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Joint ICTP-IAEA Workshop on
"Physics and Technology of Innovative Nuclear Energy Systems for Sustainable Development"
Trieste Italy
2018 August 20th – 24th

Na properties

Nota:* *New recommendations will be issued soon (IAEA NAPRO CRP: Handbooks)

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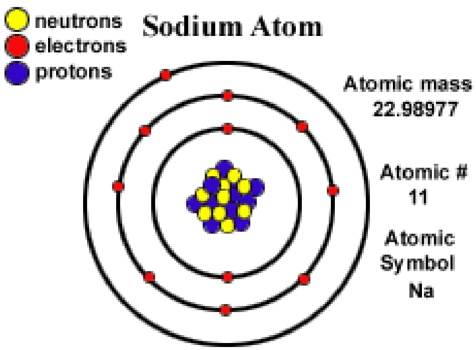
Introduction to sodium :

Na in the alkali metal family : Name coming from arabic : al kaja meaning : ashes coming from sea

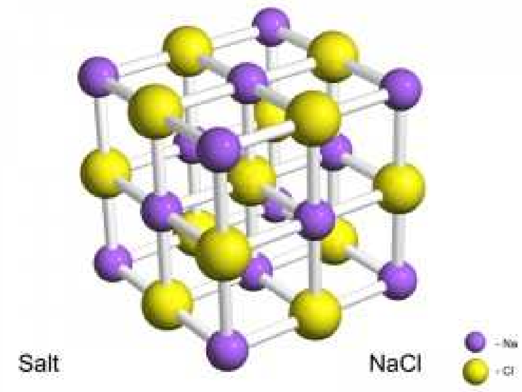
قَلَوِيّ



	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						

6	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
7	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

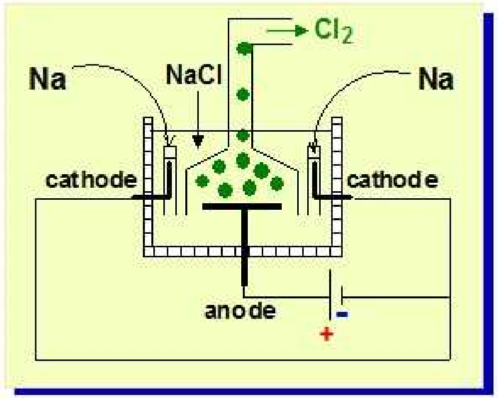
Sodium manufacturing



Varangéville France

- **Produced by electrolysis of**
- **eutectic NaCL/CaCl$_2$**

Electrolysis battery in Métaux Spéciaux (France)



Properties of sodium

- **Liquid from 97.85℃ to 882.85℃ (at Patm)**

- **Critical temperature: Between 2573 K and 2733 K, depending on author**

- **Density: Valid for the liquid state between 100℃ and 1400℃**

ρ (kg/m^3) = 950.0483 - 0.2297537 θ - 14.6045x10-6 θ^2 + 5.6377x10-9 θ^3

θ in ℃

➔ **Decrease in volume (by around 2.7%) when sodium changes from a liquid to solid**

➔ **ρ always < ρ H_2O: ρ = 850 kg/m^3 at 400℃**

- **Viscosity**

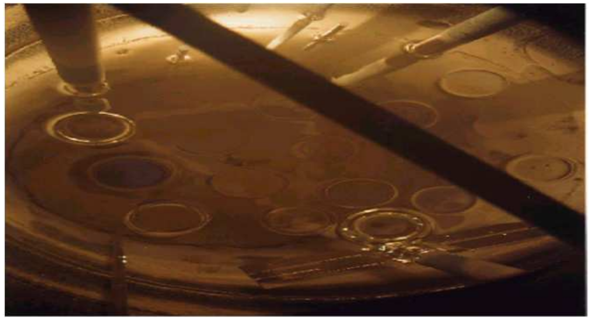
The following empirical relationship is used:

$$\log_{10}\mu = -2{,}4892 + \frac{220{,}65}{T} - 0{,}4925\,\log_{10} T$$

μ in poiseuilles (or Pa $\times$ s), T in K

Dynamic viscosity of Na compared to other liquids

Liquid	H_2O	Hg	Pb	Na
Viscosity	1000 (20°C) (1 atm)			
(poiseuilles or Pa × s)	280 (100°C) (1 atm)	1000 (200°C)	2700 (441°C)	310 (400°C)
	67 (350°C) (150 bar)	(1 atm)	(1 atm)	(1 atm)



Properties of sodium

Conductivity in the solid state is given by the expression:

$$\lambda(W.m^{-1}.K^{-1}) = 135.6 - 0.167\ \theta$$

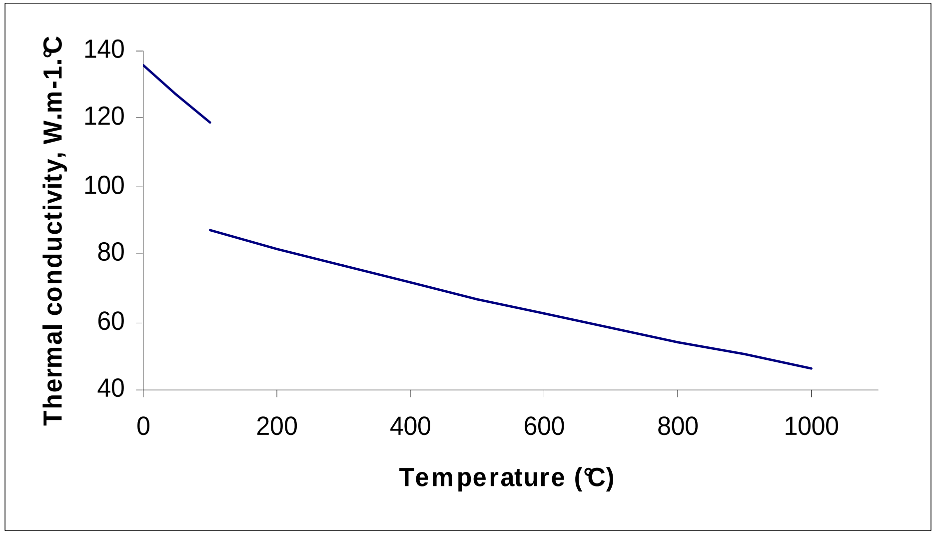
Conductivity in the liquid state is given by the expression:

$$\lambda(W.m^{-1}.K^{-1}) = 92.951 - 5.8087\ 10^{-2}\ \theta + 11.7274\ 10\text{-}6\ \theta^2$$

θ in ℃ in both cases

Thermal conductivity of Na as a function of temperature:

(water at 20℃: 0.6 $W.m^{-1}.K^{-1}$)



Properties of sodium

Specific heat in the solid state is given by the expression:

$$Cp\ (\text{joules/kg.K}^{-1}) = 1199 + 6491\ 10^{-4}\ \theta + 1052.9\ 10^{-5}\ \theta^2$$

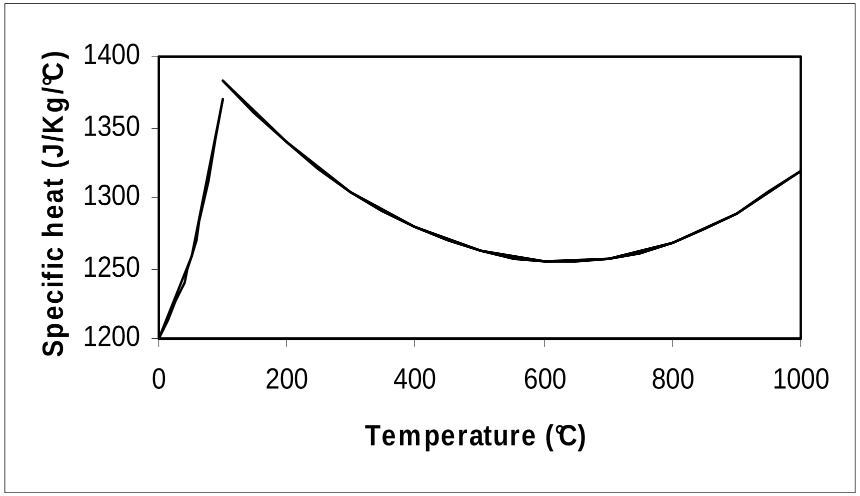
Specific heat in the liquid state is given by the expression:

$$Cp\ (\text{joules.kg}^{-1}\ \text{C}^{-1}) = 1436.715 - 0.5805379\ \theta + 4.627274\ 10^{-4}\ \theta^2$$

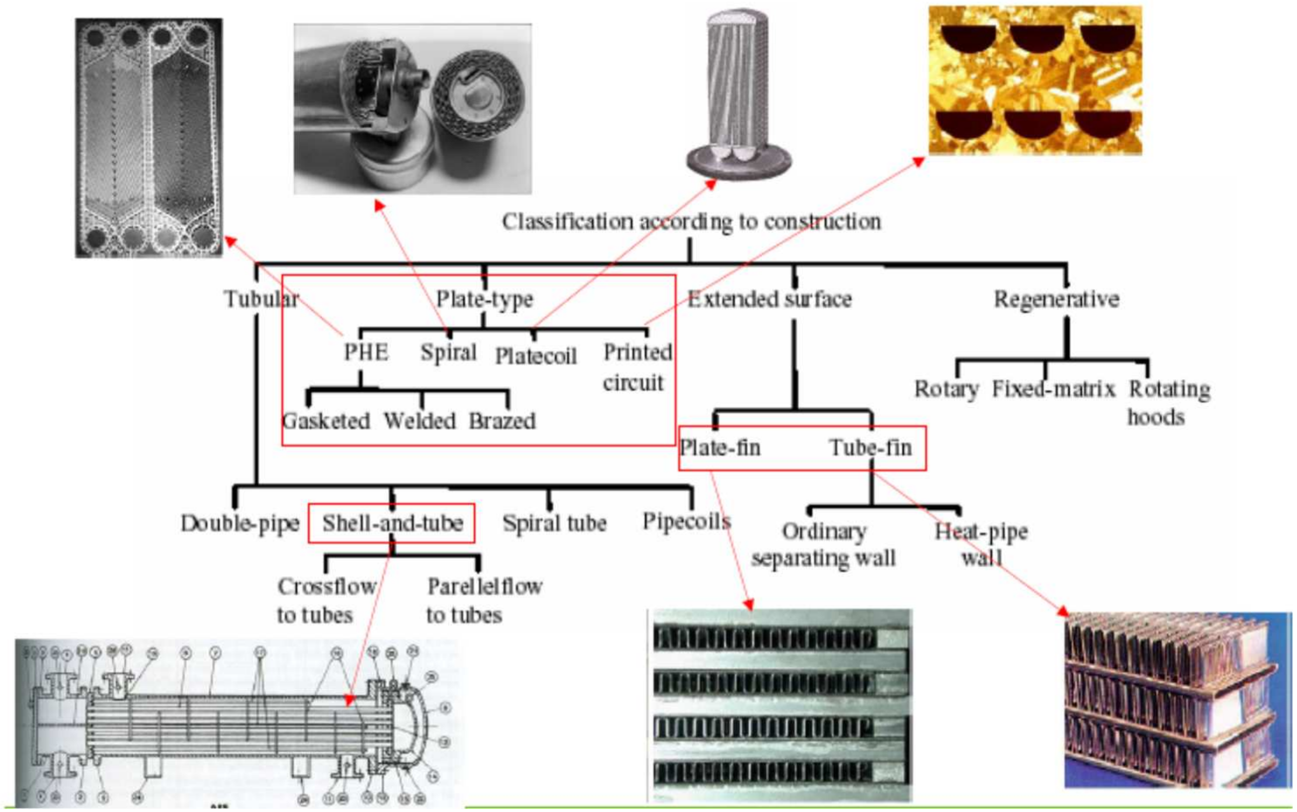
θ in ℃ in both cases

Specific heat of Na
as a function of temperature:
(Na at 400℃:
1.25 10^3 joules/kg)

(water at 20℃:
4.18 10^3 joules/kg
at 20℃)

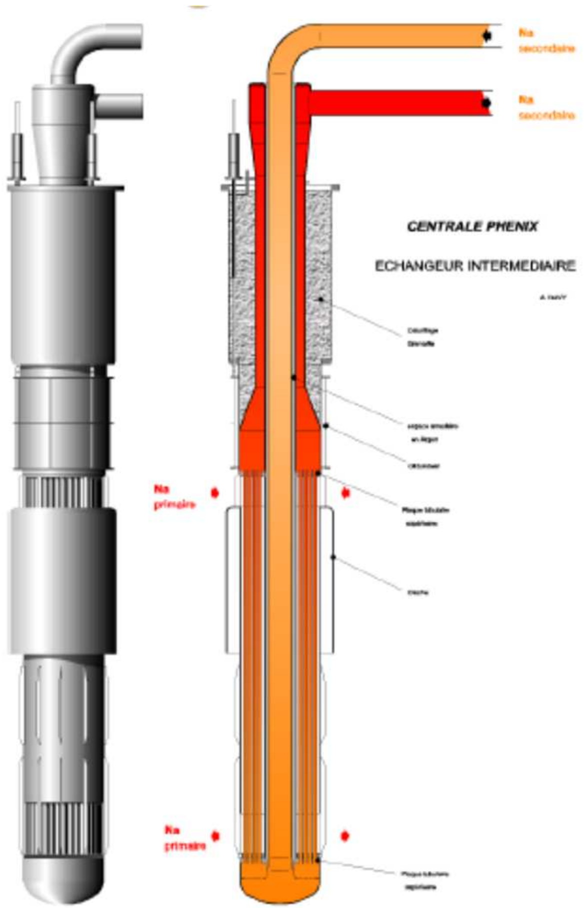


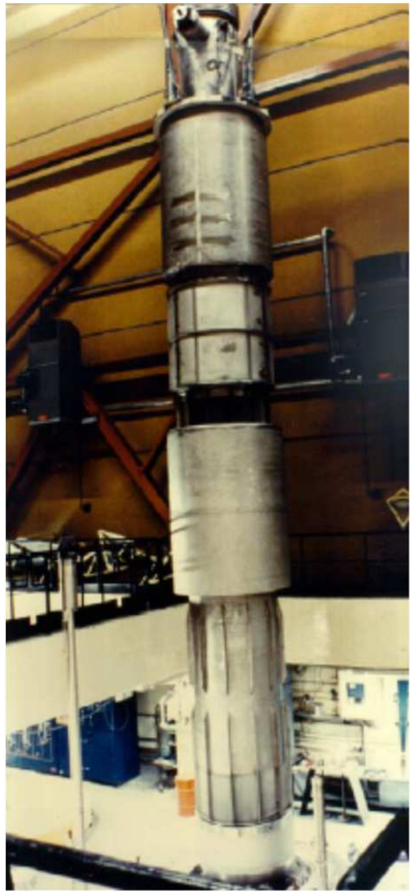
Heat transfer: several existing technologies



Several parameters to check prior to choice of technology:
- maximal pressure & temperature
- Compacity
- Efficiency
- Reliability (Thermal behaviour,…)
- Inspectability
- Reparability
- Modularity

Intermediate heat exchanger Phenix





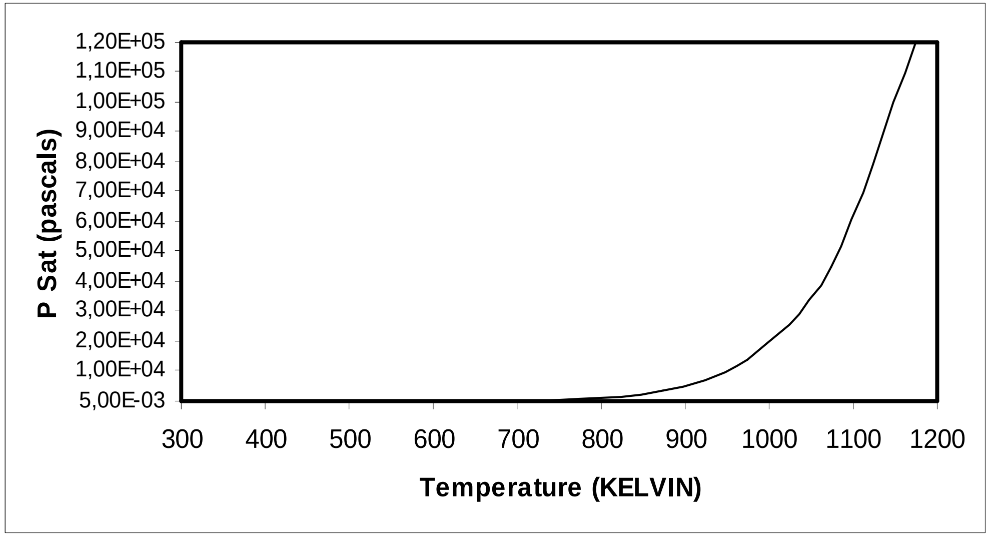
Properties of sodium

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



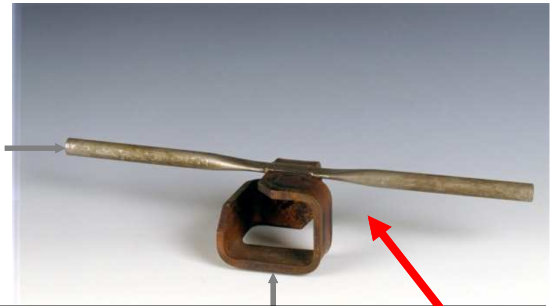
Consequences:

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

Properties of sodium

Electrical resistivity in the liquid state:

$$\rho e \ (\Omega \times m) = 6.1405\ 10^{-8} + 3.5047\ 10^{-10}\ \theta + 5.6885\ 10^{-14}\ \theta^2 + 1.66797\ 10^{-17}\ \theta^3$$



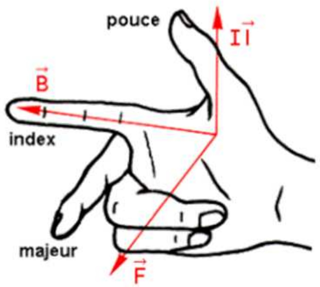
Consequences:

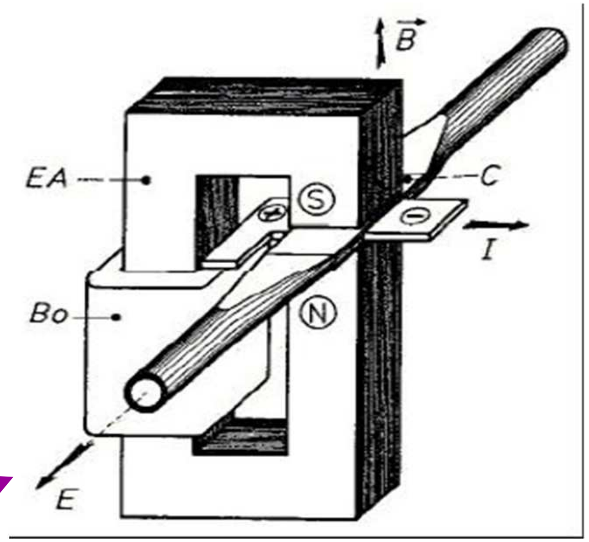
The conductive properties of sodium are used in instrumentation, flow rate measurements, electromagnetic pumps, Na leak detection, etc.

Electromagnetic pumps: basic principle

Laplace equation:

$$\vec{F} = I\,\vec{l} \wedge \vec{B}$$

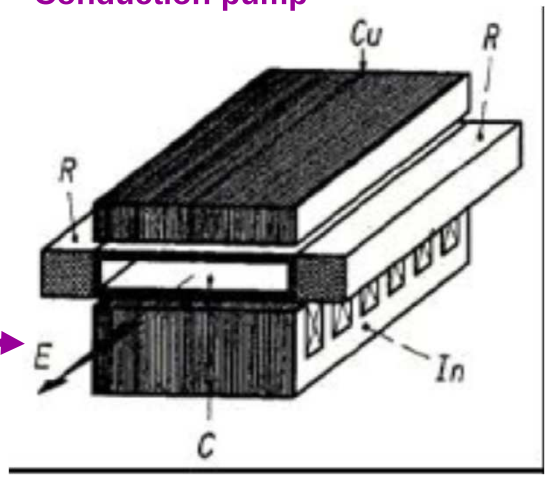




Conduction pump

Conduction pump: current is introduced by electrodes and conducting coolant (ie Na) circulates in the pipe, thanks to magnetic field.

Induction pump : current is generated directly in the liquid by induction (a variable electromagnetic field is generated in time and space in the liquid)

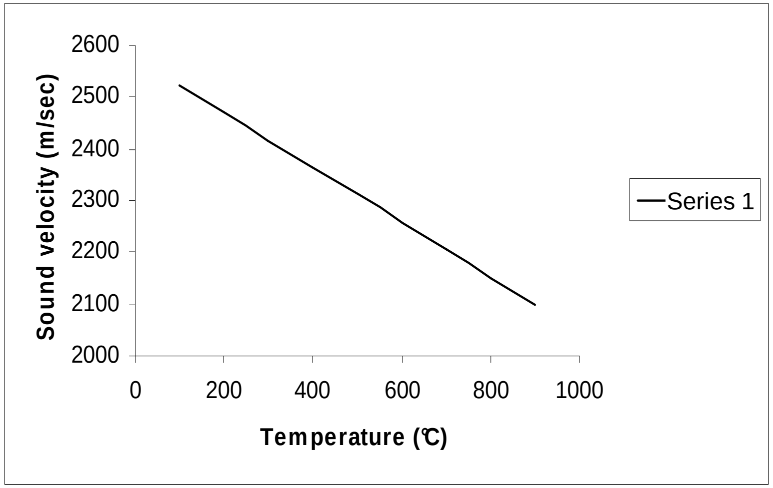


Induction pump

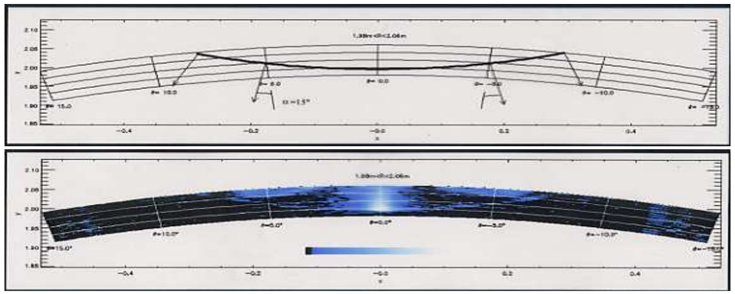
Properties of sodium

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 visualisation in sodium facilities, and for acoustic detection of events in Na

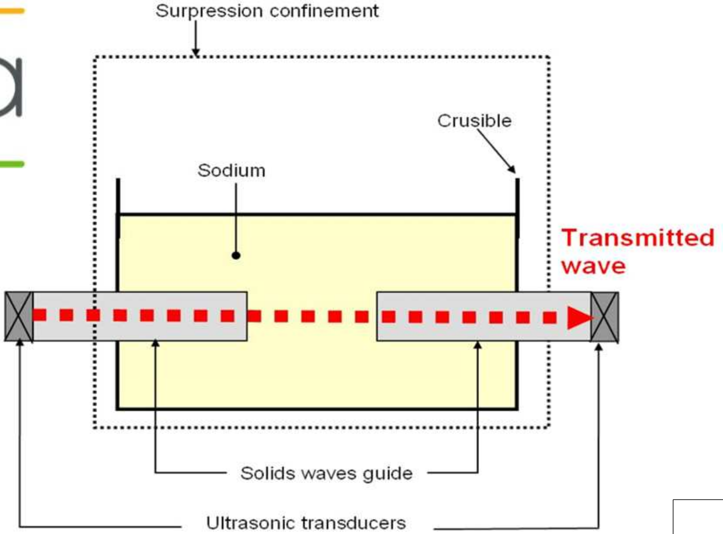


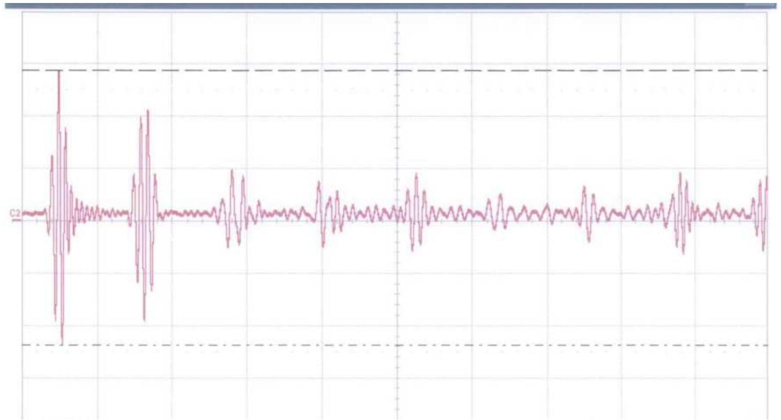
Wetting phenomena

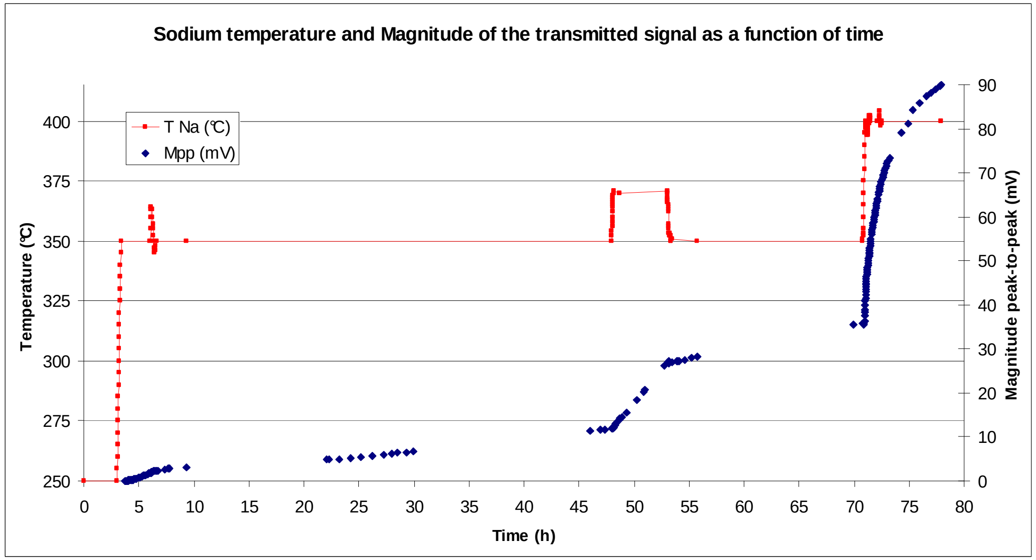
Wetting phenomena, which depend of gas adsorption, structural material oxidation,… are key interface phenomena between the coolant and the structural material. Therefore it is considered as a key factor with regards the following items:

- **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,…**

Acoustic coupling of ultrasonic transducers for SFR In-Service Inspection







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)
- Has low level of activation*

*But must be of "nuclear quality"

Radioactive isotopes resulting from neutron flux on ^{23}Na

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

Guaranteed impurity levels for nuclear-quality Na

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	

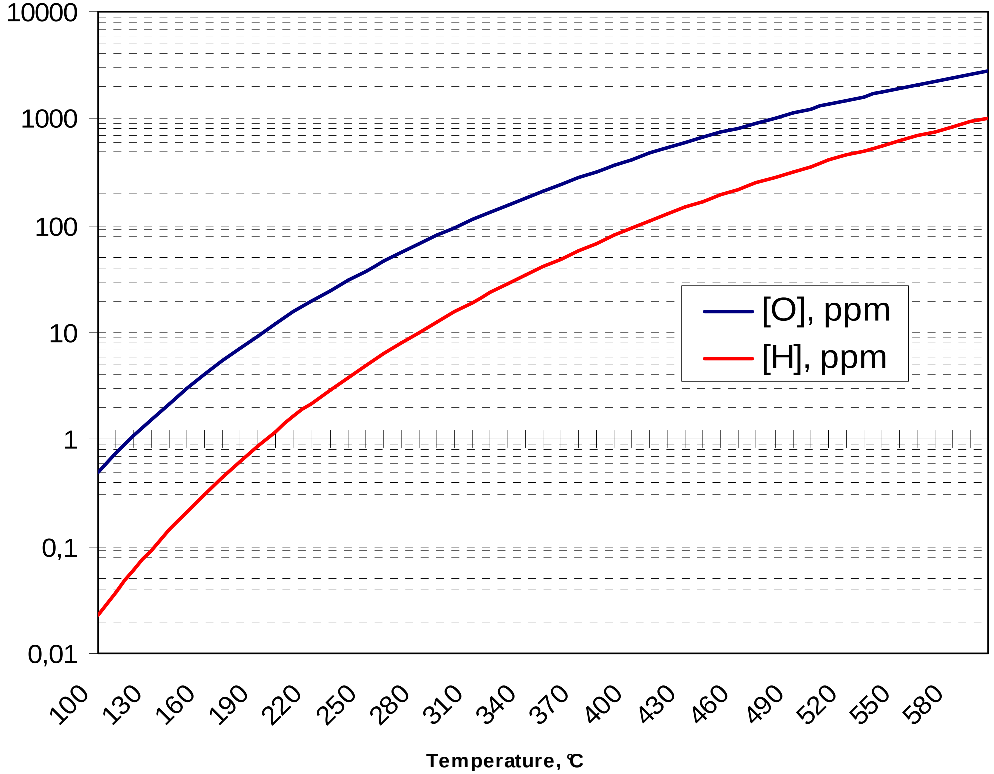
Concentration-temperature diagram

Wittingham solubility law

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

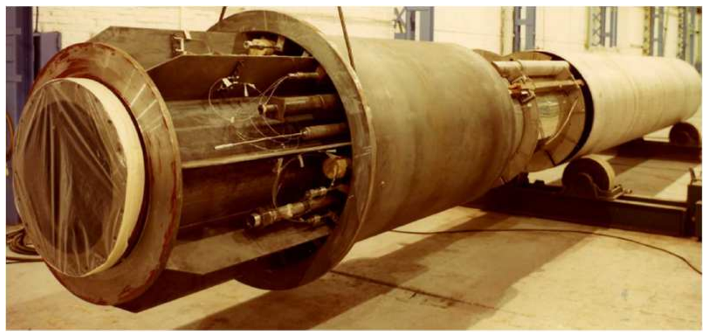
Noden solubility law

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



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"



Sodium's chemical affinity for oxygen 1/2

Self-ignition of sodium:

- Na in puddle: T around 140℃
- Dispersed Na: As soon as Na becomes liquid

➔ Sodium fires $2\,Na + \frac{1}{2}\,O_2 \rightarrow Na_2O$

and $2\,Na + O_2 \rightarrow Na_2O_2$

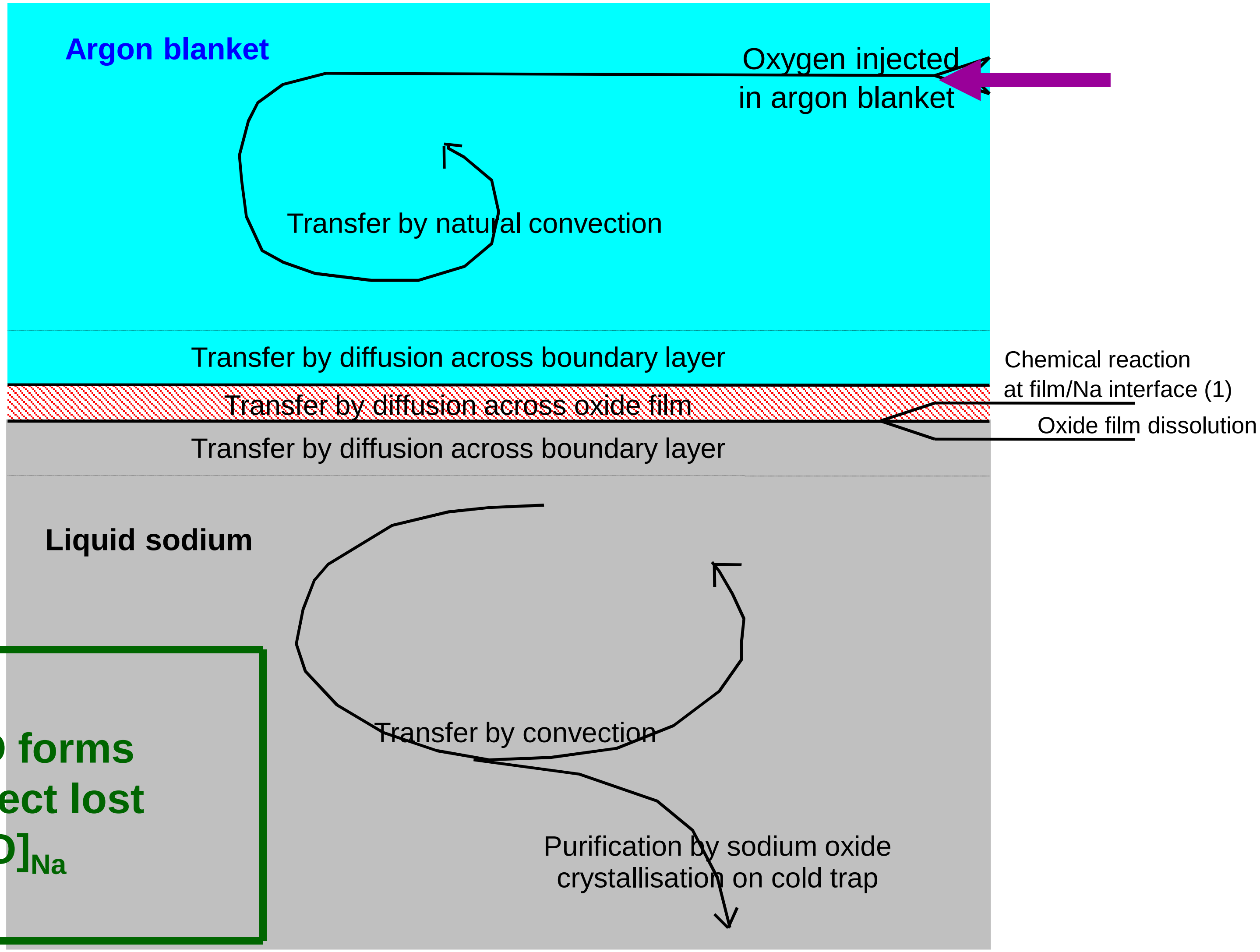
Low flames,
limited thermal radiation

Extinguished with powders (sodium carbonate, lithium carbonate and graphite)

Limited expansion by partial confinement

(collecting compartments)

Sodium’s chemical affinity for oxygen 2/2



P_O low:

No combustion

- At low T: Na_2O forms and "mirror" effect lost
- At high T: ↗ $[O]_{Na}$

Sodium's chemical affinity for water 1/2

$$Na + H_2O \rightarrow NaOH + \frac{1}{2} H_2 \quad + \Delta H$$

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

The reaction depends mainly on the type of contact:

Examples:

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

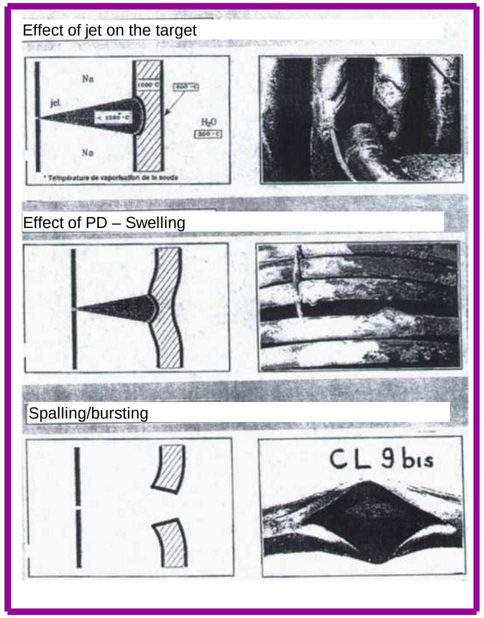
➔ *It all depends on the conditions and the objectives!*

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

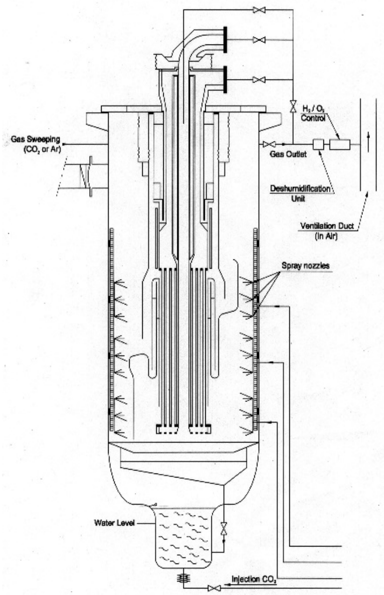
Sodium's chemical affinity for water 2/2

Laboratory

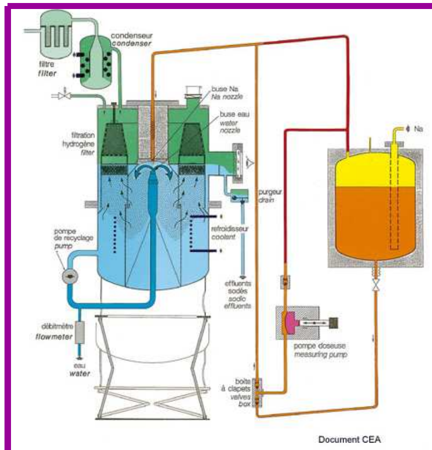
Steam generator



Cleaning pit (Phénix)



Na (Noah) treatment



Thank You for your attention !