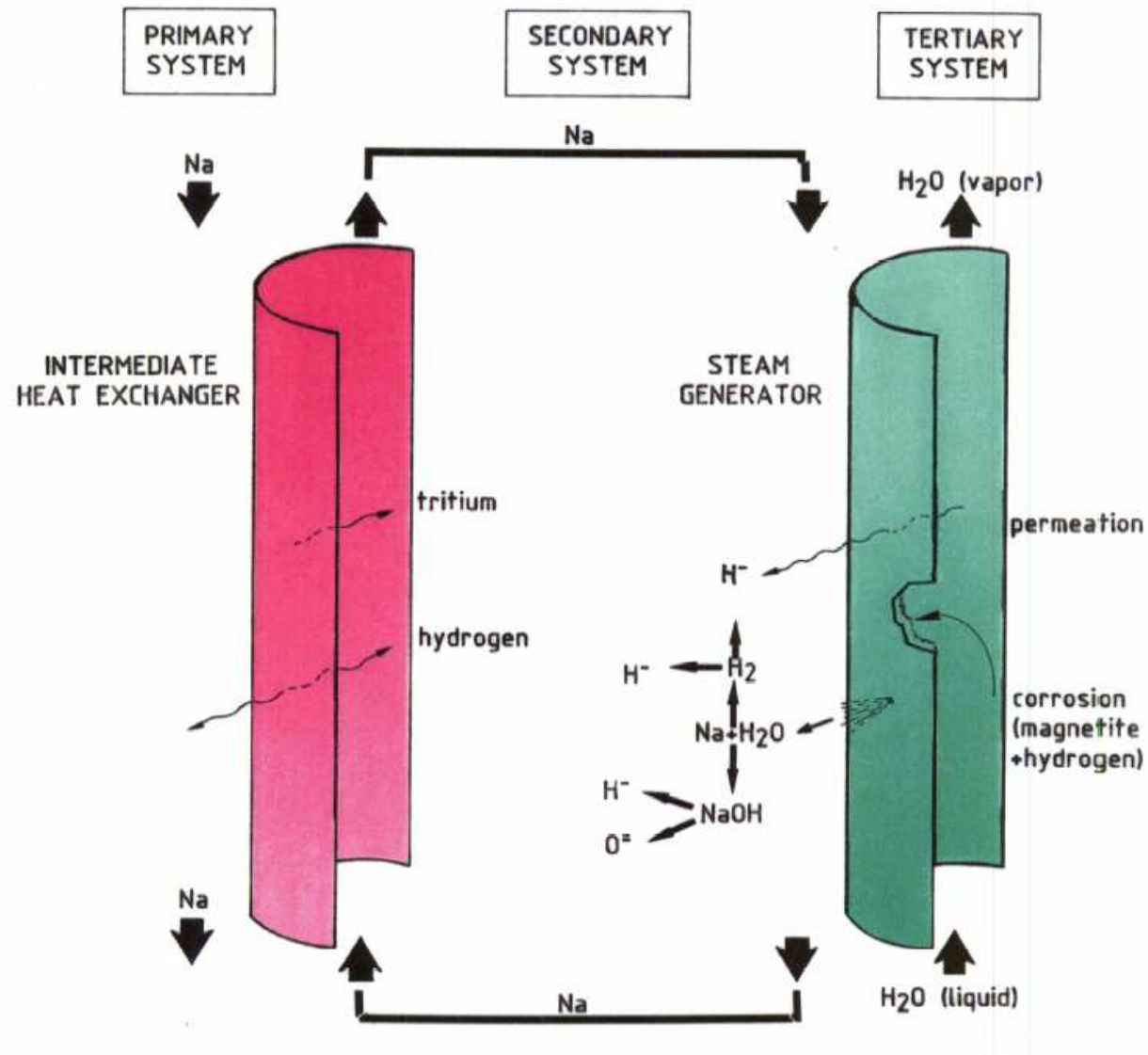
## [O] above 5ppm, Thorley's model used : (given for [O] ranging from 0 ppm to high concentrations but used in France above 5 ppm and T>817,13 K)

$$\text{If } V \leq 4 \text{ m/s, } R = (V/4)^{0.435} \cdot 10^{4.724} + 1.106 \cdot \log_{10}[O] - 3913/(T)$$

$$\text{If } V > 4 \text{ m/s, } R = 10^{4.724} + 1.106 \cdot \log_{10}[O] - 3913/(T)$$

These two semi-empirical models have been introduced in the ANNACONDA code (mass transfer assessment, contamination estimation, thanks to the description of the core (neutrons + thermal balance))

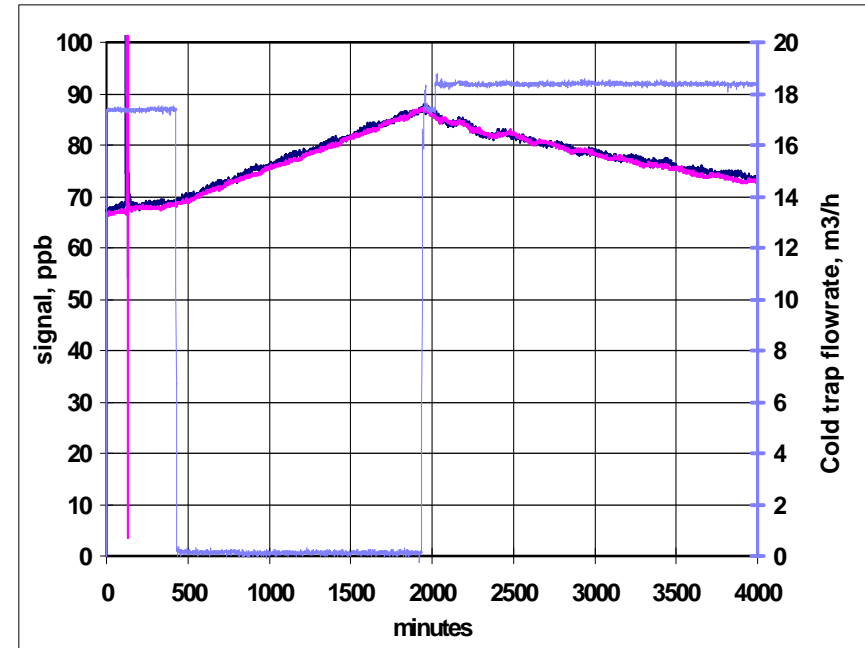
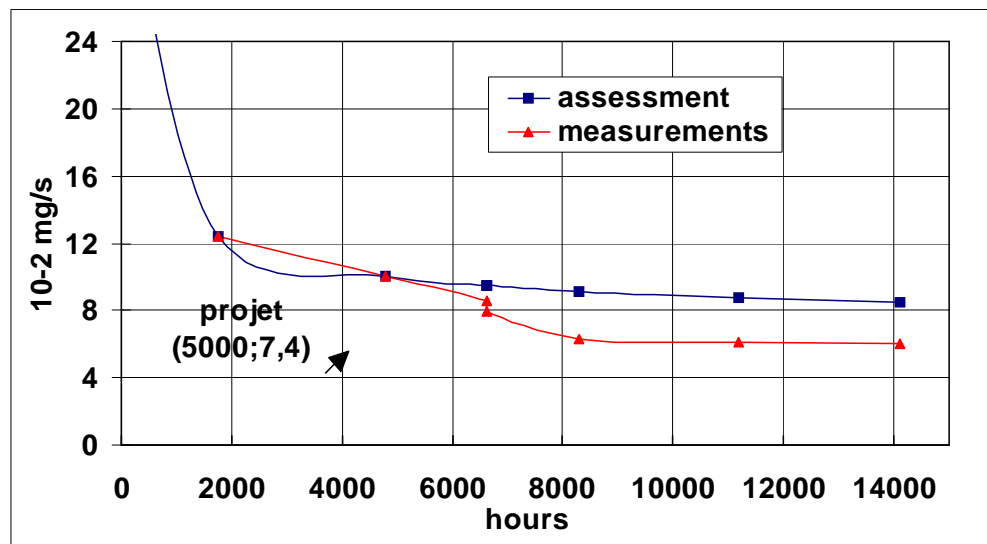
# Intermediate Na loop : contamination sources



# Hydrogen source from SGU aqueous corrosion + $\text{N}_2\text{H}_4$



SPX Hydrogen source = f (time)



SPX Hydrogen source measurement

# Tritium behaviour and mass balance

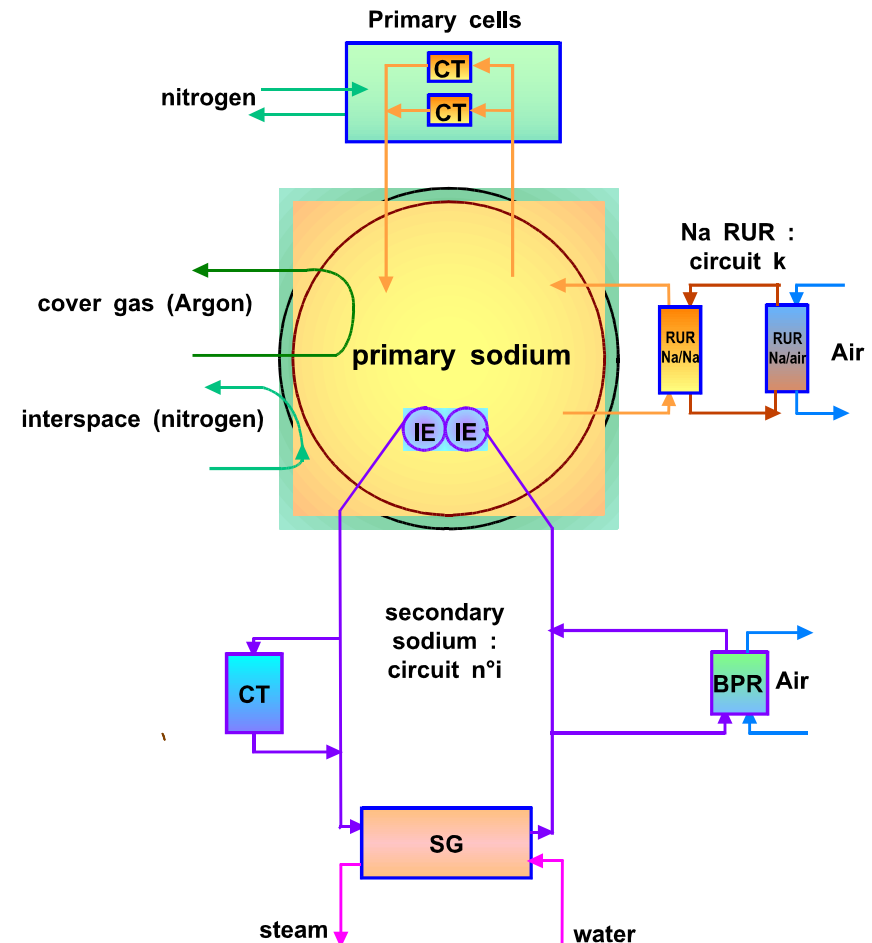


**Tritium issue - Distribution of the two hydrogen isotopes (tritium) in the different media of the reactor :**

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

→ *first objectives of the code :*

- Assess tritium releases to the environment (gaseous and aqueous)
  - at the operating stage, guarantee that they are below the authorised thresholds
  - at the design stage, request realistic release limits to the Safety Authorities
    - If this last case is not verified, alternative solutions can be proposed.
- Assess tritium activities in the different media
- tritium build-up in purification units



Abbreviation  
CT : cold trap  
SG : steam generator  
IE : intermediate heat exchanger  
Interspace : between the main vessel and the security vessel  
RUR : auxiliary cooling system for the primary sodium circuit  
BPR : auxiliary cooling system for a secondary sodium circuit

# Why is it necessary to purify Na?



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

- **Primary Na :**

- [O] is a key parameter of corrosion → contamination
  - Consequences on dosimetry → necessity to decontaminate (handling, repair, ISI,..)

- **Intermediate Na :**

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

- **For all the circuits :**

- Control the risks of plugging, seizing of the rotating parts, reduction of thermal transfer coefficient...
- to limit the plugging risk in narrow sections, tubing, openings, ...

→ Necessity to maintain  $[O] < [O]^*$  and  $[H] < [H]^*$  at the coldest point of the circuits, for all operating conditions ; value recommended :  $T_{sat} < T_{cp} - 30^\circ\text{C}$

# [O] specification

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- **In France**, [O] has to be maintained below 3 ppm
  - After SPX pollution a new constraint :
  - $3\text{ppm} < [\text{O}] < 5\text{ppm}$  during less than 1 month
  - ➔ Corrosion and contamination control
- 
- **UK view** : [O] can be in range up to 10 ppm.
  - Corrosion allowances have assumed 10 ppm, expected to improve friction/wear at oxygen levels in range of 5-8 ppm.

# Strategy for Na quality control

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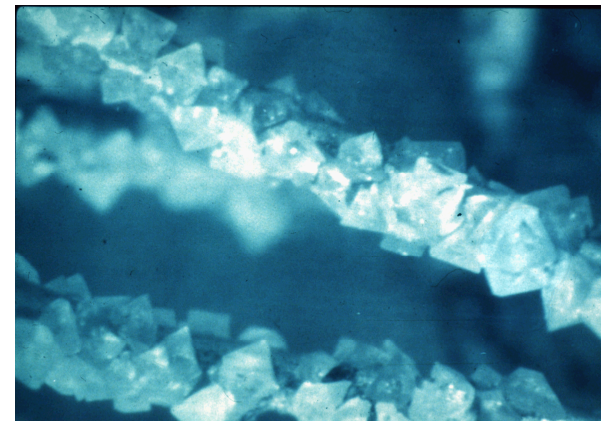
- Specific methods to obtain nuclear grade sodium
- Initial cleaning of loop, components and vessels
- Filtering
- **Cold trapping**
- Hot trapping
- And of course limiting ingress of pollution by appropriate operating rules

# Crystallization methods

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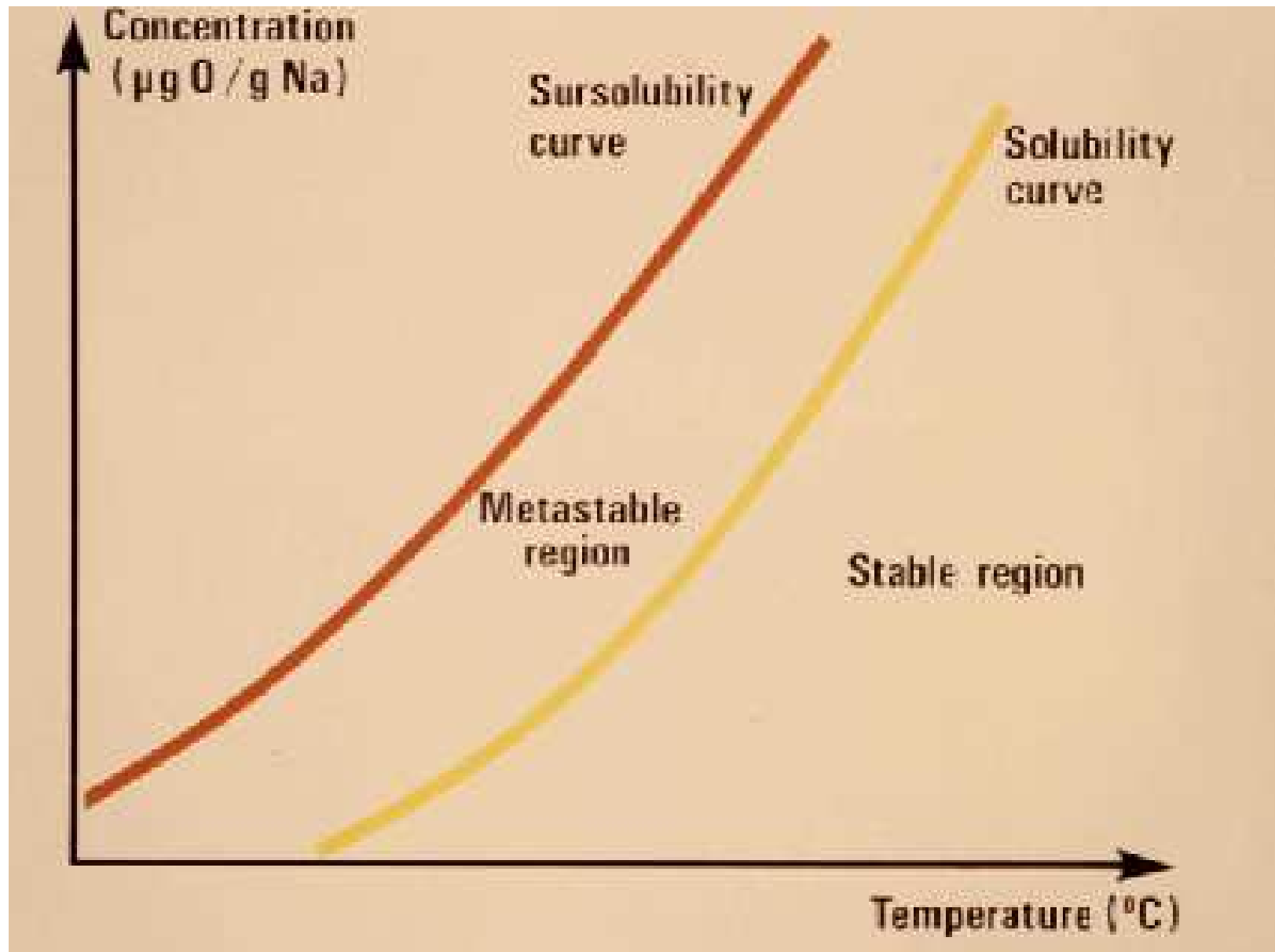


- Liquid evaporation (like salt)
- Reduction of the solubility by adding some additive impurity
- Cooling the liquid below saturation temperature
  - This last option is the most attractive :
    - Convenient solubility laws for O and H (reach almost 0 near the Na melting point)
    - Easy implementation : cooling
    - and solid retention



# Concentration-temperature diagram

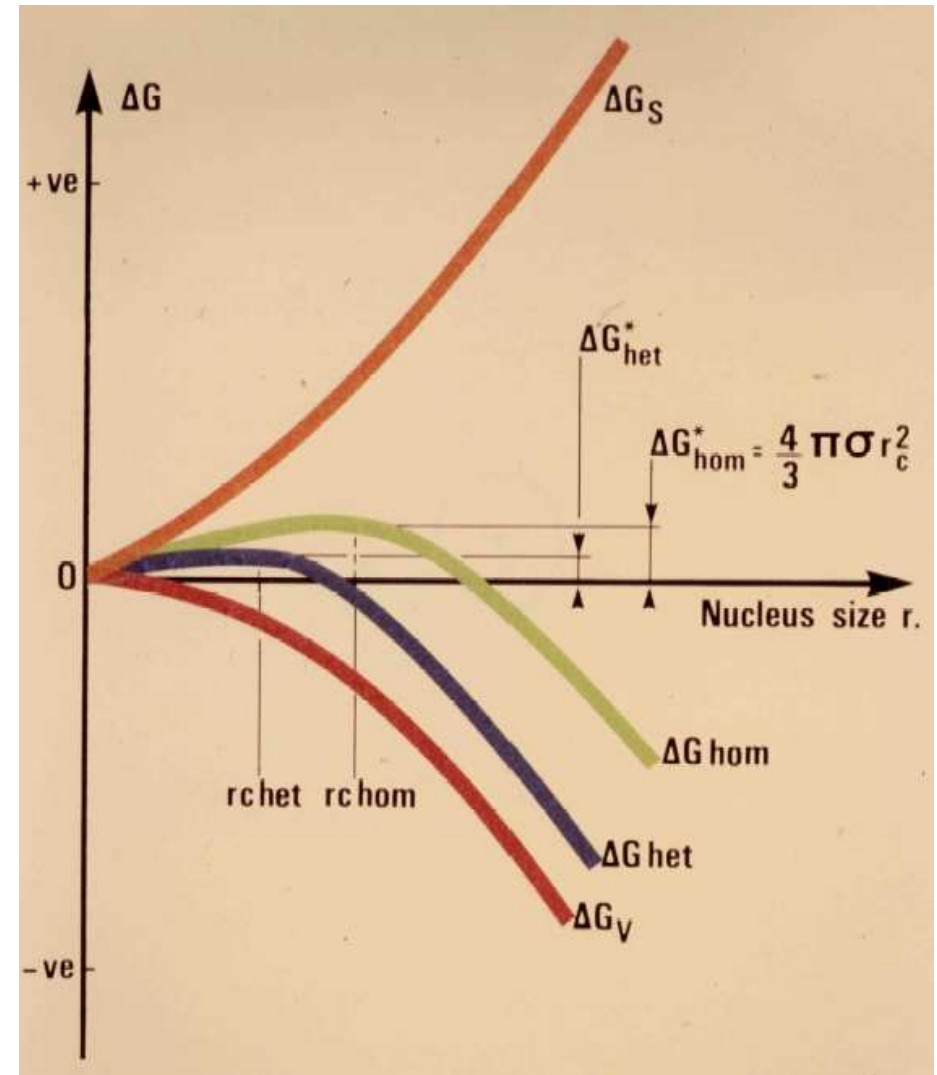
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# Nucleation phenomena



- 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 1/2



→ Several theories to explain growth

- **Theory of Burton Cabrera and Franck (BCF)**

- Model of atom migration

- $x_s = (D_s \cdot \tau)^{0.5}$
- $x_s$  = free distance performed by molecule/atom
- $D_s$  = diffusion constant at the crystal surface
- $\tau$  : duration of adsorption phenomenon on the crystal surface
- $x_s = f(S_0 = C/C^*)$ ,  $S_0$  is the supersaturation ratio
- If  $x_0$  is the average distance between adsorption sites on the crystal surface,  $S_1$  is the critical supersaturation for which  $x_s = x_0$

- Crystal growth kinetics :  $R_g = K \cdot S_0^2 / S_1 + \text{th} S_1 / S_0$

- For low supersaturations  $S_0 \ll S_1$  thus :  $R_g = K / S_1 \cdot S_0^2$
- For high supersaturations  $S_0 \gg S_1$  thus :  $R_g = K S_0$  ( $x_s < x_0$  and diffusion is the limiting step)

# Growth phenomena 2/2

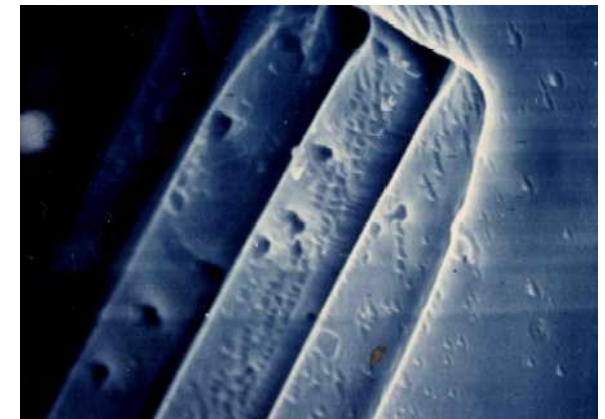
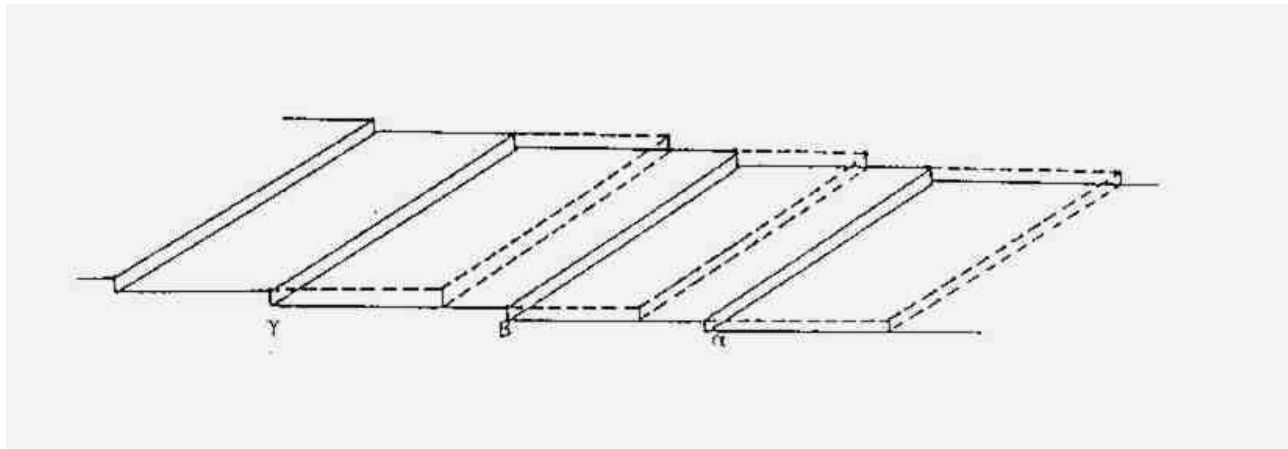


- Theory of diffusion through a boundary layer
  - Growth can be considered as two consecutive phenomena :
    - A diffusion step through a boundary layer
      - $Dm/dt = k_D.A.(C-C_i)$
    - An integration step at the crystal solution interface
      - $Dm/dt = k_R.A.(C_i-C^*)^{n_R}$
    - Due to the fact that it is difficult to know  $C_i$ , we use an overall equation :
      - $Dm/dt = k_G.A.(C-C^*)^{n_G}$
  - Two situations
    - If growth is limited by diffusion step, then  $k_G = k_D$  and  $n_G = 1$
    - If growth is limited by integration step, then  $k_G = k_R$  and  $n_G = 2$ 
      - These values of  $n_G$  have been established by Burton Cabrera and Franck

# Growth phenomena



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



Na<sub>2</sub>O

# Growth phenomena



Two growth phenomena :

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



REGULAR GROWTH (X500)



DENDRITIC GROWTH (X20)

# Kinetics of NaH and Na<sub>2</sub>O

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- **Nucleation**

- Na<sub>2</sub>O : EN = - 60 kJ/mol   nN = 5
- NaH : EN = - 450 kJ/mol   nN = 10

- **Growth**

- Na<sub>2</sub>O : EG = - 45 kJ/mol   nG = 1
- NaH : EG = - 43.6 kJ/mol   nG = 2

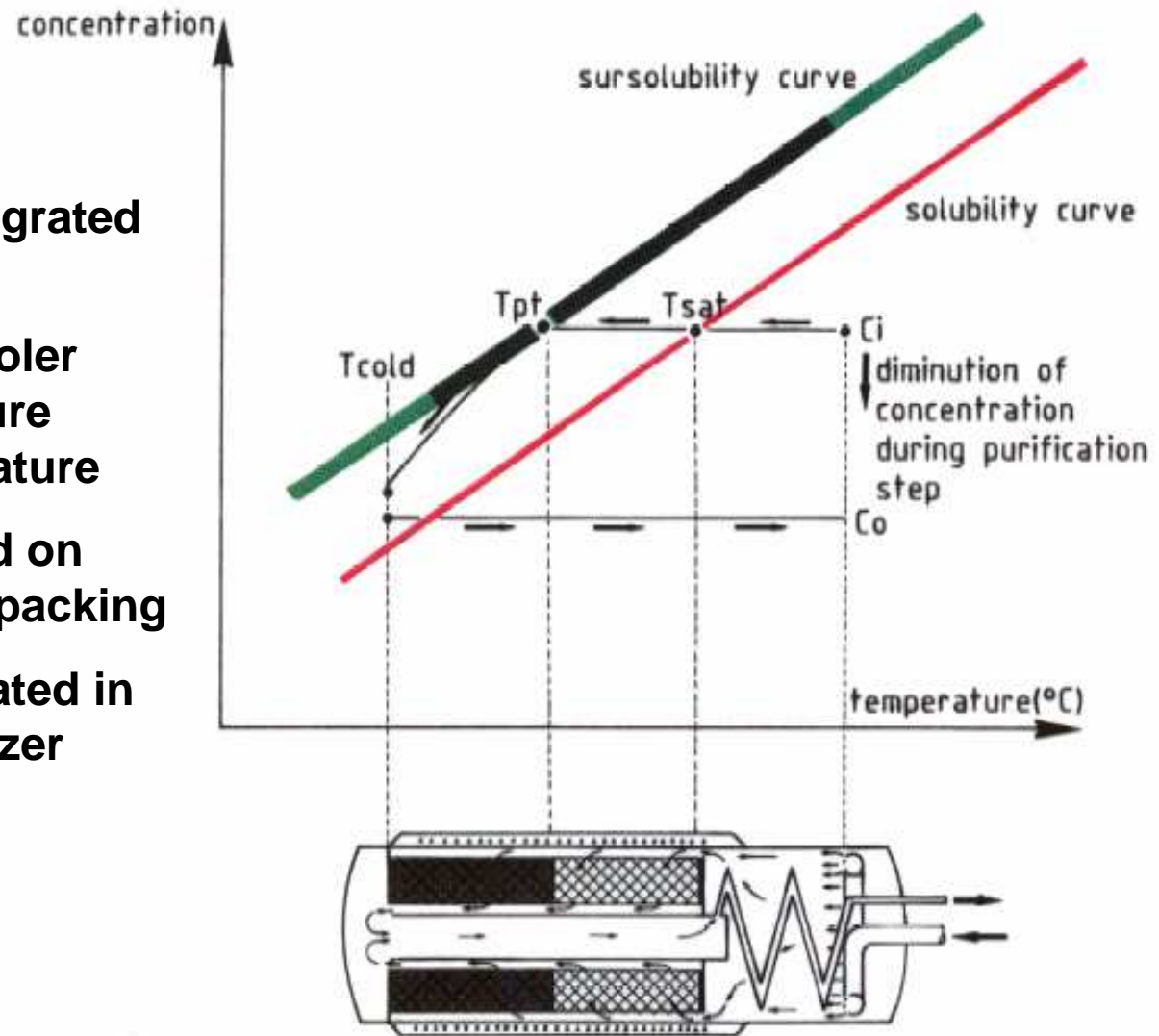
- **Thus, different cristallization mechanism**

- Possibility to obtain crystallization of NaH on cold walls (large influence of supersaturation and nucleation)
- Necessity to provide steel packing for Na<sub>2</sub>O

# Cold trap : operational diagram



- First, Na is cooled in an integrated heat exchanger-economizer
- Then Na flows through a cooler where it reaches a temperature below the saturation temperature
- Crystals formed are retained on cold walls or stainless steel packing
- The outlet flow is then reheated in the heat exchanger-economizer



# Performance criteria for cold traps

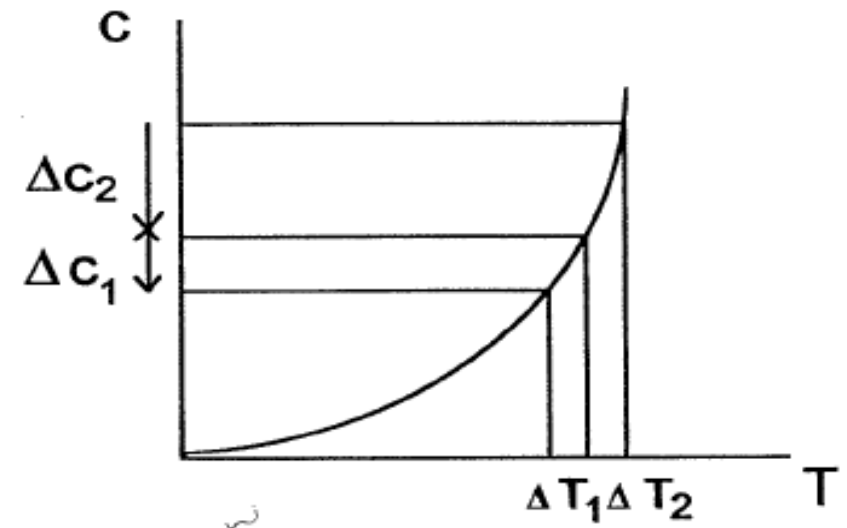


- **Instantaneous efficiency:**  $E = (C_e - C_s) / (C_e - C^*)$   $0 < E < 1$ 
  - $C_e$ : concentration at the cold trap inlet
  - $C_s$ : concentration at the cold trap outlet
  - $C^*$ : concentration at equilibrium (solubility)
- **Purification rate :**  $V_p = E \cdot (C_e - C^*) \cdot D_{na}$
- **Capacity :**  $Cap = \sum \tau_r \cdot E_d$  (in unit of volume)
  - where  $\tau_r$  = filling rate
  - and  $E_d$  = deposited element concerned (area, volume)
- **Compactness:**  $Comp = V_1 / V_2$ 
  - $V_1$  = Maximum volume of the impurities retained in the trap
  - $V_2$  = Internal volume of the trap in which the deposit zones are located

# Purification rate



- $C$  = concentration
- $T$  = temperature
- $v_{\text{purif}}$  =  $f(D \times E \times \Delta C)$
- $D$  = Na flow rate
- $E$  = Cold trap efficiency
- $\Delta C$  =  $C(T_{\text{sat}}) - C(T_{\text{PF}})$



→ purification rate higher in the area of high concentrations

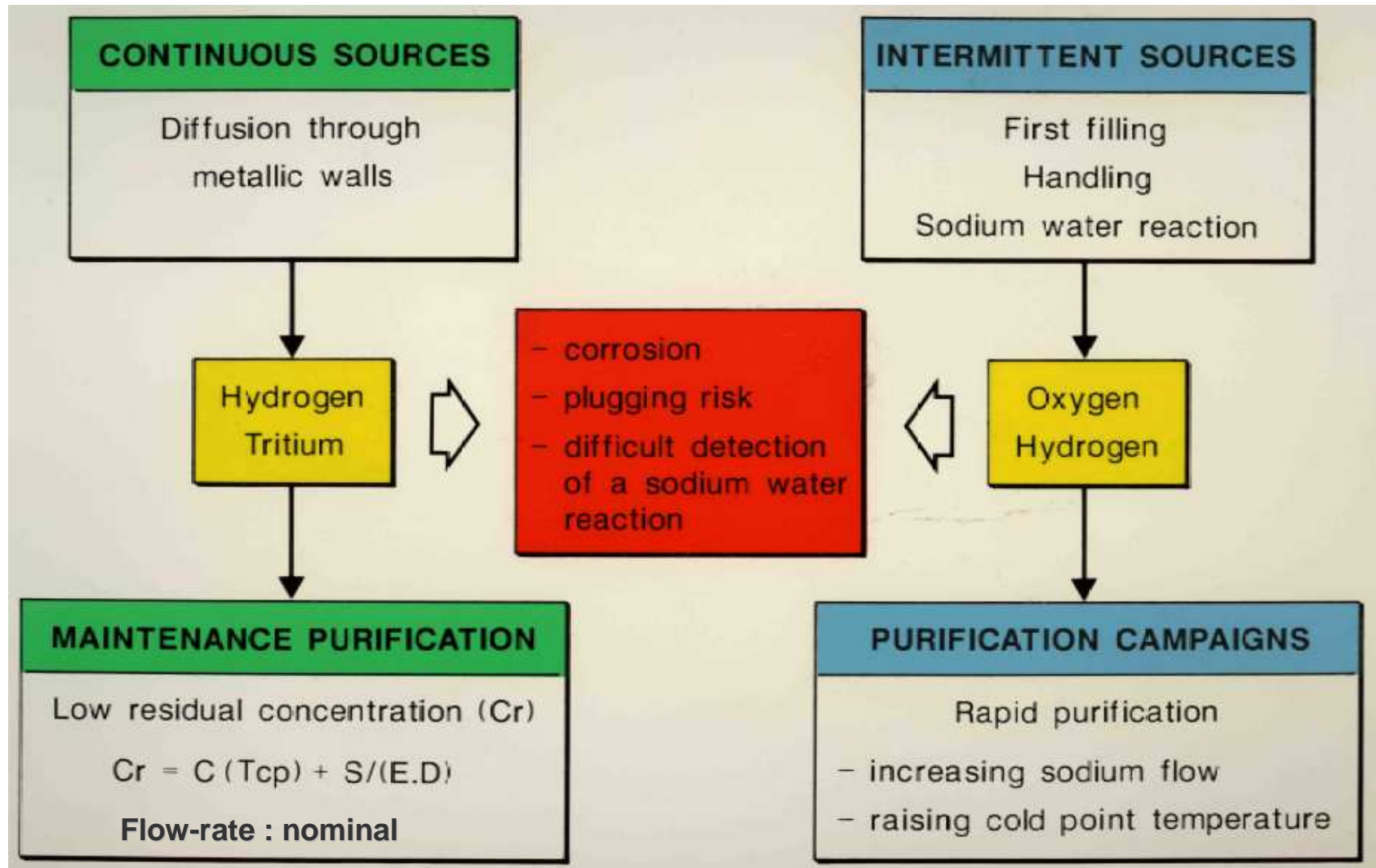
# Design requirements

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- **Vp** : highest value, in case of large pollutions. There is generally no specifications on efficiency, nevertheless a high value of efficiency allows generally to obtain a high purification rate
- **Comp** : the highest value is the best
- **Cap** : depends on the policy chosen for the cold trap
  - If the source of impurities is low, possibility to size the trap for the whole service life duration
  - If the source of impurities is high, possibility to size a large trap for a long service life or a smaller cold trap which can be replaced or regenerated and hence reused

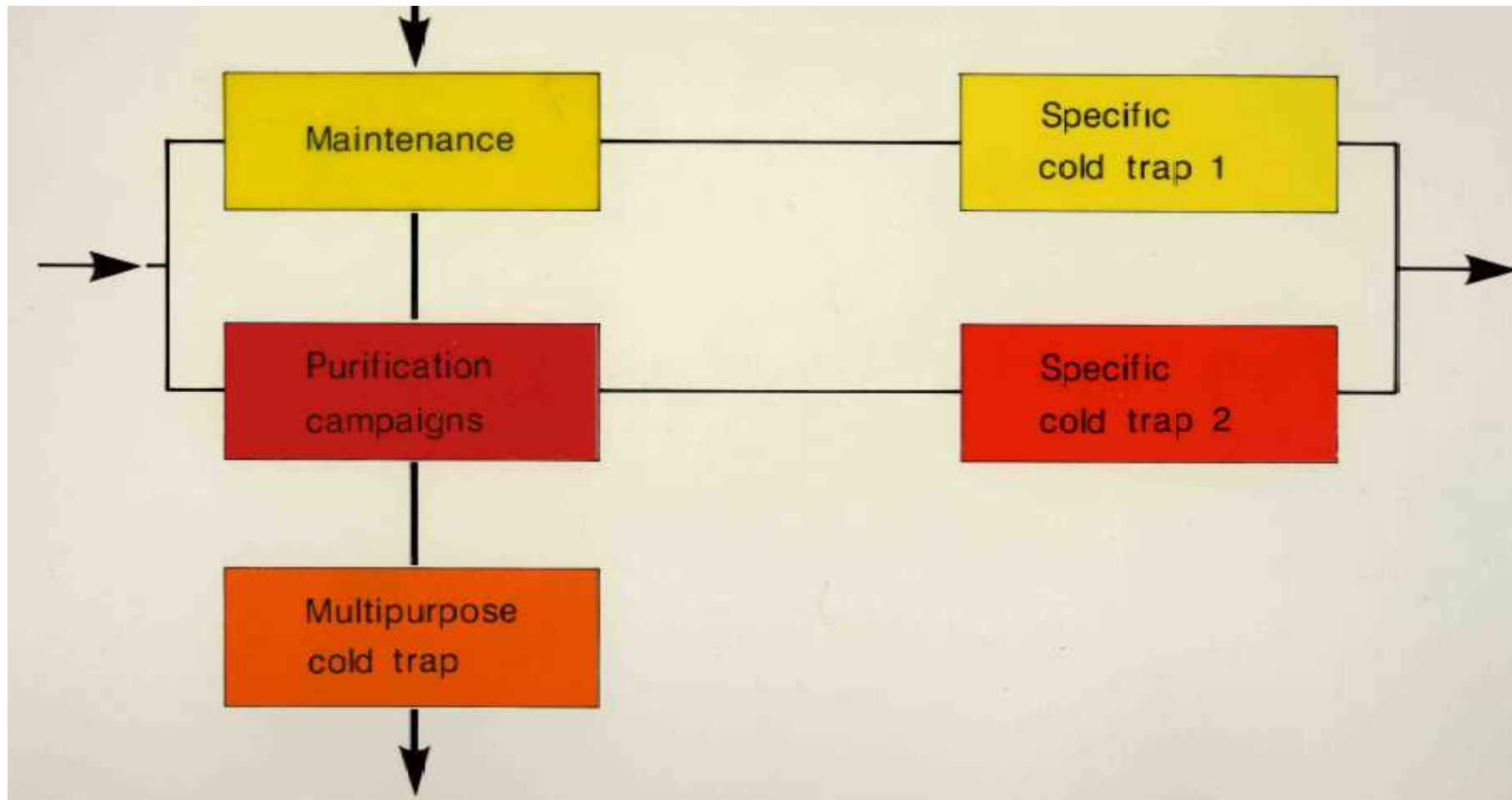
# Cold Trap Operational rules



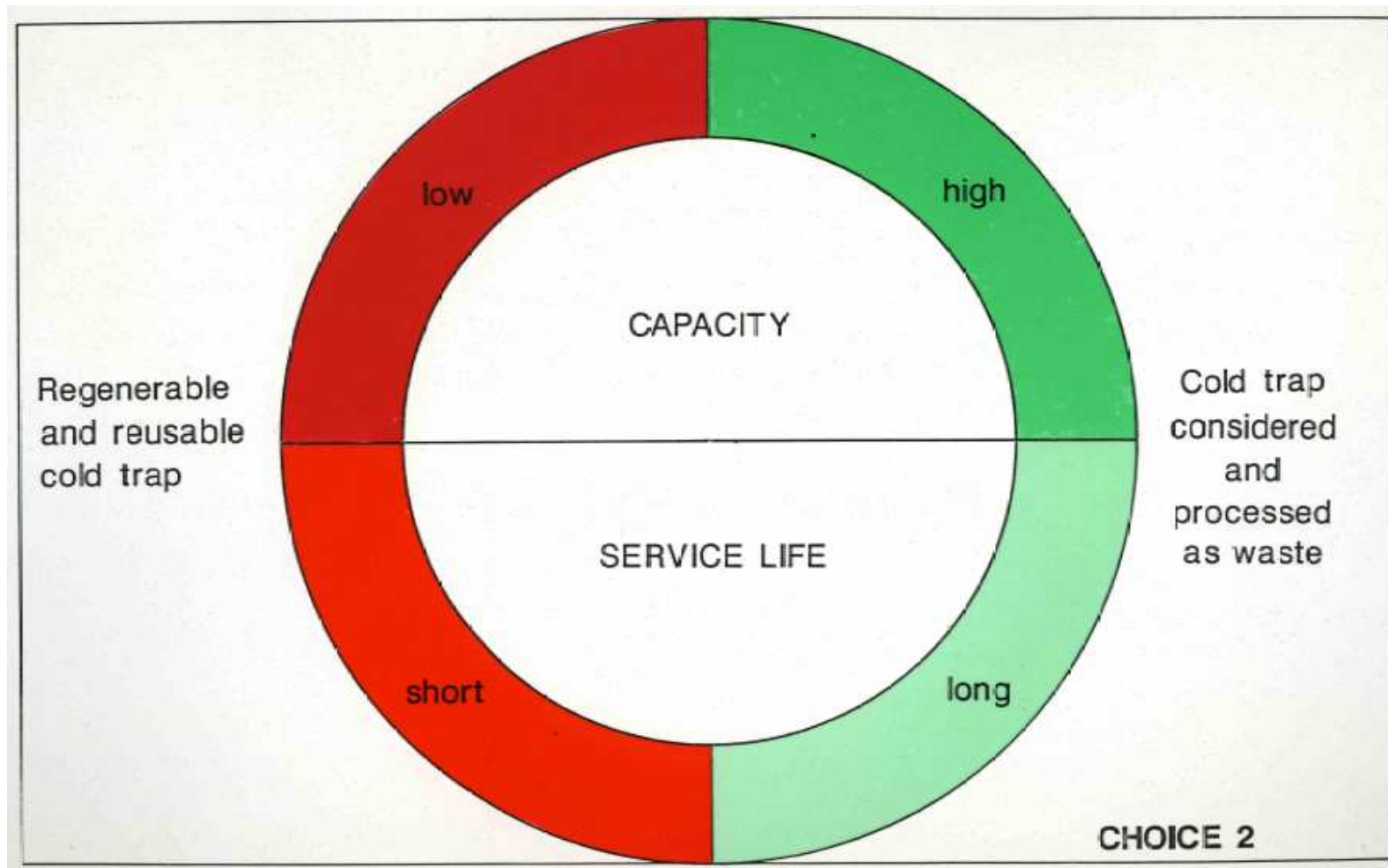
$$T_{cp} = T_{sat} - \Delta T$$

## Basic choice N°1 for purification :

cea



## Basic choice N°2 for purification :



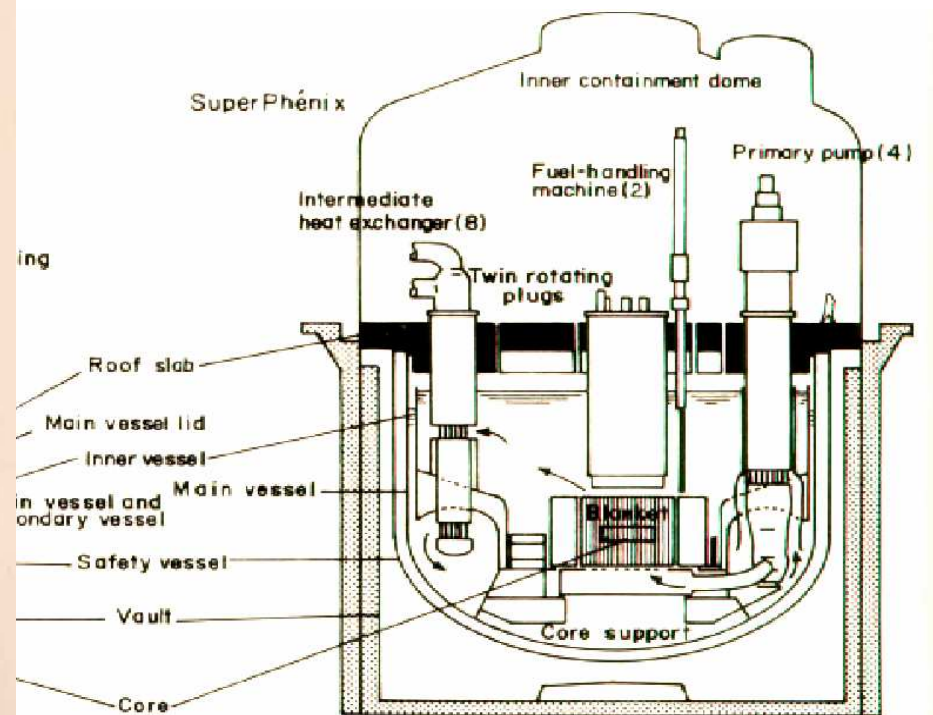
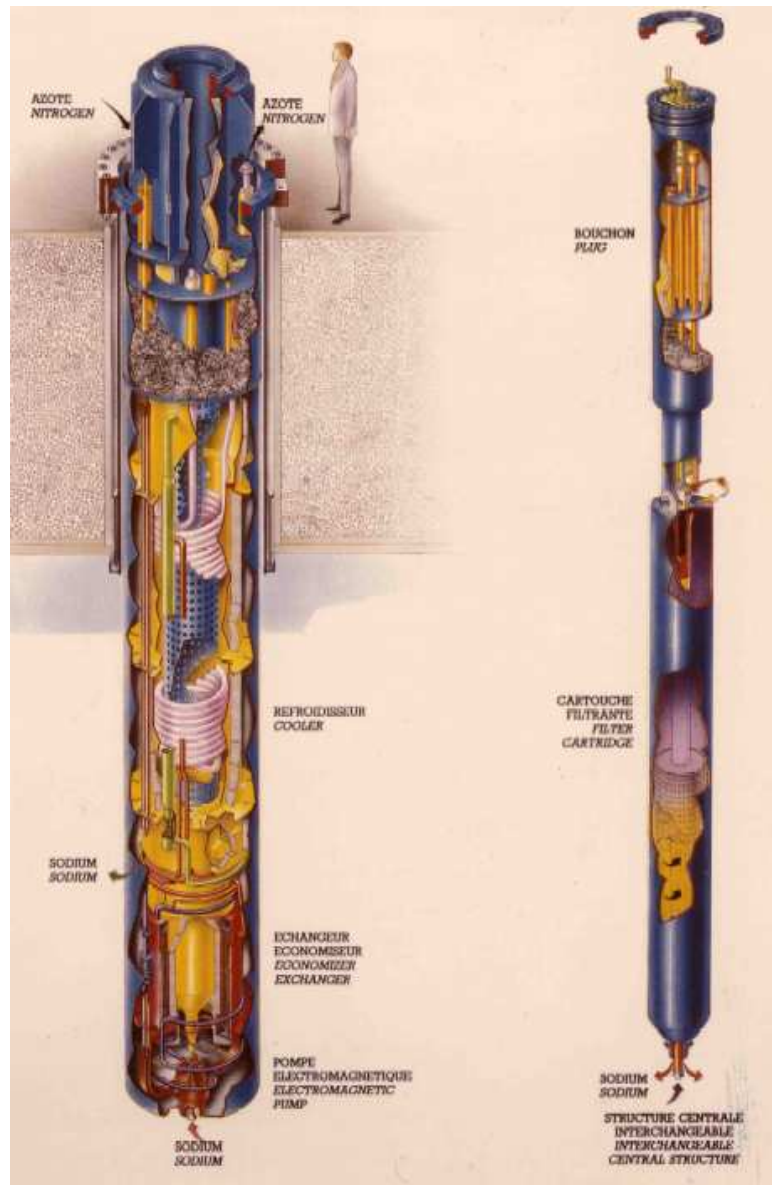
## Some design options

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- **Sodium distribution in the cold trap** : ring type header
- **Cooling fluid** : air, oil, NaK oil in static NaK, ...
- **Internal exchanger-economizer** : to avoid plugging of the inlet pipe (Rex : SNR 300)
- **Cooler** : one cooler or modular coolers (to adapt thermal gradient with source of impurities (i.e. : hydrogen))
- **Support for impurities** : knitted mesh, pall rings, cooled wall,...
- **Location of support** : location and surface per volume depends of the design requirements.

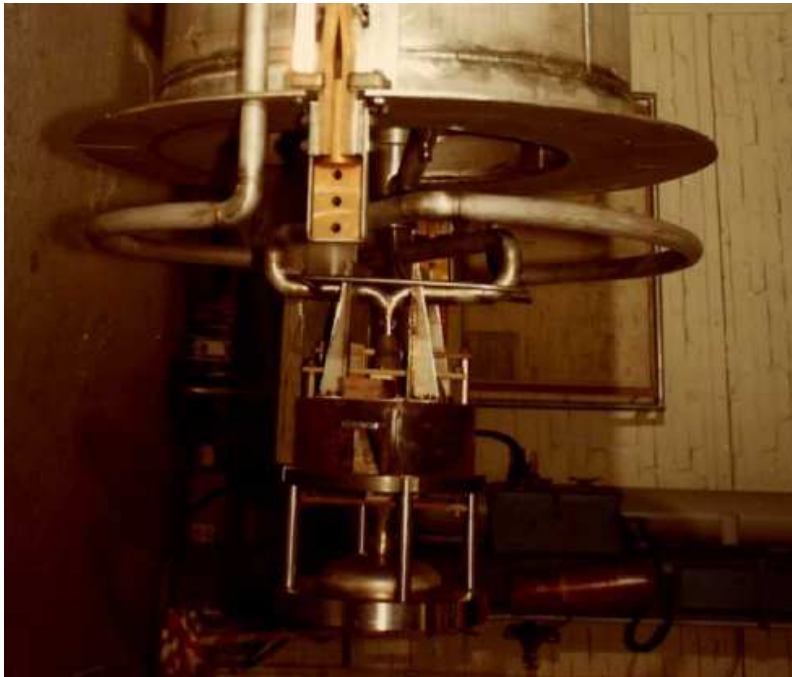
# Primary Integrated Purification system



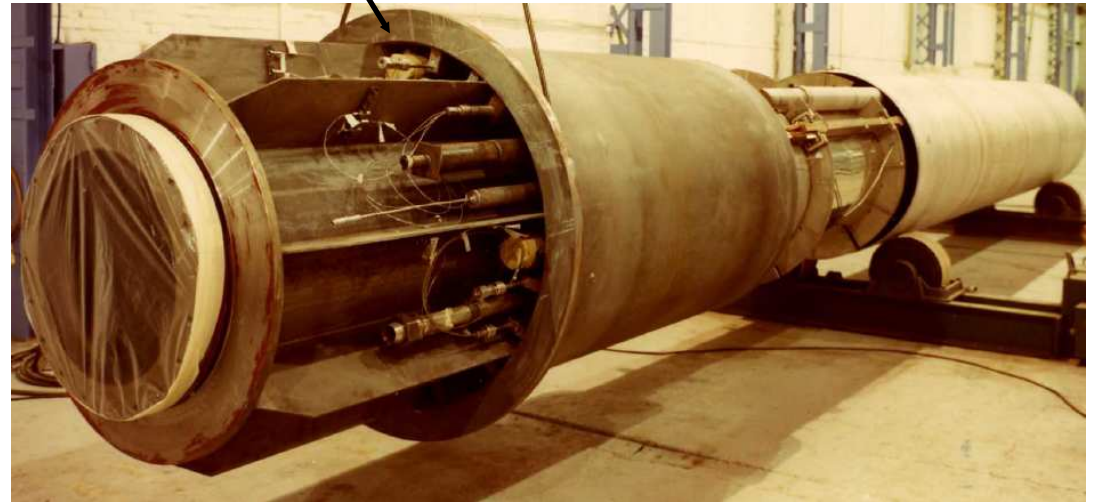
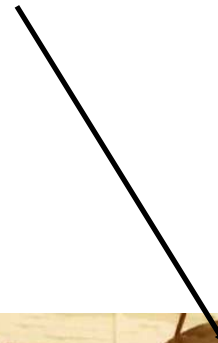
# Integrated purification unit



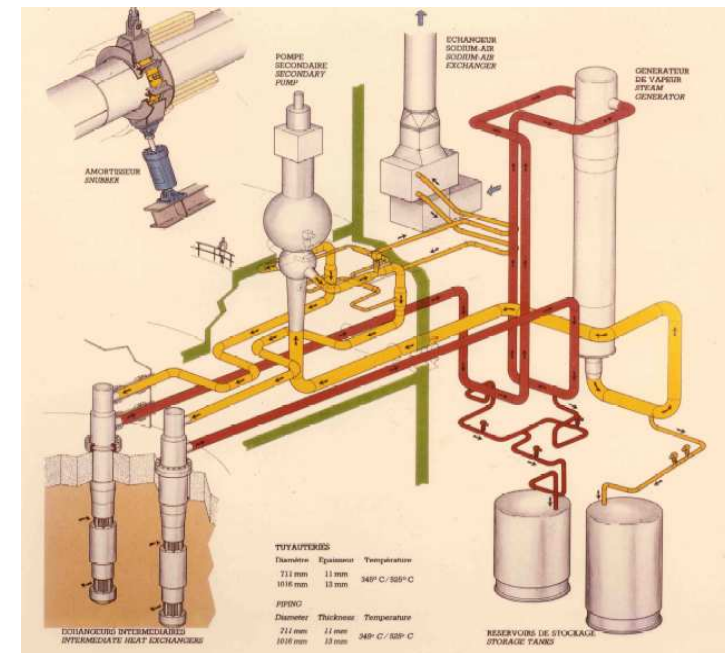
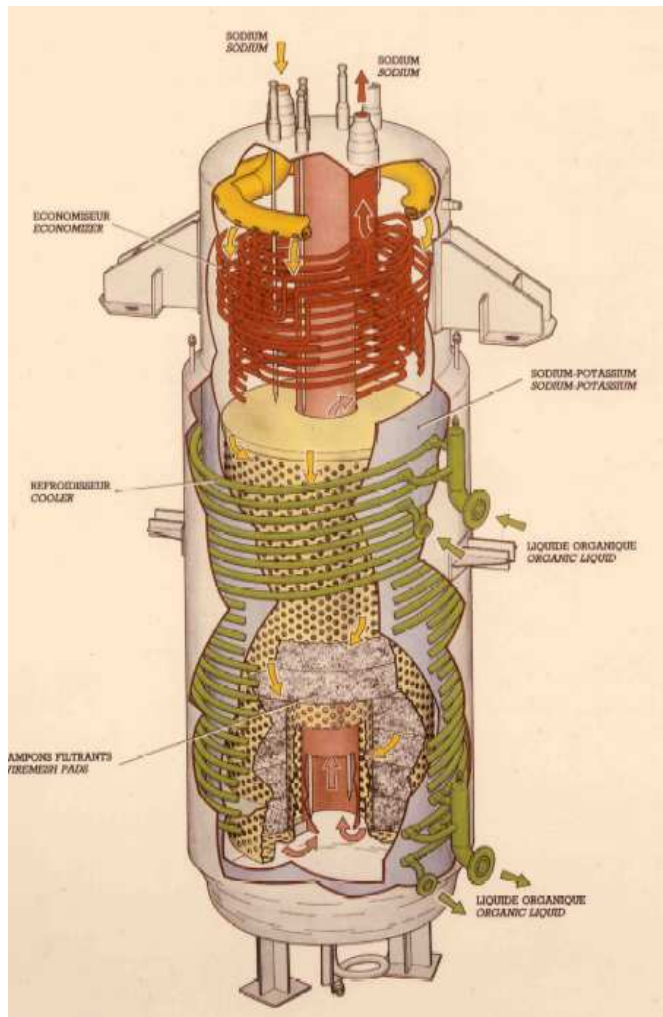
Lower part



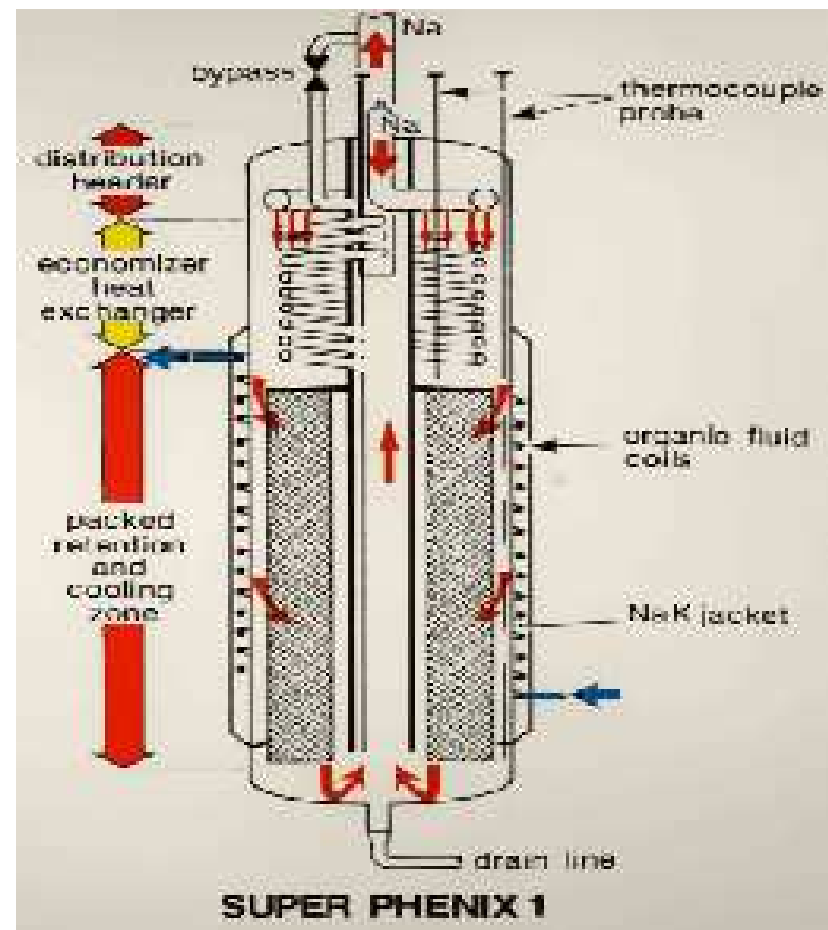
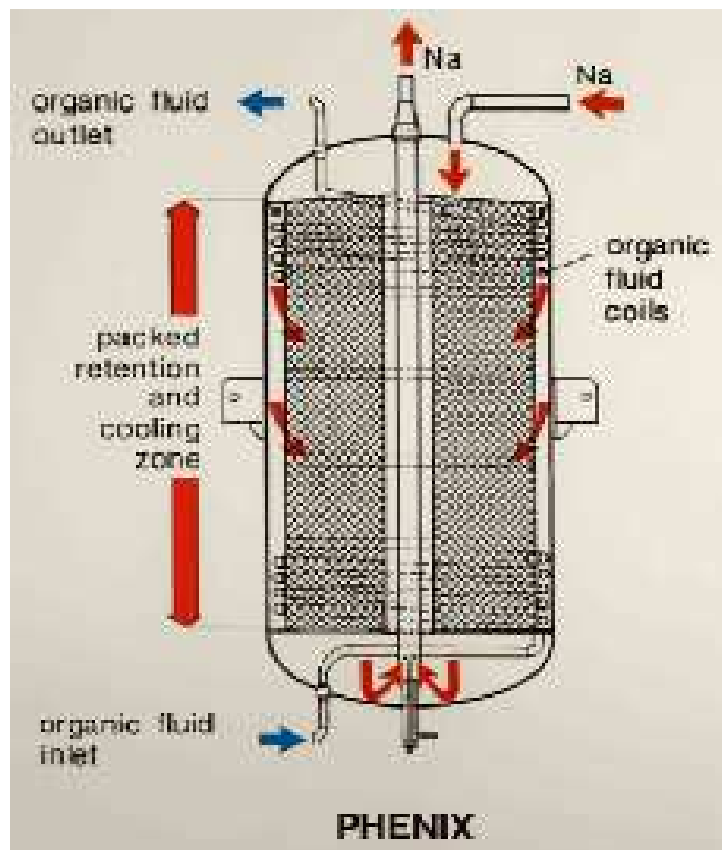
Upper part

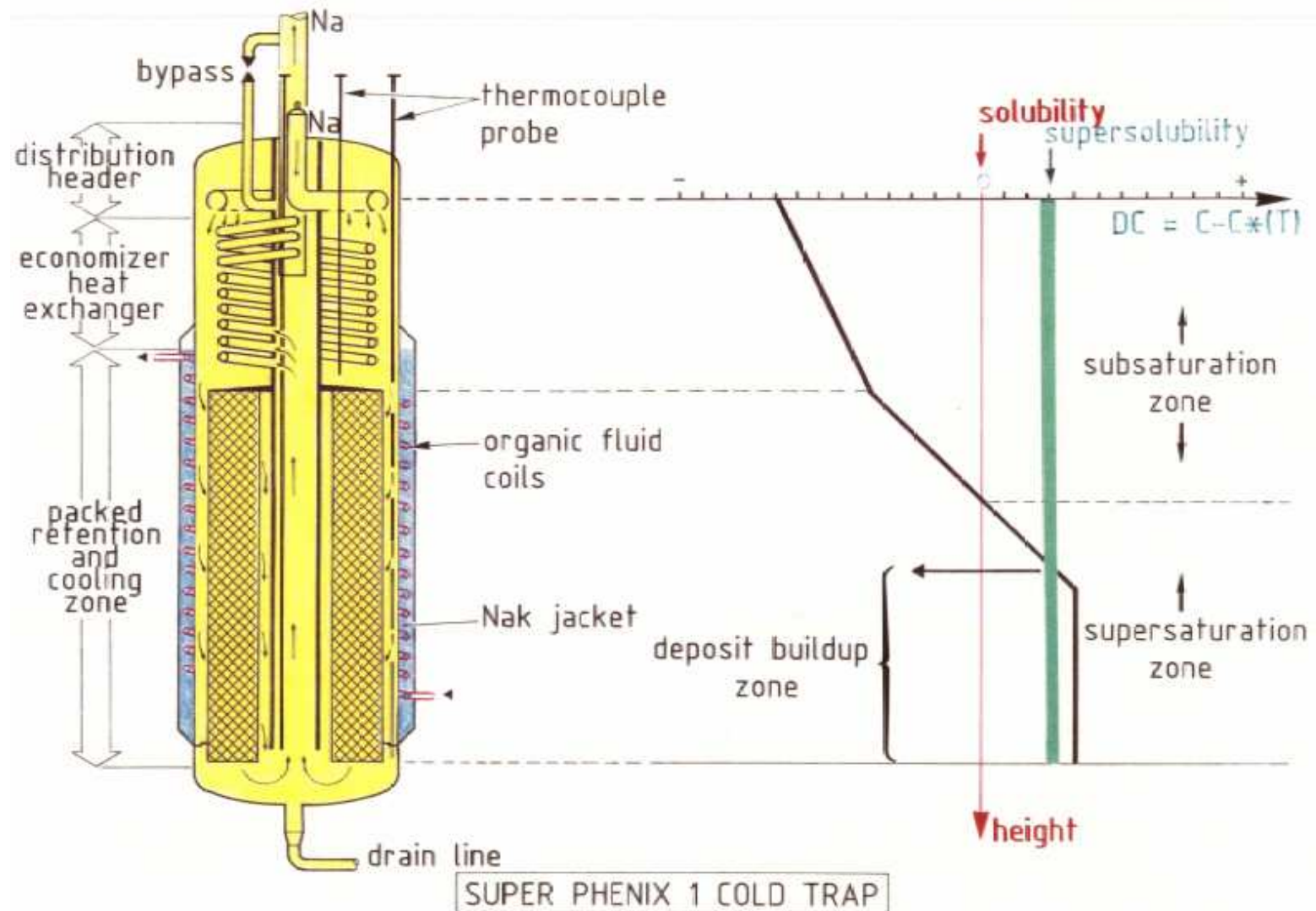


# Intermediate purification system of SPX



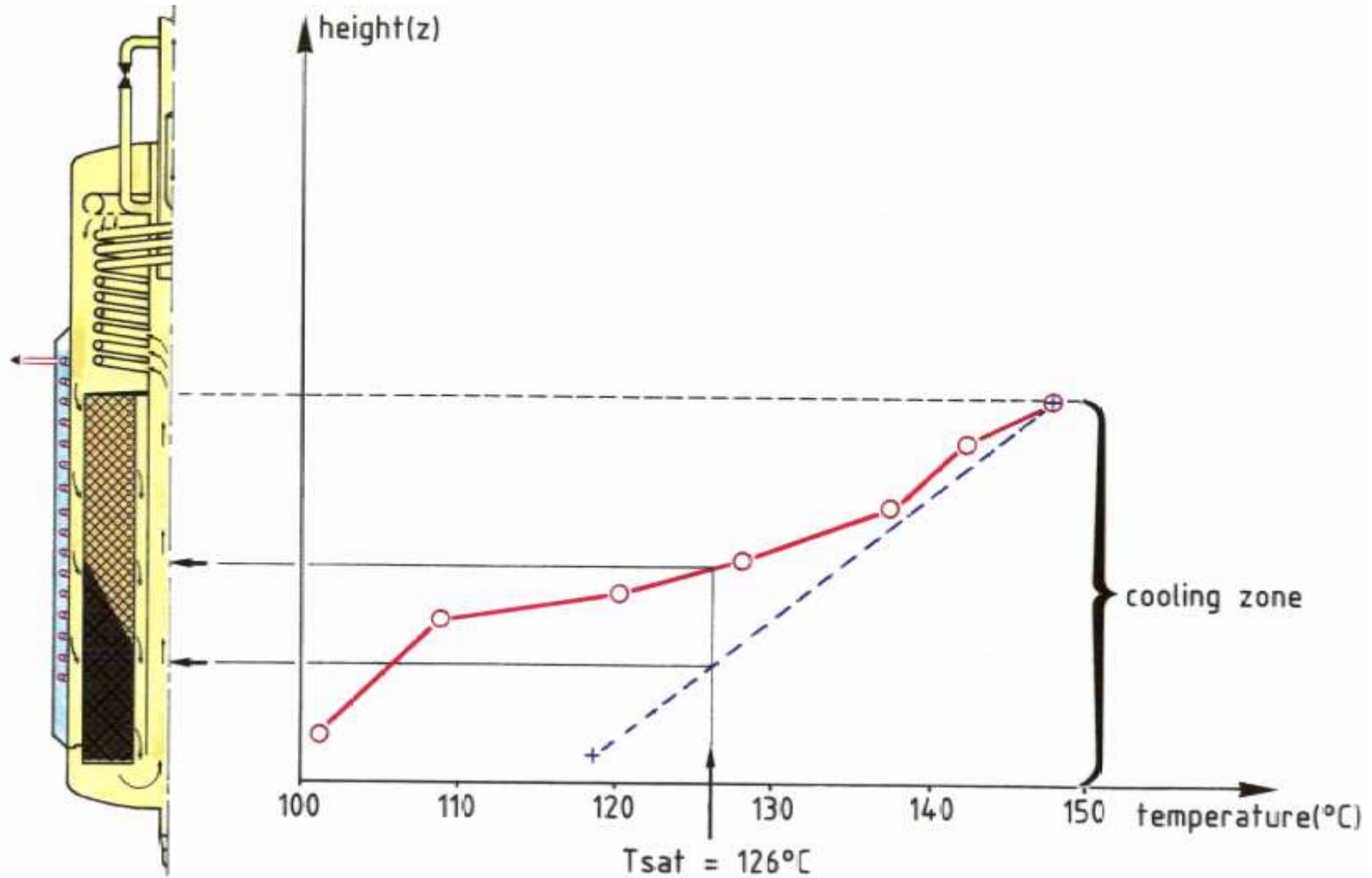
## Intermediate purification system of Phenix and SPX



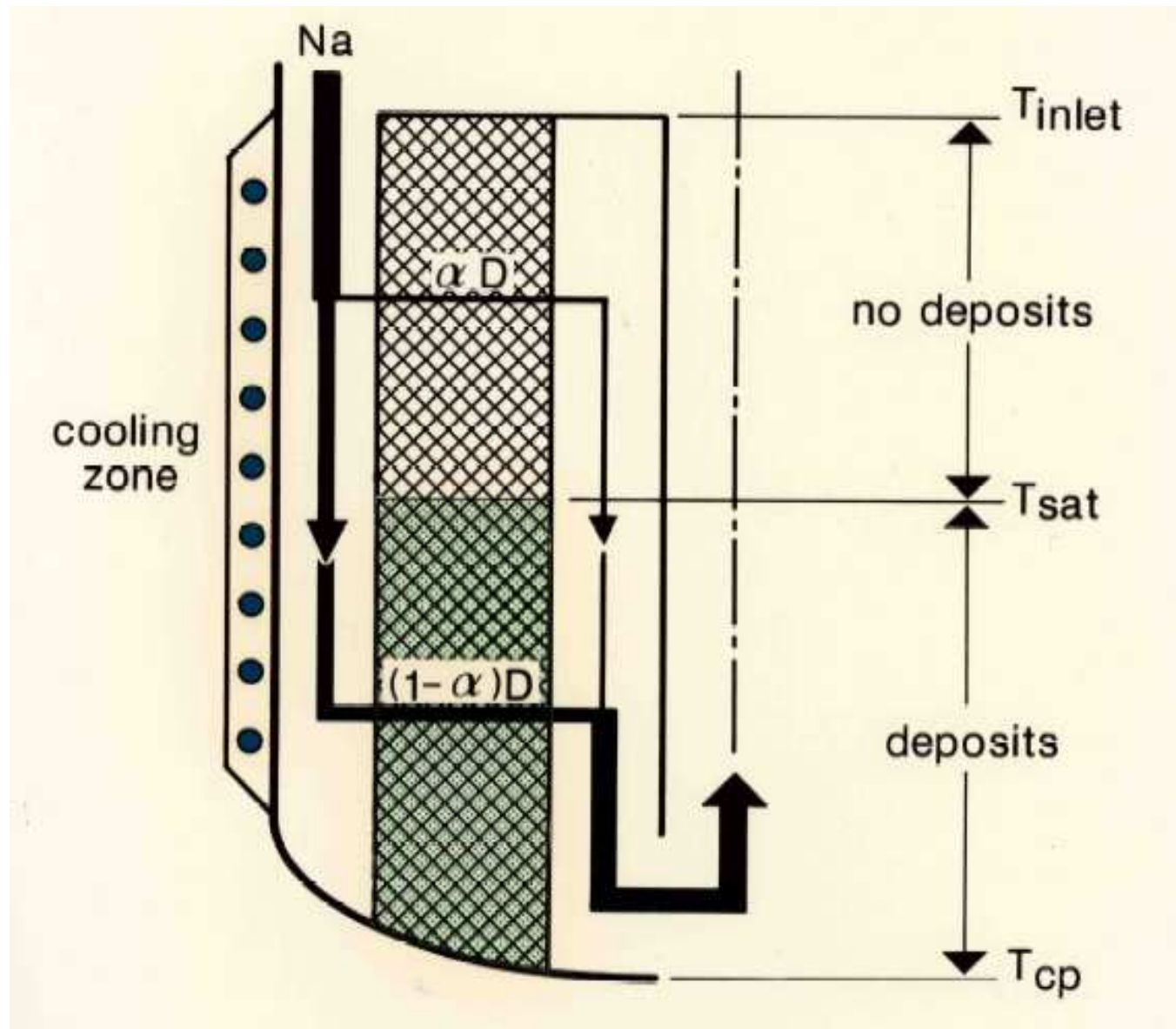


## SPX Intermediate cold trap: filling area

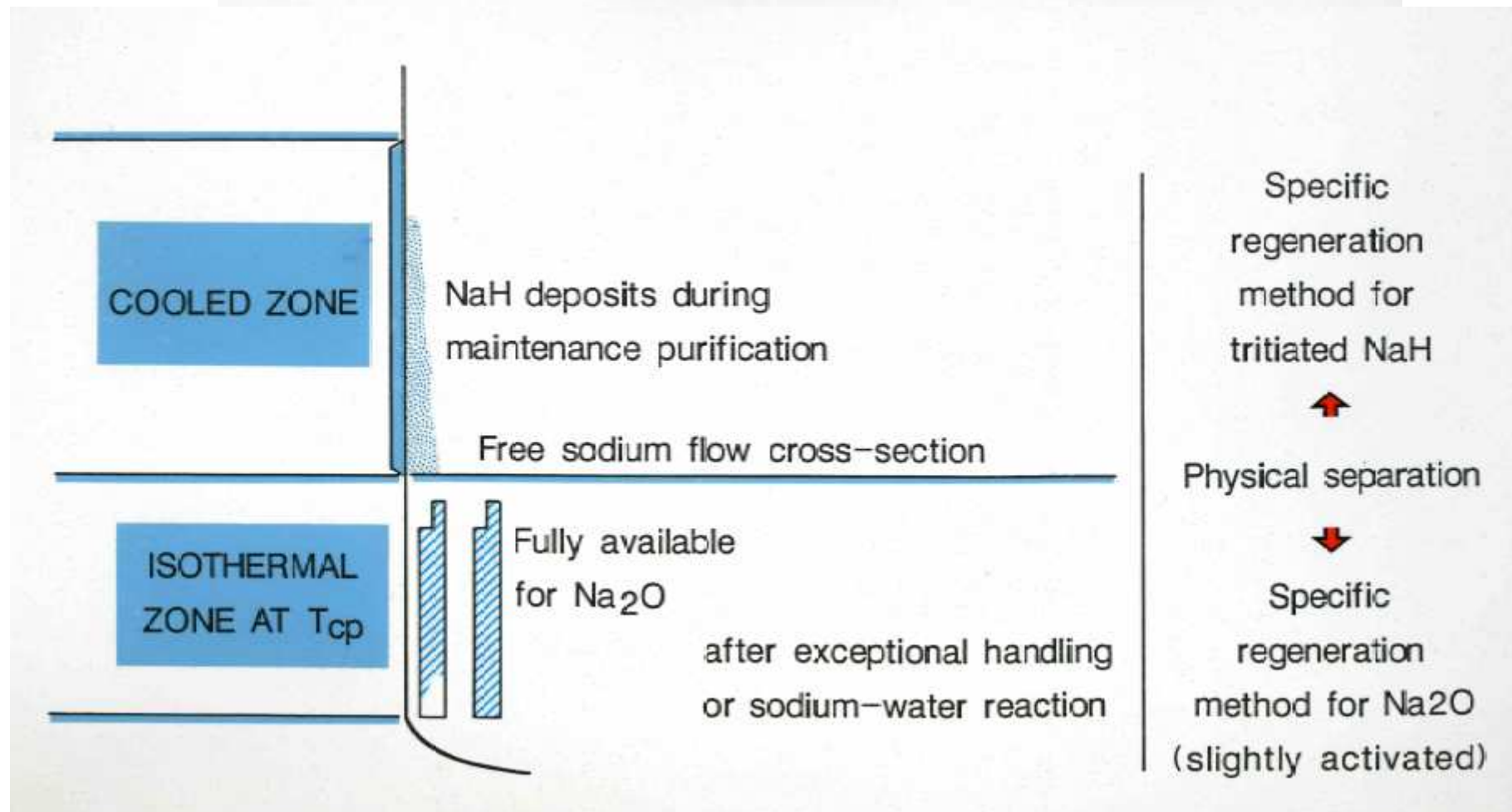
cea



# Efficiency of a « one-zone » cold trap



## ADVANTAGES IN HAVING TWO ZONES



# Packing distribution

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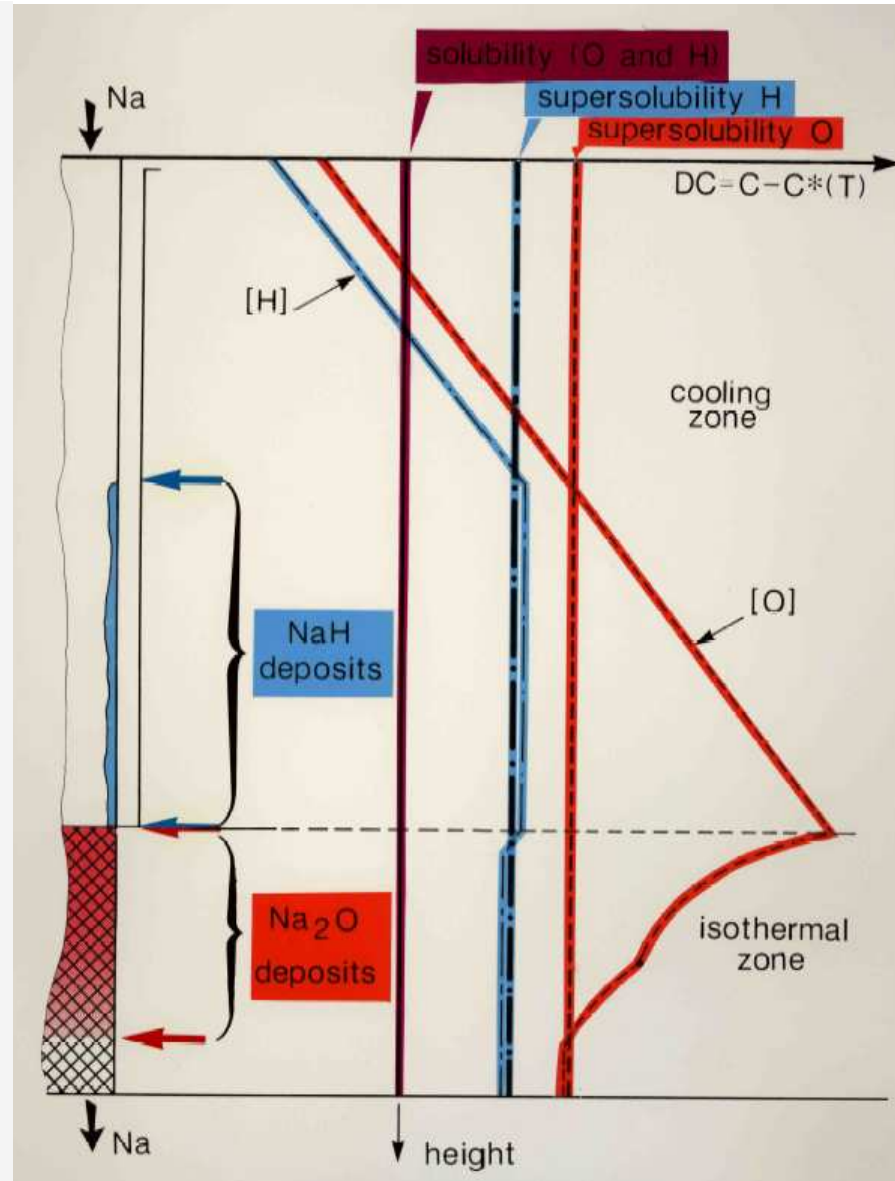
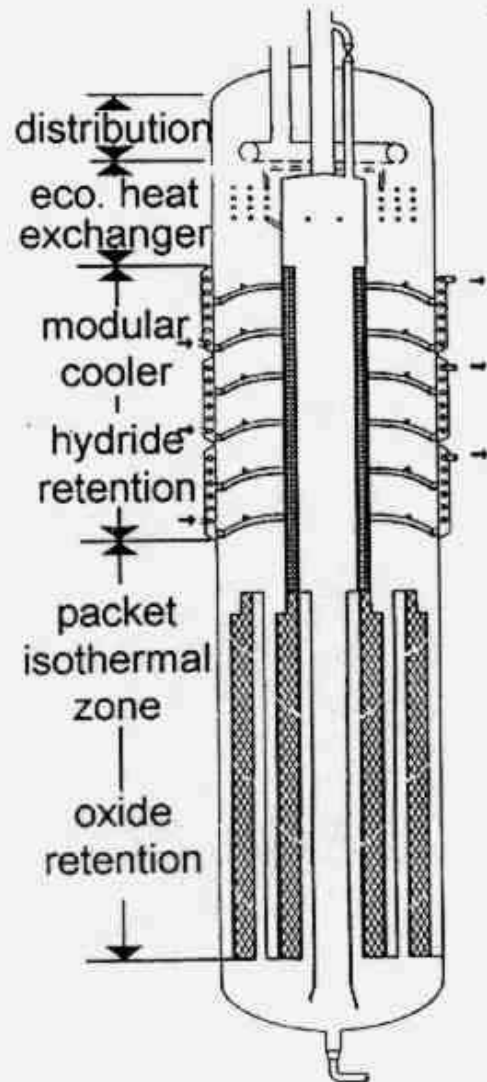
- **Trap with only one zone** (cooling and mesh at the same level) to trap the two impurities together
  - In this case, the capacity is proportional to the mesh volume and depends on the operating conditions
- **Trap with two different zones**
  - One meshless cooled zone, able to trap NaH
    - Capacity is function of cold wall surface and operating conditions
    - Efficiency of one versus NaH (if modular cooler)
  - One meshed isothermal zone (at  $T_{cp}$ ), located downstream the above mentioned zone, able to trap  $Na_2O$  and residual NaH
    - In this case Capacity =  $K.A$  with  $A$  = inlet surface of the packing (it is better to implement several concentric meshes instead of a single large volume mesh)
    - Efficiency of one versus  $Na_2O$

# PSICHOS concept

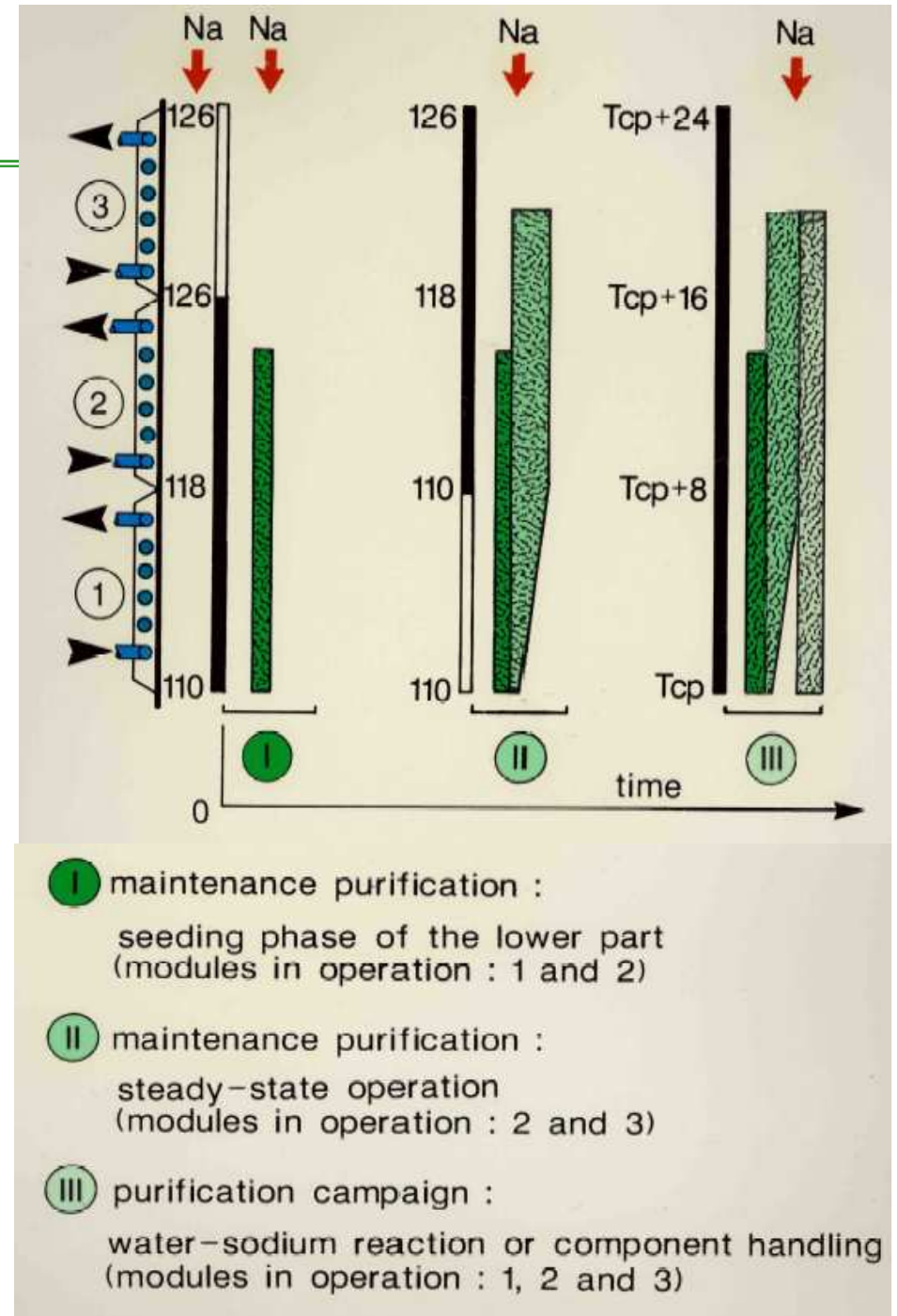
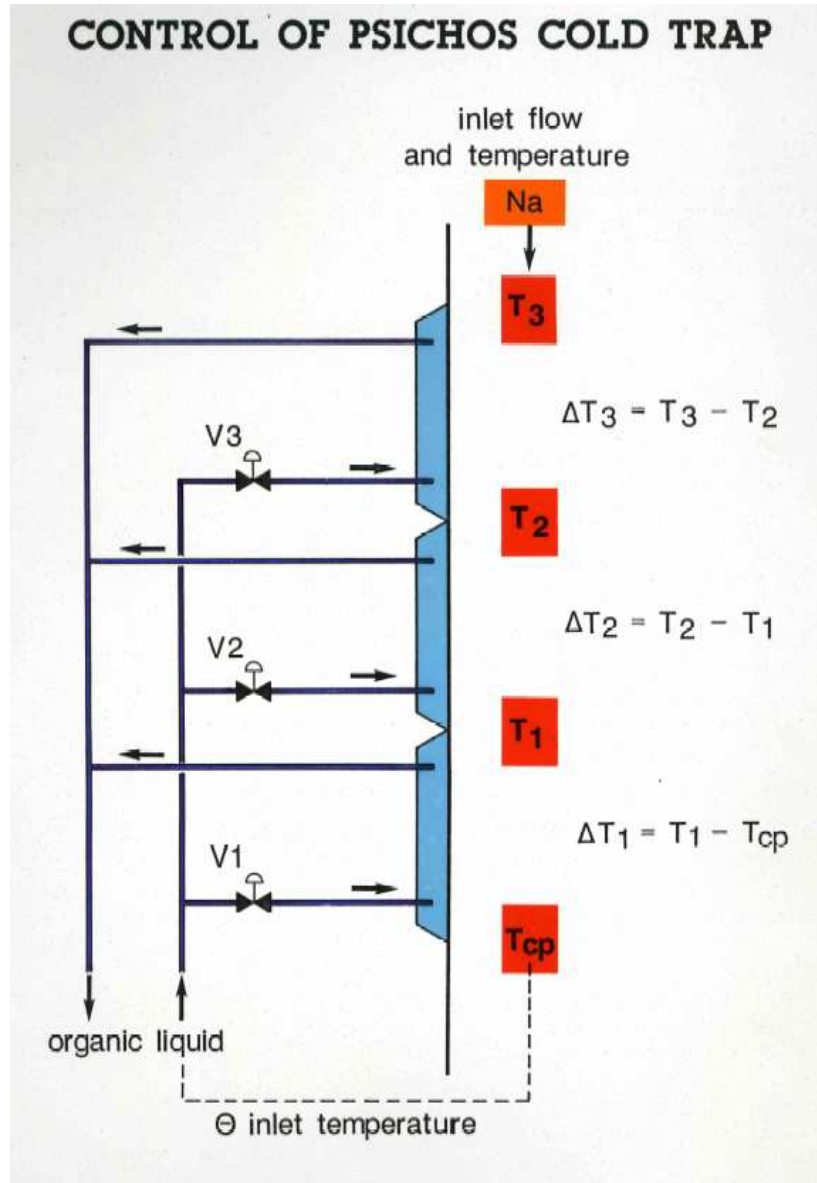
---



- Designed for SUPERPHENIX intermediate loops in 1987
- Main advantages :
  - Efficiency = 1/ NaH and 1/ Na<sub>2</sub>O
  - Flowrate minimized to limit heat loss in the circuit (about 17 m<sup>3</sup>/h)
  - Large capacity (for NaH and Na<sub>2</sub>O reaction) : more than 0.420m<sup>3</sup> (Generation 1 : about 0.160 m<sup>3</sup>)
- History
  - Developed in Cadarache
  - Patented by CEA in 1987
  - Built in GEC-Alsthom Company
  - Implemented on SPX in 1995



# Modular cooler operating diagram



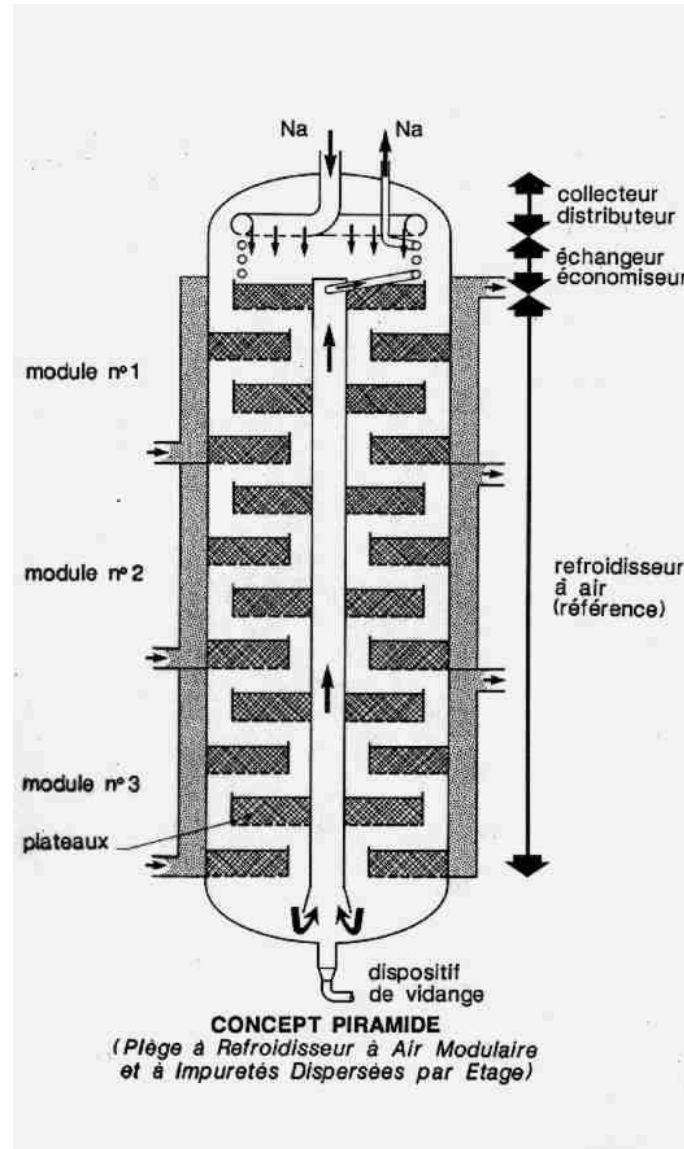
# PIRAMIDE CONCEPT

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- **Designed for European Fast reactor Project (UK, GERMANY and France)**
- **Main advantages**
  - Efficiency = 1/ NaH and 1/ Na<sub>2</sub>O
  - Flowrate minimized to limit heat loss in the circuit (about 17 m<sup>3</sup>/h)
  - Large capacity : for NaH and Na<sub>2</sub>O : more than 0.520 m<sup>3</sup>
- **History**
  - Patented by CEA in 1987
  - Built in GEC-Alsthom Company
  - Sized for EFR and SPX, tested in experimental loop

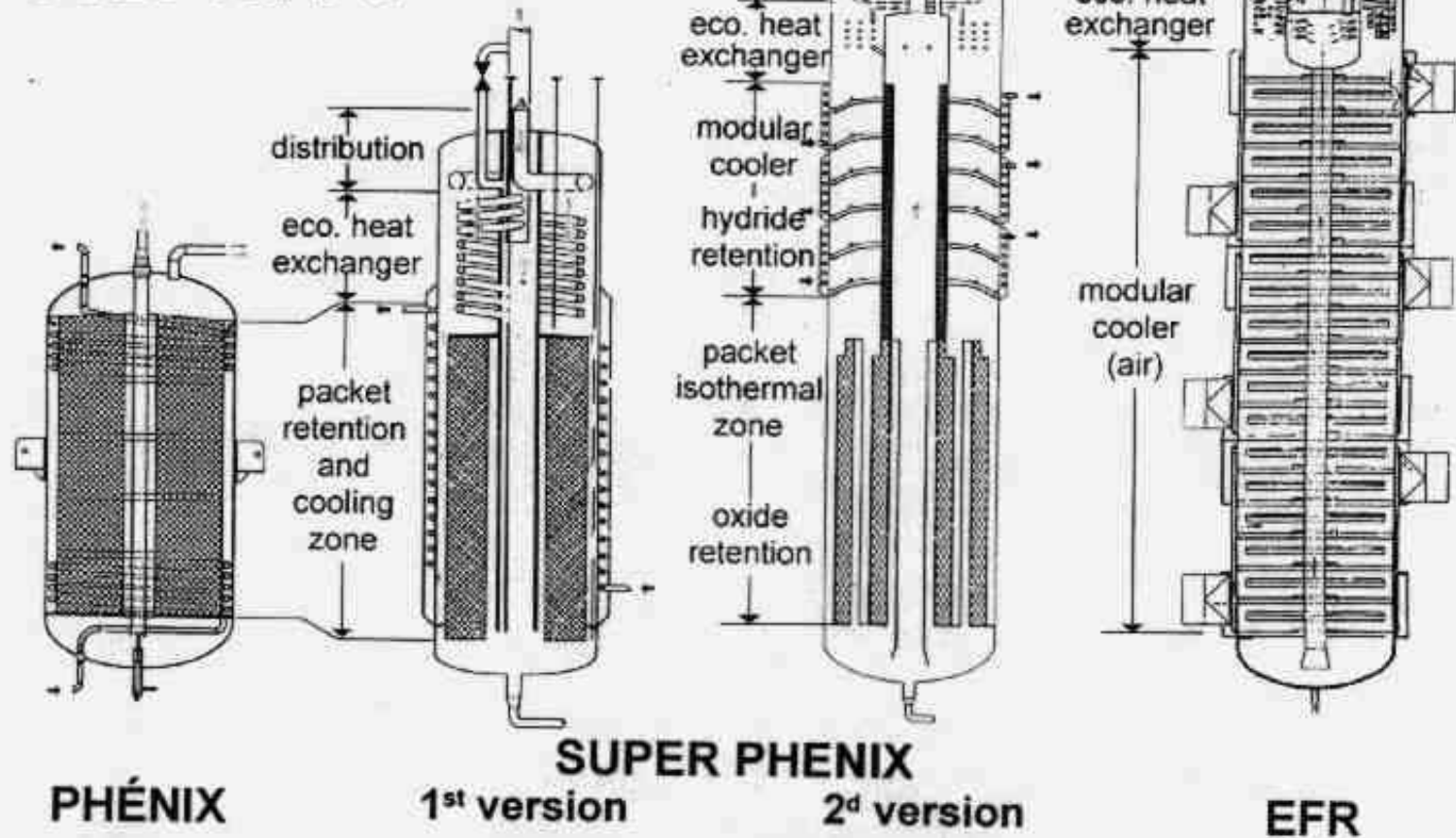
# PIRAMIDE COLD TRAP



# Intermediate Cold Trap evolution from Phenix to EFR



## EVOLUTION of the SECONDARY COLD TRAPS



# How to control the filling rate of a cold trap

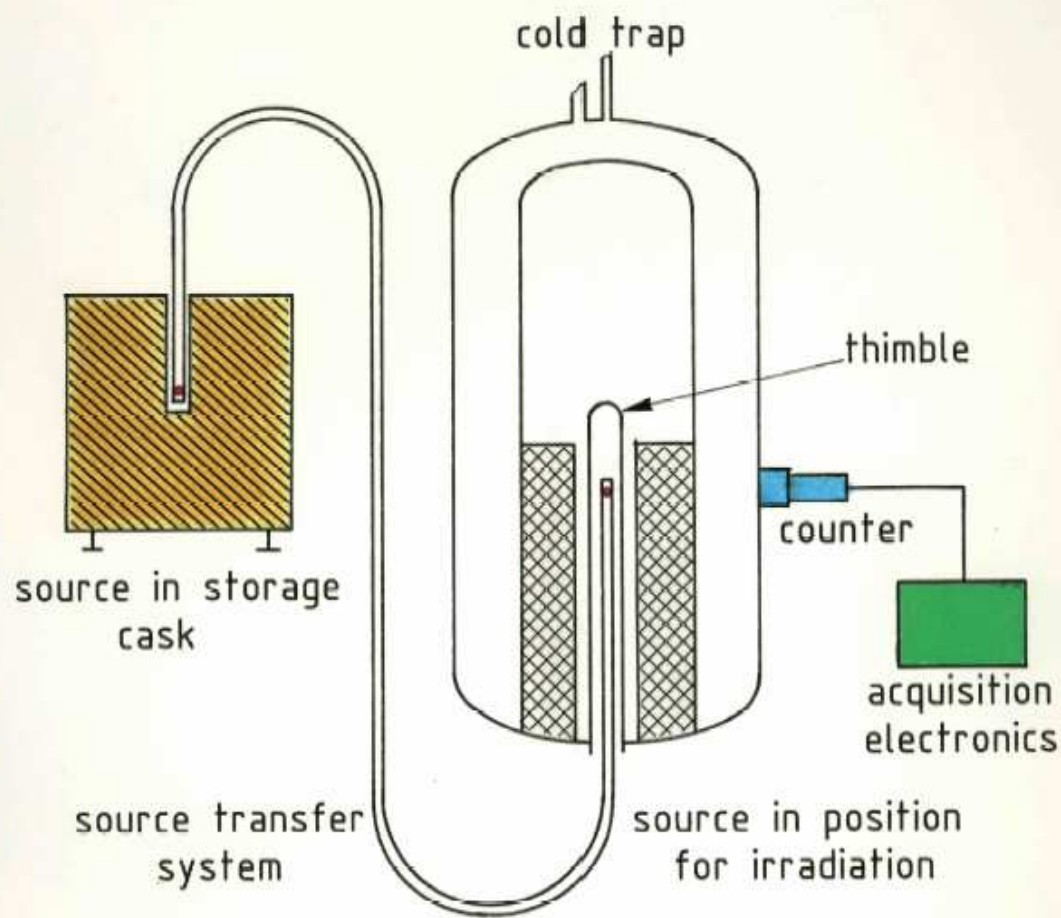
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- **How to control the filling rate of a cold trap :**

- **Mass balance**
- **Monitoring of the pressure drop of the pump**
- **Neutron transmission measurement,**
- **Visual control by endoscopy,**

# Neutron transmission measurement



## •Basic principle :

- 1- Slowing down of neutrons emitted by a source ,by elastic diffusion with light nuclei.
- 2- Counting of the thermalized neutrons.
- 3- Comparison of the measure with a baseline. reference value (trap first placed into operation)
- 4- Calculation of the attenuation ratio.

## •Implementation :

Source : Californium 252

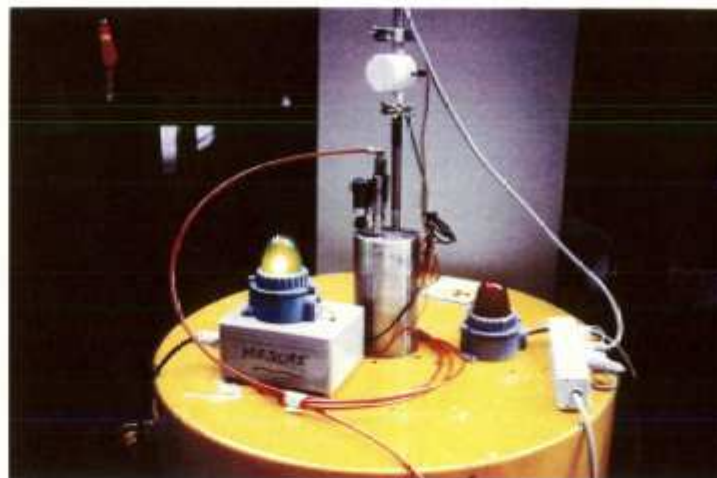
Counter :  $^3\text{He}$  ionization chamber

- The neutron counter is mounted on the outer wall ,on the same radius as the measurement point.
- The source is extended from a storage cask to the measurement point.
- Determination of the attenuation ratio profile along several generatrix.

NOTA : This method can be used ,without shutting down the cold trap.



① SPX1 : Secondary cold trap

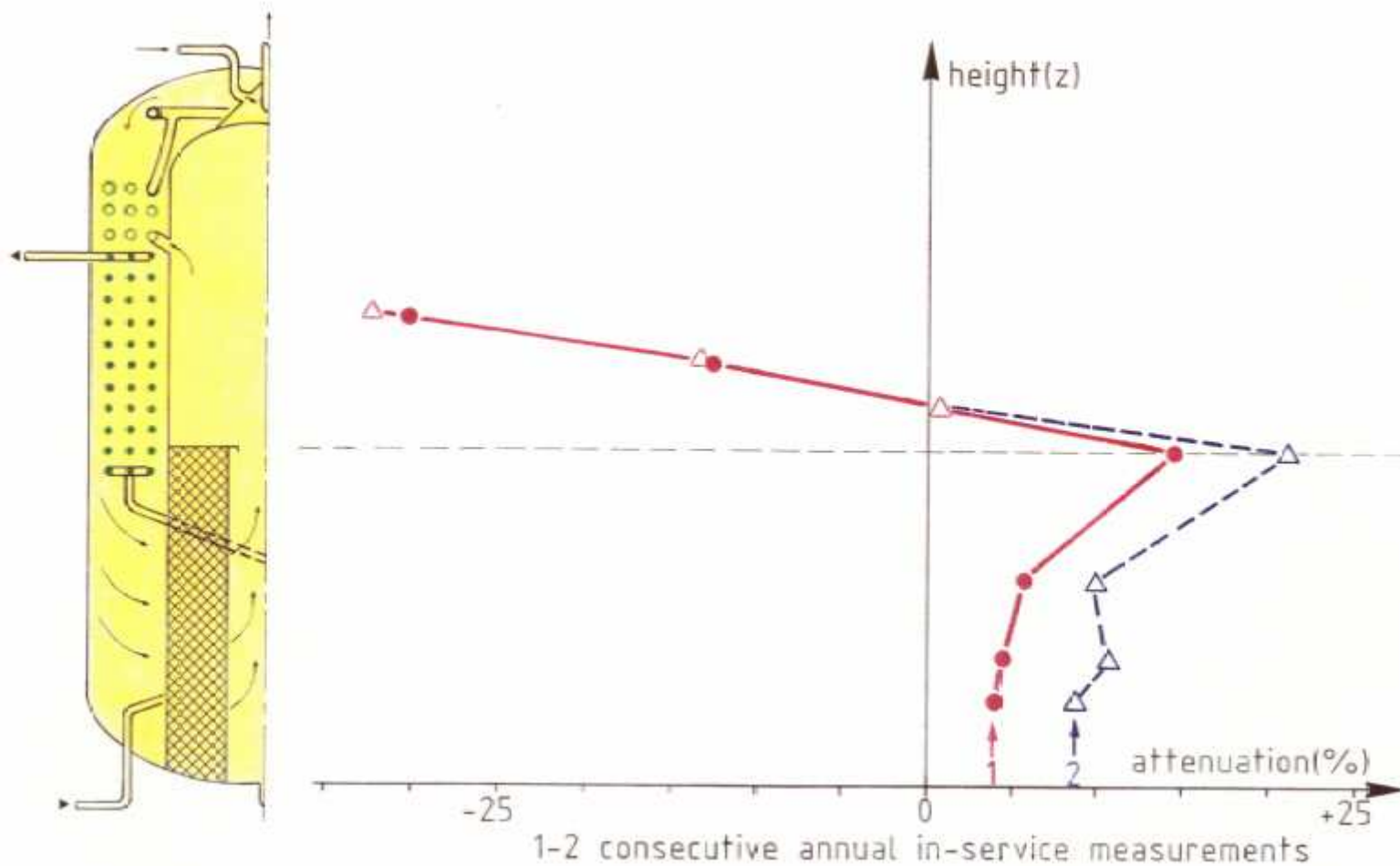


② Storage cask

③ Neutron counter  
( $^3\text{He}$  ionization chamber)



## Phenix cold trap : Neutron transmission measurement



**Phenix cold trap : Neutron transmission measurement**

# Hot trapping

---



- **Several hot traps were developed in the past**
  - **ZR0.87-Ti0.13 alloy for O** : allows to reach very low O concentration (below solubility), but low capacity and necessity to implement a filter downstream
  - **Yttrium foils for hydrogen**
    - Same comments as for Zr-Ti
  - **Hot traps present interest in two cases :**
    - Stable trapping in case of temperature rise up (avoid to release pollution)
    - Easy to implement in small experimental circuits or vessels (can be static)



- $R = 41.26 \cdot 10^{-3} \cdot \exp(-40.3 \times 10^3 / RT) \cdot C \text{ kg O}/(\text{h} \cdot \text{m}^2)$
- Kinetics are established in the range of 1 – 200 ppm
- The flowrate does not seem to have significant effect on the oxidation rate
- Thus the limiting step is oxygen diffusion in the alloy
- Capacity : 0.234 g(O)/g alloy



# Trapping by magnetical fields

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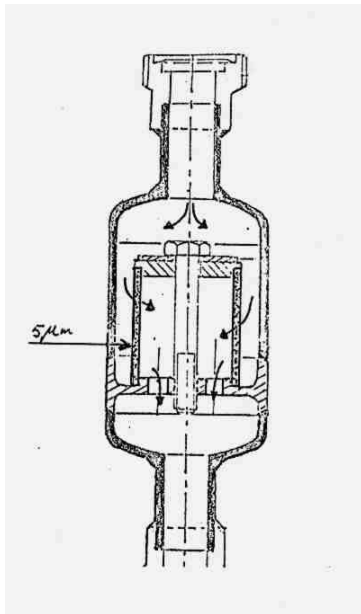


- **Use magnetical field to trap metallic particles**
  - **Low efficiency and low capacity, not adapted for main pollution (O, H)**

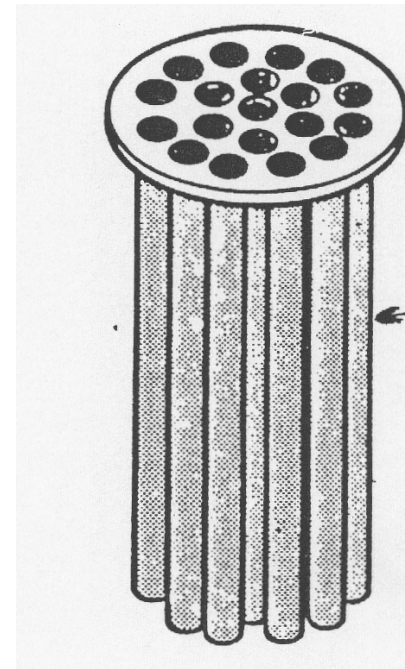
# Trapping by filtering



- Use of sintered filters, meshes,



**Filter used in Rapsodie**



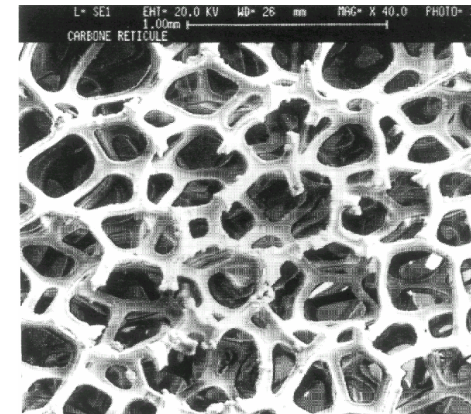
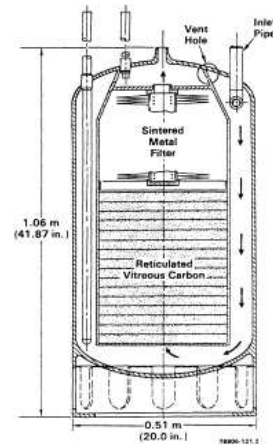
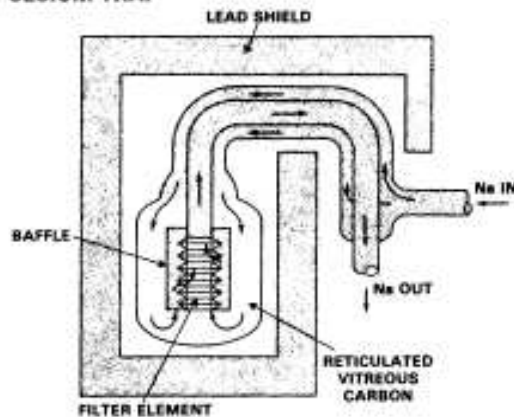
**Sintered filter**

# Caesium trapping



- Use reticulated vitreous carbon,(operated around 200°C)

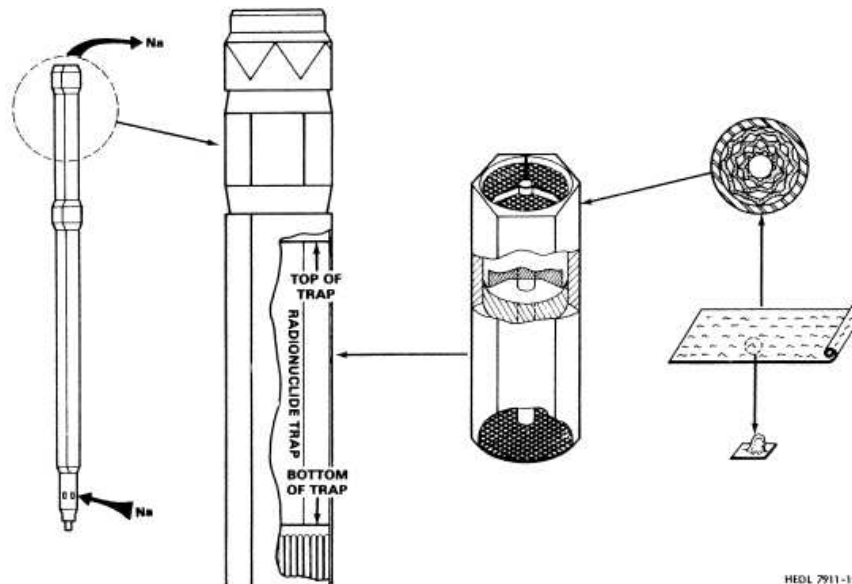
EBR-II CESIUM TRAP



# Trap for activated products (Ni, alliages Ni,..)

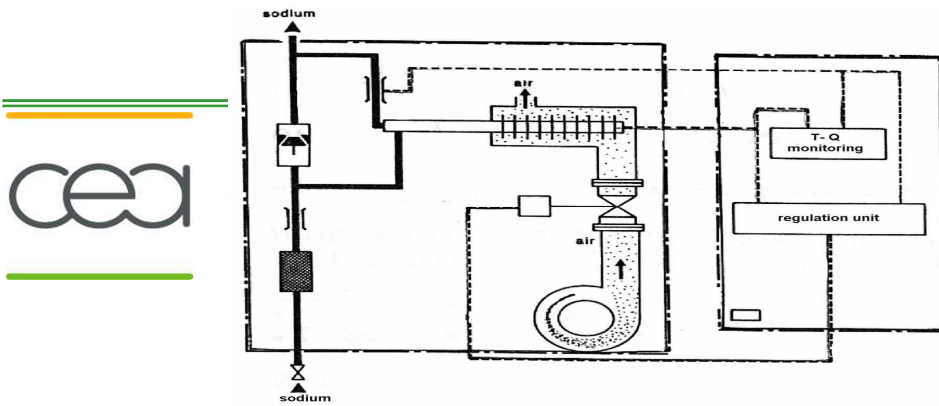


- Feedback from Germany :
- Ex :  $^{54}\text{Mn}$ ,  $^{65}\text{Zn}$  50h in Na at 360°C 1mmNi : 83kBq/cm<sup>2</sup>
- Feedback from France (SILOE),and Belgium (BR2)
- Test wit Ni foils in EBR2 (USA)

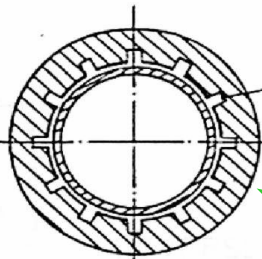


HEOL 7911-191,1

# Standardized Plugging Meter



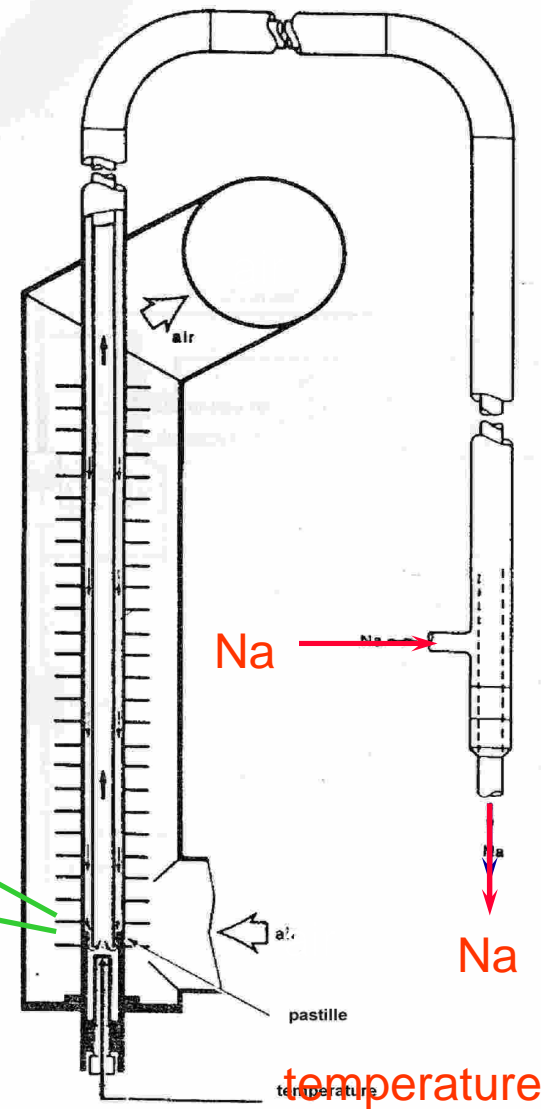
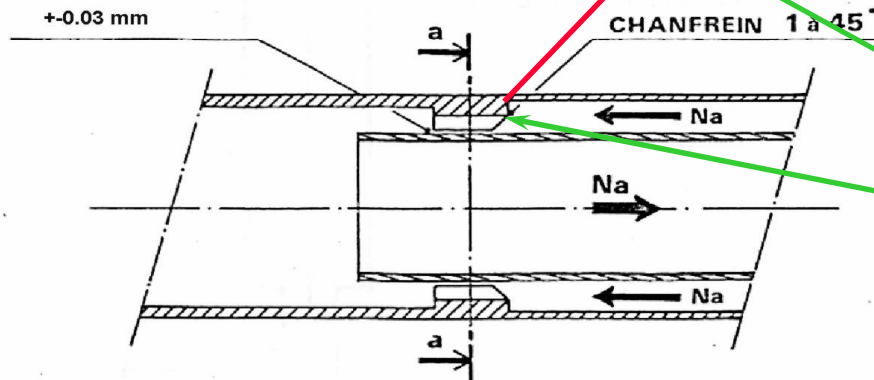
SECTION aa



12 grooves

12 RAINURES 1x1 ± 0,0  
EQUIDISTANTES à 30°  
Etat de surfaces  
LCA 16

Chamfered edge



# Plugging-meters operation

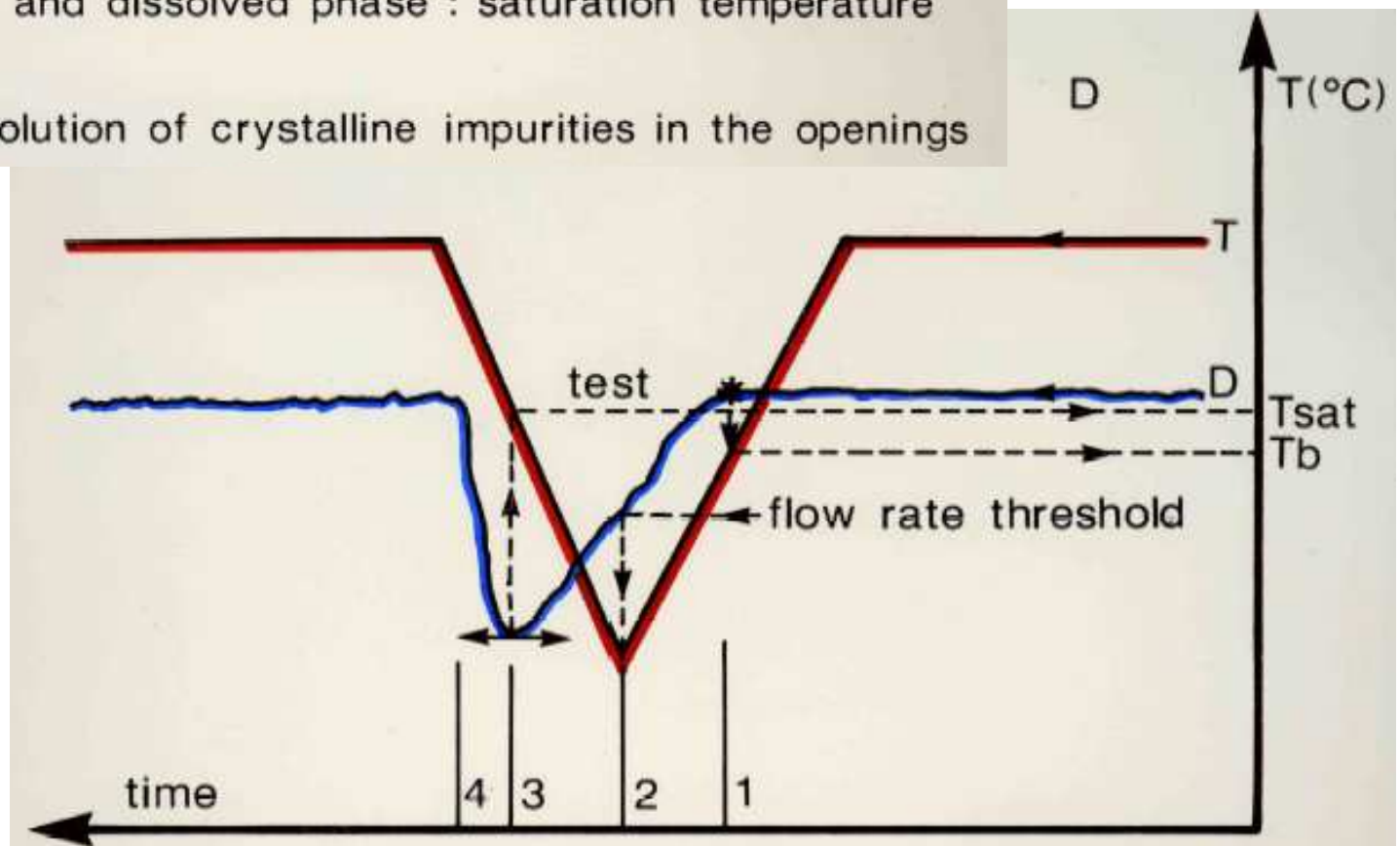


1-appearance of first crystals in plugging indicator openings

2-flow rate threshold reached (temperature raise triggering)

3-temperature at which there is equilibrium between solid phase and dissolved phase : saturation temperature

4-end of dissolution of crystalline impurities in the openings



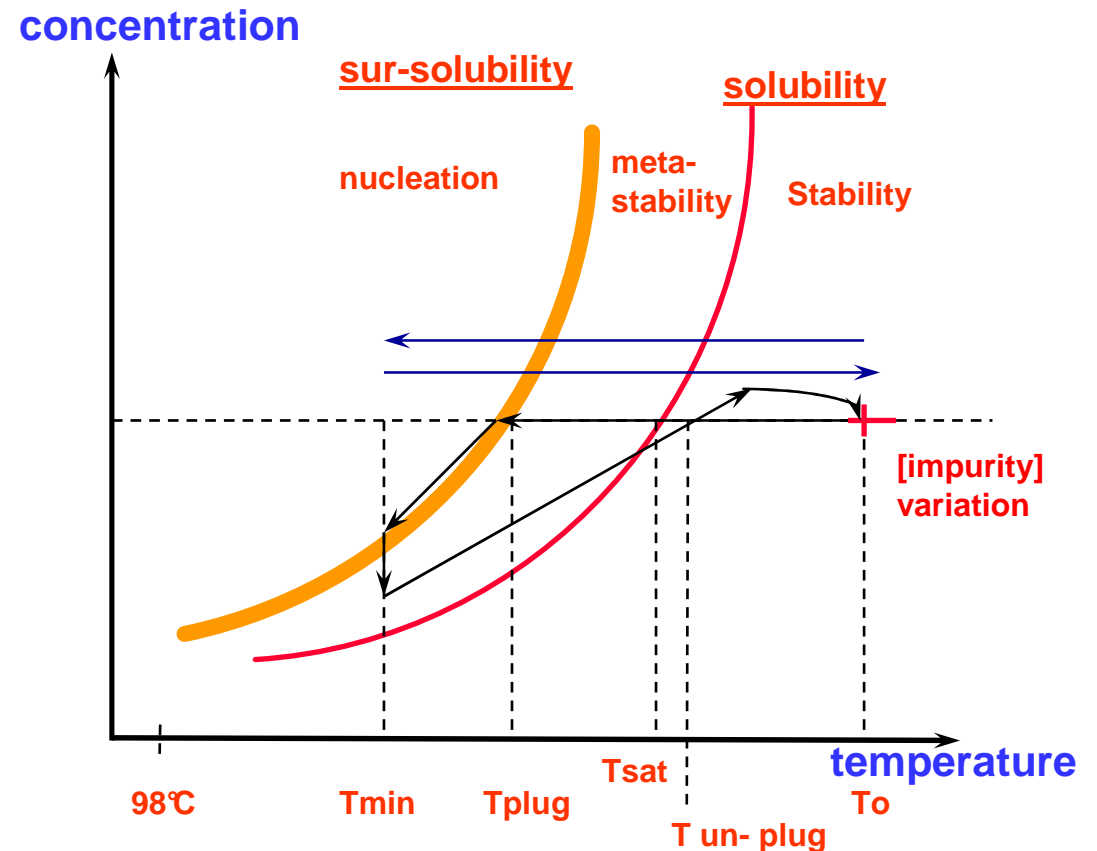
# Quality monitoring by plugging meter



- Ostwald and Miers temperature-concentration graph for a defined impurity : O; H ; ...
- temperature cycle
- record the plug formation with flow rate monitoring
  - restricted area at the cold point (“12 grooves”)
  - constant pressure drop line

⇒ indication of the temperature where the impurities are starting to precipitate  
 plugging T

⇒ As well as indication of  
 ⇒ Dissolution temperature :



# Plugging Meter : T plug and T un Plug measurement



$$T_{\text{sat}}O = T_bO + \Delta T$$

$$T_{\text{sat}}H = T_bH + \Delta T$$

$T_bO$  and  $T_bH = T_b$ , measured by the plugging Meter, a non specific device.

## Operating parameters :

- Tmax = 350°C , in order to dissolve residual NaCrO<sub>2</sub>.
- Cooling rate : 3°C/min
- Qmin = 50% of nominal flowrate (if pollution increases, possibility to increase up to 80%).

temperature

high T stage

T plug

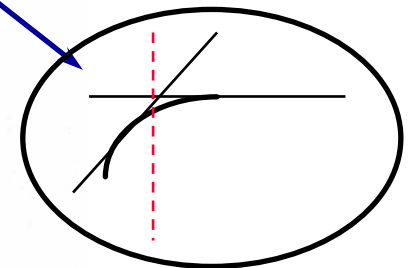
T un-plug

low T stage

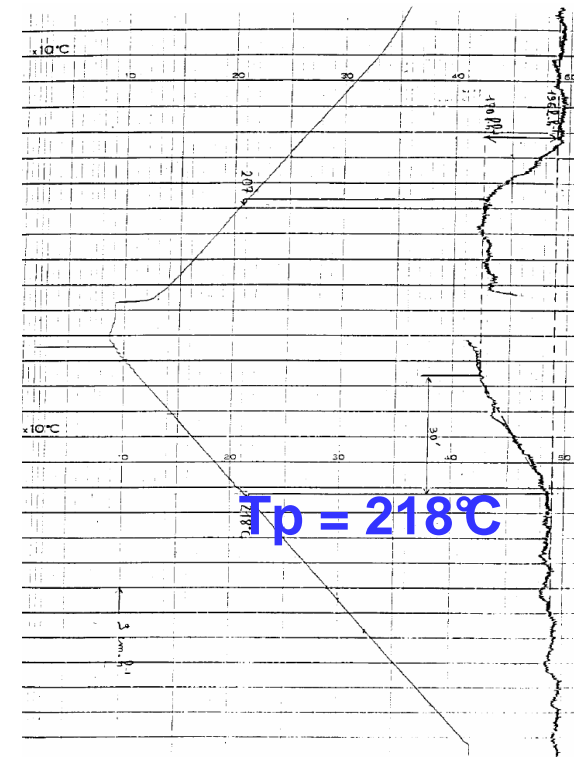
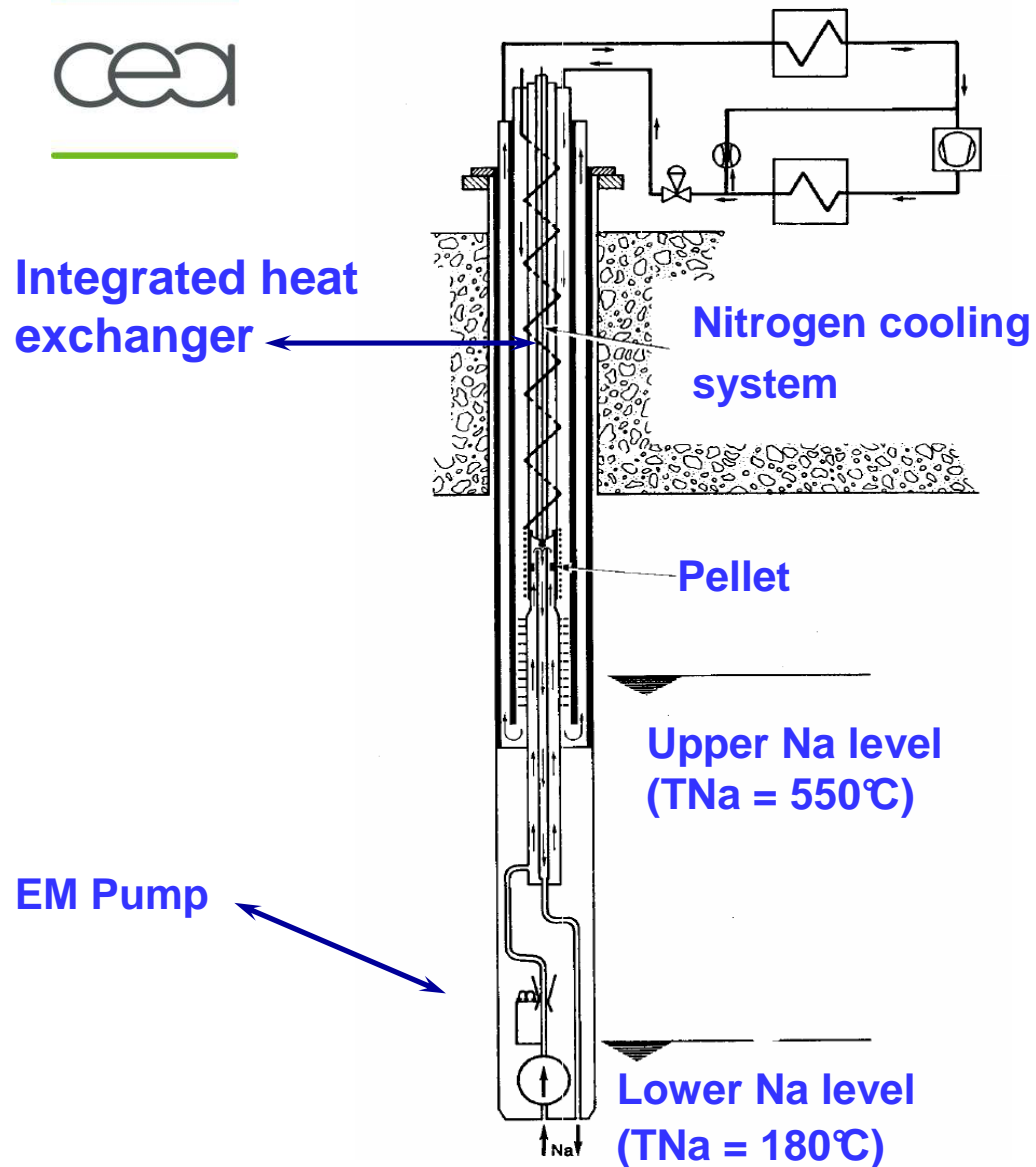
flowrate  
initial flow rate Qn

0.5 Qn

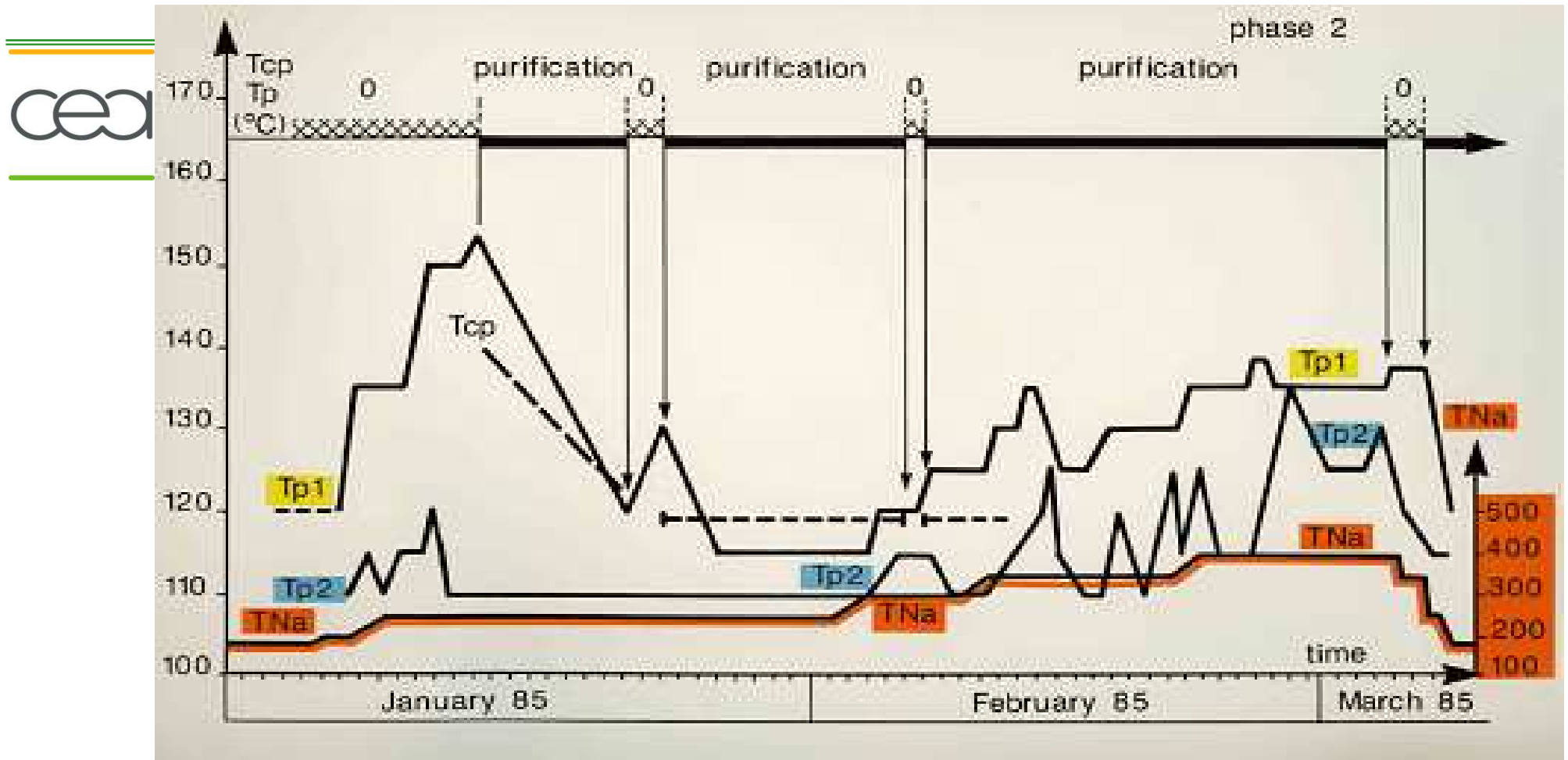
time



# SuperPhenix Integrated plugging-meter (50 l/h)



# $T_{\text{plug}}$ during purification campaigns



**Tp1** : Tplugging in primary Na  
**Tp2** : Tplugging in intermediate Na

**Tcp** : T cold trap



## **THE HYDROGEN DETECTION**

### **✓ FUNCTION**

**Continuous surveillance of hydrogen concentration  
in sodium and argon  
(detection of threshold exceeding)**

### **✓ ROLE**

- rapid detection of any water leak, in order to assume automatically a safe state for steam generator units (SGU)**
- preservation of the materials (SGU modules)**
- evaluation the importance of the leak**
- participation to leak localisation operations**

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## THE HYDROGEN DETECTION

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### ✓ PRINCIPE

Measurement of hydrogen quantity, dissolved in sodium (or in argon) :  
diffusion through a nickel membrane, immersed in sodium

### ✓ REQUIRED CONDITIONS

- temperature high enough at membrane location ( $H_2$  diffusion)
- dynamic vacuum behind the membrane (ultra-vacuum :  $10^{-8}$  mbar)

### ✓ BACK GROUND NOISE

Hydrogen level in sodium (and argon) is not null, even when there is no  
incidental pollution due to :

- permanent diffusion through SGU tubes ( $H_2$  rate in water ; magnetite)
- permanent sodium purification induces low  $H_2$  back ground noise
- depend on SGU operation rate

# THE HYDROGEN DETECTION



## BACK GROUND NOISE OF H<sub>2</sub> IN SODIUM

Diffusion of H<sub>2</sub> through SGU heat exchange tube thickness

→ 2 origines of hydrogen diffusion:

✓ aqueous corrosion of heat exchange tubes (formation of a magnetite layer, on water side) :



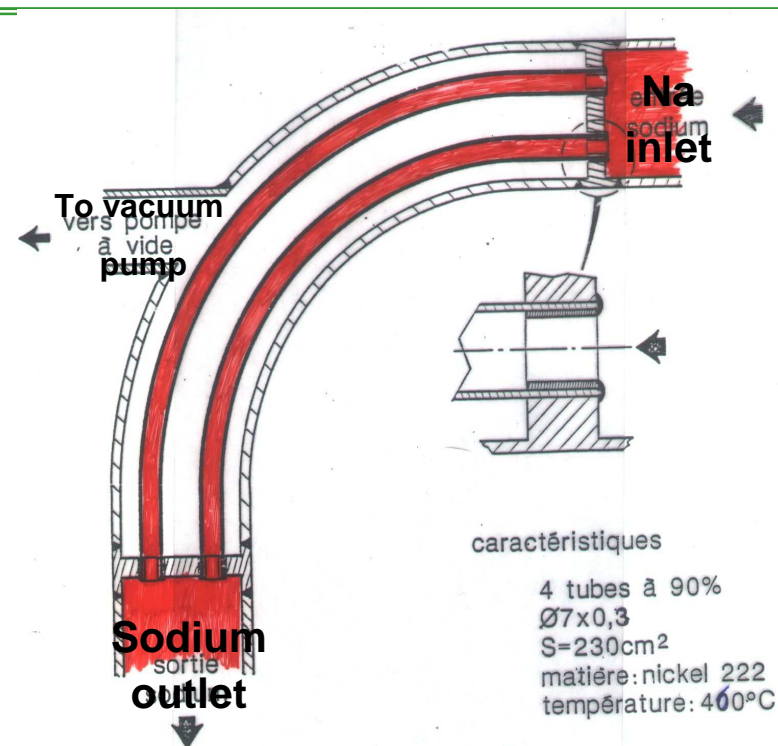
✓ decomposition of hydrazine which is injected in SGU feed water



Back ground noise depends on these source terms and of operating parameters of cold traps (sodium purification)

## • THE HYDROGEN DETECTION

### NICKEL MEMBRANES



#### analyse du nickel 222

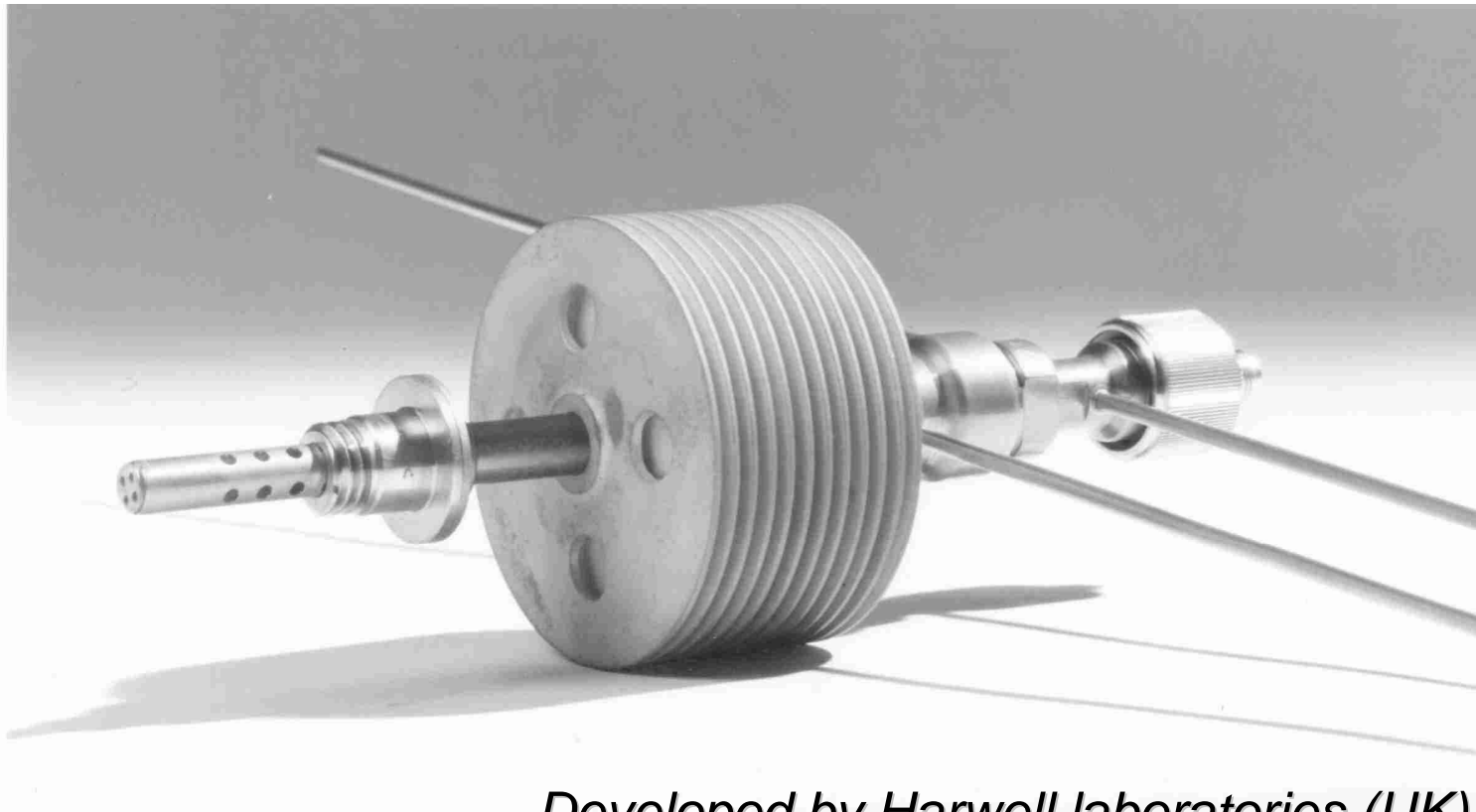
C : 0,006 %	Ti : < 0,005 %
Si : 0,006 %	Al : < 0,01 %
Cu : < 0,01 %	Co : 0,05 %
Fe : 0,04 %	Mo : < 0,05 %
Mn : < 0,01 %	S : 0,004 %
Mg : 0,064 %	Ca : < 0,001 %
Cr : < 0,01 %	B : 0,0005 %

CAPTEUR D'HYDROGÈNE DANS LE SODIUM

# Oxygen-meter



**Electrochemical cell : Thoria doped with Yttria,  
Reference electrode : air, In/ $\text{In}_2\text{O}_3$**



*Developed by Harwell laboratories (UK)*

# Why other energy conversion systems?



**SPX:** Tout (core) = 530°C ,  
Tin (core) = 377°C  
SGU : Tout = 490°C, Tin = 237°C  
Pout = 180b  
Net efficiency = 40%



Why other cycles? ( SC H2O, SC CO2, N2, N2-He,...) ?

## Economical attractiveness :

- Obtain a better thermodynamical efficiency with the same core,
- Simplify or eliminate the intermediate loops,
- Reduce the cost of the energy conversion system (i.e small turbine, ...)

Safety : better compatibility with Na than water but

potential gas injection in primary Na to be investigated and prevented.

# Supercritical CO<sub>2</sub> cycle :

➤ With <sub>sc</sub>CO<sub>2</sub>, high efficiency can be obtained with complex cycle structures



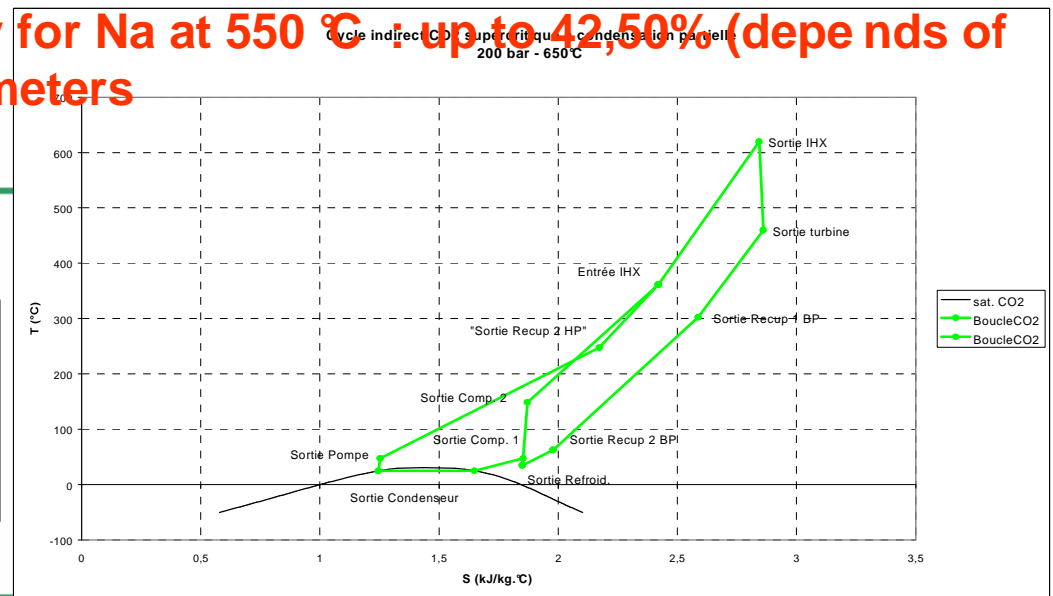
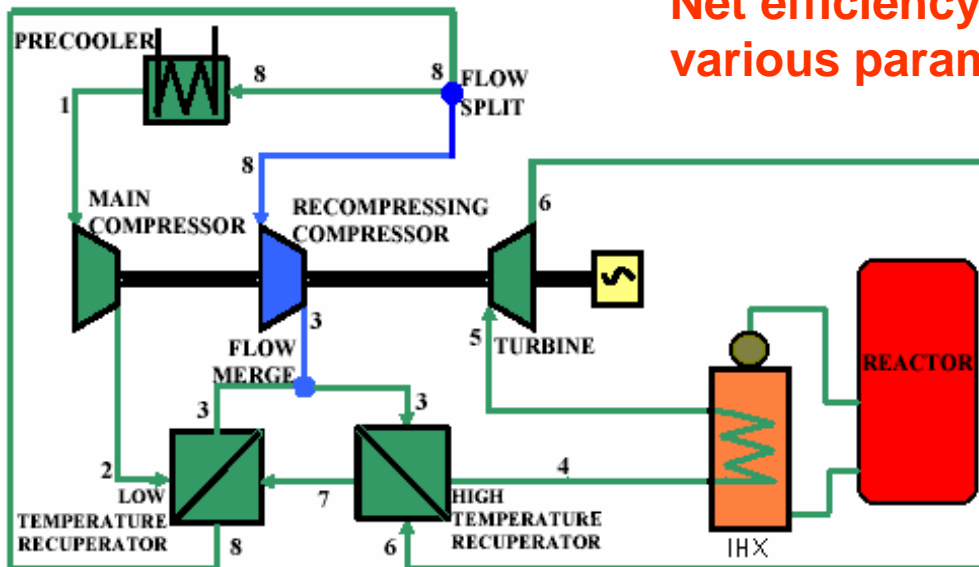
➤ Very compact turbines

➤ Na –CO<sub>2</sub> interaction acceptable (?)

➤ Material behaviour

➤ Assessment of other consequences : tritium transfer, purification,

Net efficiency for Na at 550 °C : up to 42,50% (depends of various parameters)

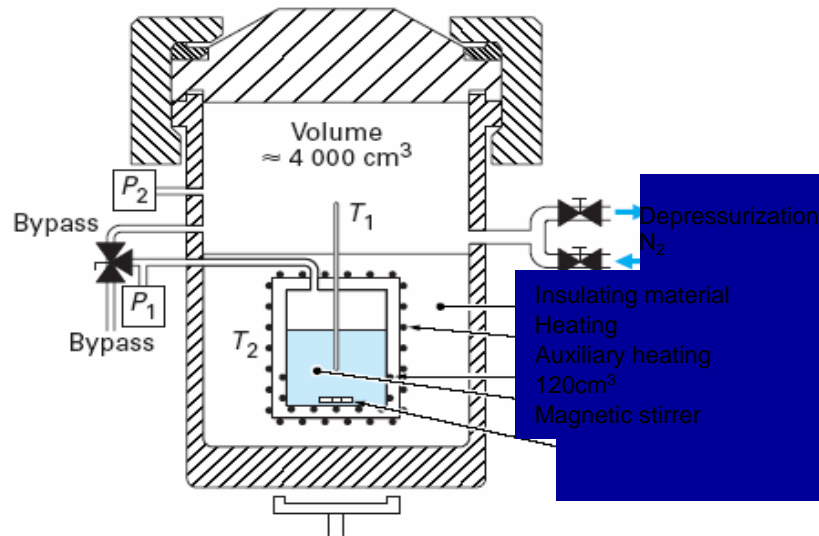


➔ New Research and development activities!

# Pressure compensated calorimeter Pseudo-adiabatic experiments



temperature and pressure measurement versus time

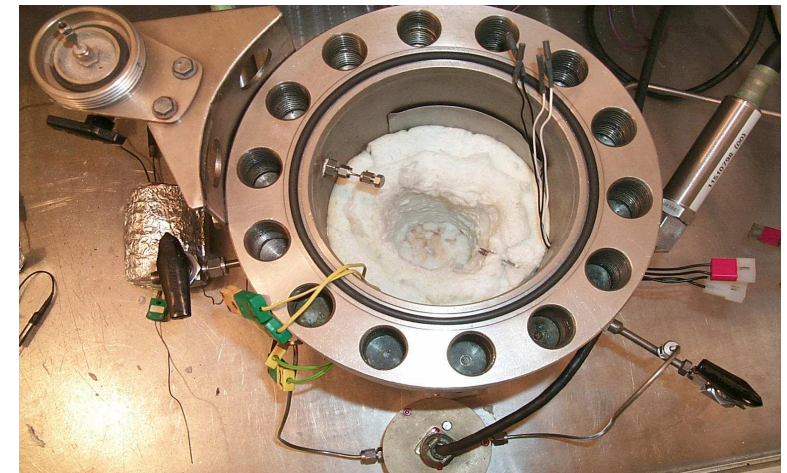
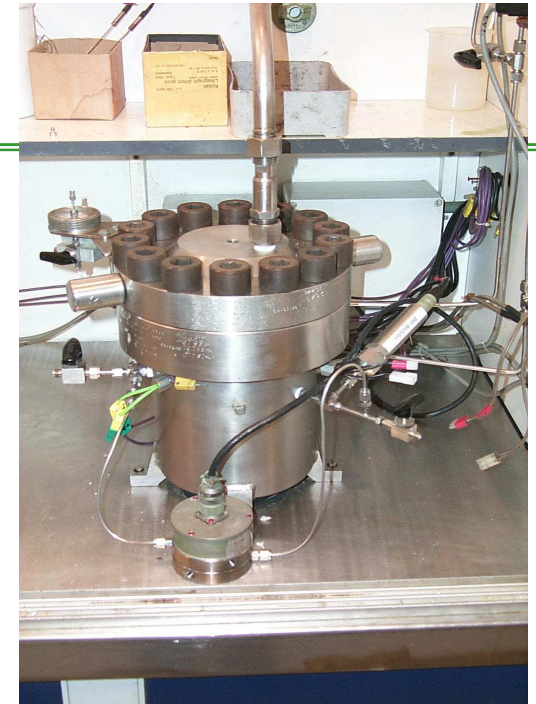


Thin wall test cell  
Very small heat capacity



\*DIERS :

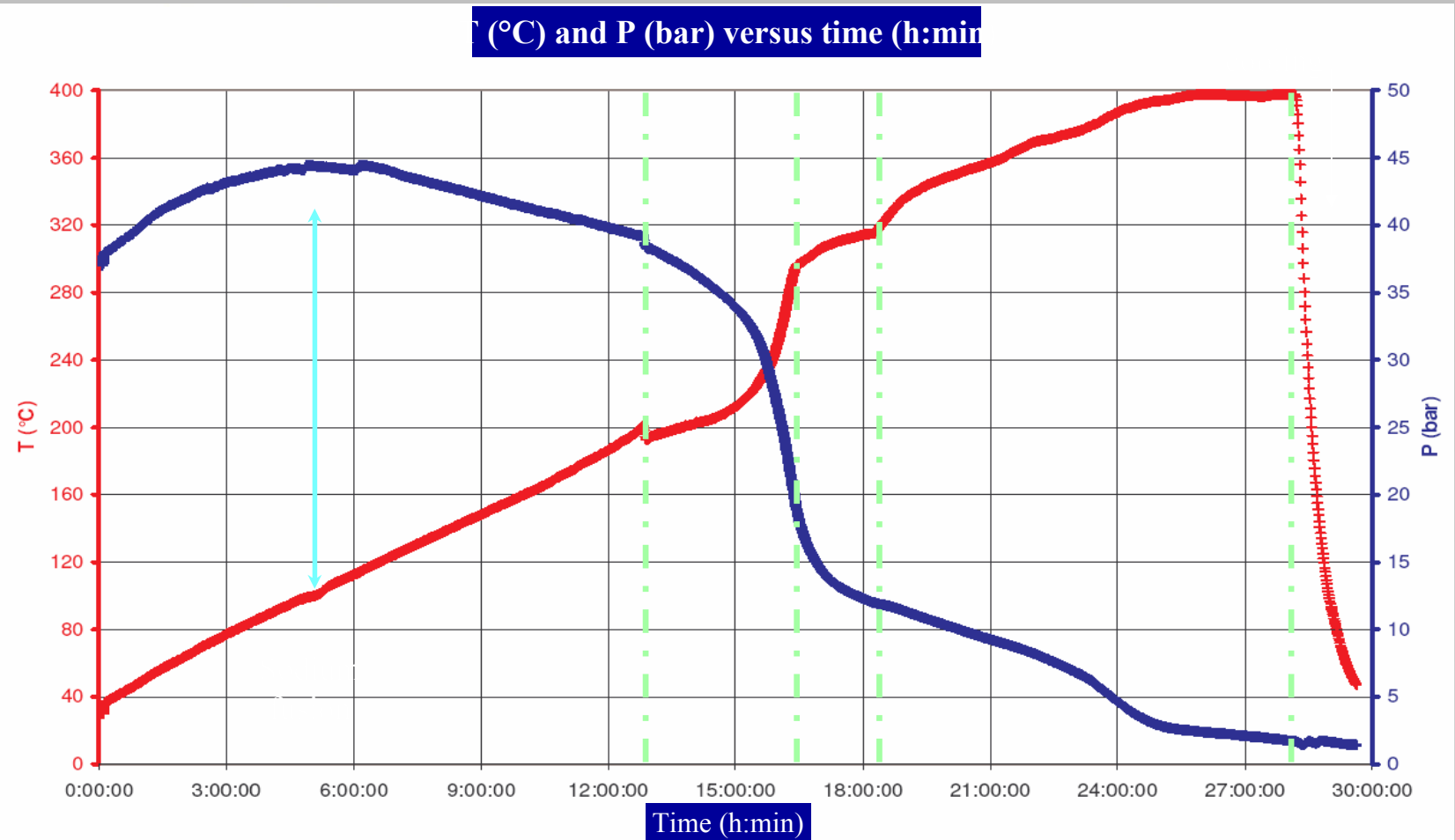
Design Institute for Emergency Relief Systems



with the courtesy of Rhodia

## Example of VSP results

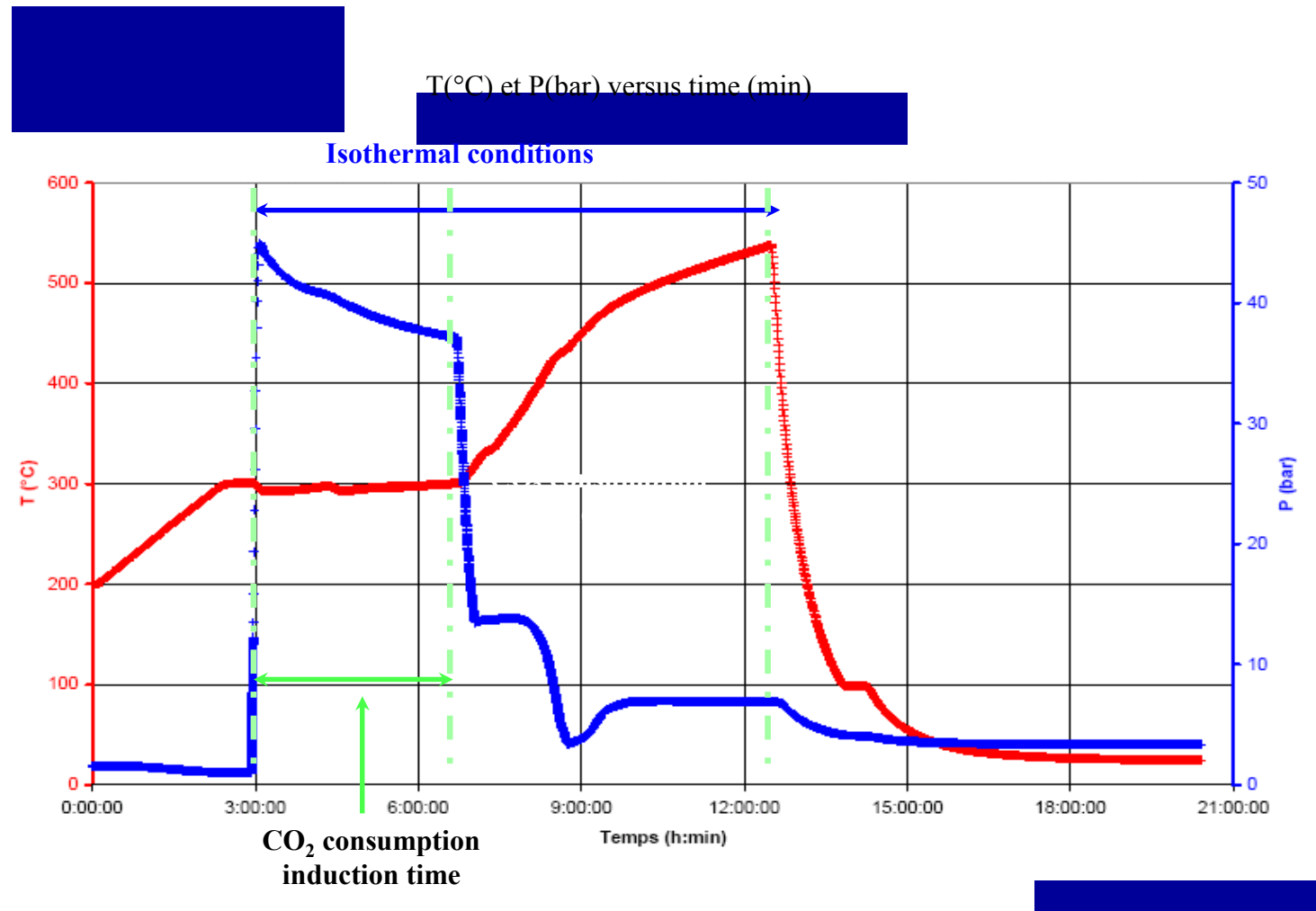
## Temperature scan



- An exothermic event consistent with slow exothermicity observed with DSC ( $T < 400^{\circ}\text{C}$ )
- CO gas formation

## Example of VSP results

### Isothermal study



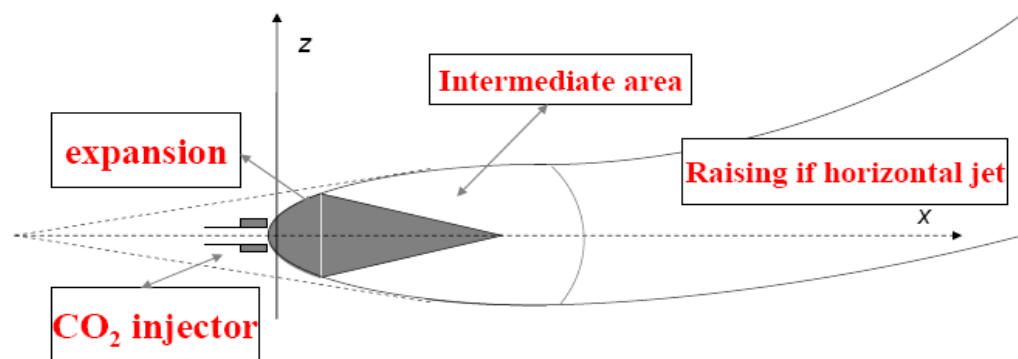
- CO<sub>2</sub> introduced at the beginning of the isotherm period
- Induction time before the reaction

# Main consequences of this interaction



- The interaction depends mainly of the temperature:  $< \text{ or } > 500^\circ\text{C}$ 
  - the scenario in the heat exchanger : depends of the position of the leak, (quite different from the situation with sodium-water interaction). → From literature, the interaction depends also of stirring.

- Therefore, knowledge of kinetics is of great importance to check the occurrence possibility of a wastage scenario, leading to damage of several walls of the exchanger with thermal, mechanical and chemical effects. One of our challenges is now to determine the main kinetic parameters of the reaction.
- It has been decided to use a methodology able to establish the kinetics in realistic conditions.
- A rack of thermocouples able to move inside the biphasic jet will allow to establish thermal profiles in Na-CO<sub>2</sub> interaction area. Then modeling of CO<sub>2</sub> injection in Na, in realistic conditions, will allow to extract the main parameters of the kinetics.



# Conclusions

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- **To maintain the sodium at its « maximal » purity can be obtain if operator will follow six essentials recommendations**
  1. **Supply high purity sodium (take care with specifications for the supplier)**
  2. **Filter the sodium at different stages (initial transfer before filling and during start up operations; after specific pollutions, after repair)**
  3. **Carry out purification campaign during start up, after specific pollutions, after repair,... with cold traps**
  4. **Design cold traps adapted to the needs (size, coolant, location of packing)**
  5. **Design cold traps easy to dismantle.**
  6. **Limit the introduction of impurities (fillings, O<sub>2</sub>, H<sub>2</sub>O, oil, ...)**

The French Sodium School  
a partnership with French INSTN Institute  
a need for CEA, EDF, AREVA...



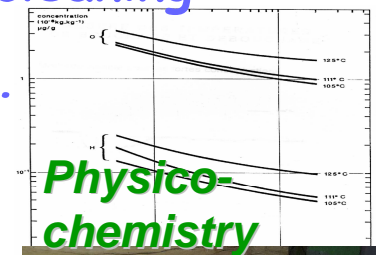
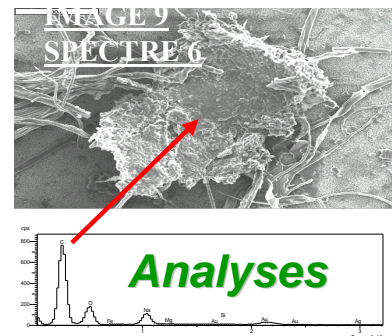
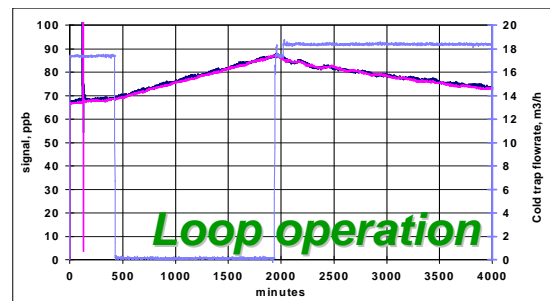
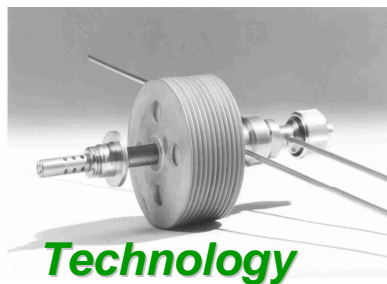
Located at Cadarache, equipped with specific loops

30 specialized teachers

10 to 20 sessions per year

4000 trainees in 32 years

10 training modules : basics, safety,  
sodium equipment, operating, cleaning  
decommissioning, NaK ...





- *Thank You for your kind attention!*



**Na school in CEA-Cadarache**

