DE LA RECHERCHE À L'INDUSTRIE

Séminaire

FLUIDES CALOPORTEURS POUR REACTEURS À NEUTRON RAPIDES

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Fondation Simone et Cino del Duca
10 rue Alfred de Vigny
Paris 8e

Sodium : Incidence du choix du sodium sur la conception et le fonctionnement du réacteur. Coexistence de l'eau et du sodium, contrôle préventif des fuites et options possibles pour les échangeurs de chaleur

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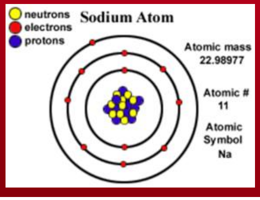
SELECTION CRITERIA FOR A HEAT COOLANT (PRELIMINARY THOUGHTS)

LES CRITÈRES DE CHOIX D'UN CALOPORTEUR (RÉFLEXIONS PRÉLIMINAIRES)



The selection of a heat coolant can only be the result of a compromise where must be listed the whole characteristics of properties

Thus the selection of heat coolant must gather a wide list of scientific domains :

- neutronic, thermodynamic, thermohydraulic, materials, metallurgy, technology, chemistry, chemical engineering, mechanic, and even toxicology and geology
- this must be crossed by experts dealing with safety aspects, economic aspects, strategic aspects

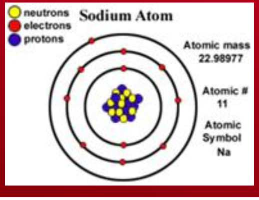
This choice is never a unique heat coolant but several according to the matrix of evaluation and the weight put on different parameters

It worth making regularly a round table of the potentiality of every heat coolant, because the sensibility regarding different items (and the quoting) can change with time but it must be kept in mind that it is a very low probability to discover the « Miracle heat coolant » (because the Mendeleev table is not expanding !)

Metallic sodium has oftenly been reviewed as a heat coolant for nuclear or solar or thermal conventional power. This presentation aims at recalling the criteria of choice, the recent study leading to replace sodium as heat coolant and recent progress in mitigation aspects (regarding interaction with air or with water).

Through this presentation the aim is to highlight how through time this compromise is permanently taken into consideration.

THE METALLIC SODIUM : POSITIVE ASPECTS AND CONSEQUENCES (1/3)



THE MOST FUNDAMENTAL ONE : DO NOT SLOW DOWN NEUTRONS => We can use it for fast spectrum reactors !

Sodium has a low cross section neutron capture

Activitation of sodium is rather limited under neutron flux

Tableau 2 – Réactions neutroniques avec le sodium 23

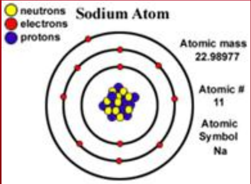
Réaction avec ^{23}Na	Produit formé	Période	Principaux rayonnements émis	Énergie (MeV)
(n, γ)	^{24}Na	15 h	γ γ	1,37 2,78
(n, p)	^{23}Ne	38 s	γ γ	0,44 1,65
(n, 2n)	^{22}Na	2,58 ans	γ	1,28
(n, α)	^{20}F	11 s	γ β	1,63 5,4

Like all liquid metals, sodium is an excellent heat transfer medium, with a large thermal inertia => positive impact on design & safety (Decay Heat removal systems)

	T [°C]	P [bar]	Masse volumique [$kg.m^{-3}$]	Cp [$J.kg^{-1}.K^{-1}$]	Viscosité dynamique [Pa.s]	Conductivité thermique λ [$W.m^{-1}.K^{-1}$]
Eau	300	155	727	5460	$0,09.10^{-3}$	0,6
Sodium	400	1	856	1278	$0,28.10^{-3}$	72
Plomb	400	1	10508	147	$2,25.10^{-3}$	17

These properties are necessary <u>but not sufficient</u> to definitely select sodium as a coolant

THE METALLIC SODIUM : POSITIVE ASPECTS AND CONSEQUENCES (2/3)



SOME OTHER VERY INTERESTING COMPLEMENTARY PROPERTIES :

Large liquid domain (from 98 to 883°C) =>

- no vessel pressurisation (positive impact on design and safety),
- significant margins to boiling (positive impact on safety)

Density and viscosity at 300°C close to water at 40°C =>

- no oversizing compared to water hydraulic design (impact on design)
- water can be widely used as simulant for TH studies (impact on R&D development)

Sodium is not toxic, no lethal, no carcinogenic =>

- No big healthy constrainsts regarding its daily use

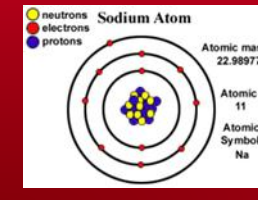
Sodium is a very common material =>

- No problem on its availability on earth (coming from NaCl/CaCl electrolysis), no risk of shortage for the coming centuries
- Sodium manufacturers are not « waiting for SFR » to produce yearly huge amount of Na (no manufacturing risks)

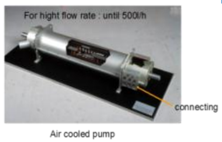
Industrial production of sodium (France)

These properties are positioning sodium as a good candidate for a coolant

THE METALLIC SODIUM : POSITIVE ASPECTS AND CONSEQUENCES (3/3)



Sodium has excellent electric and magnetic conductivities =>



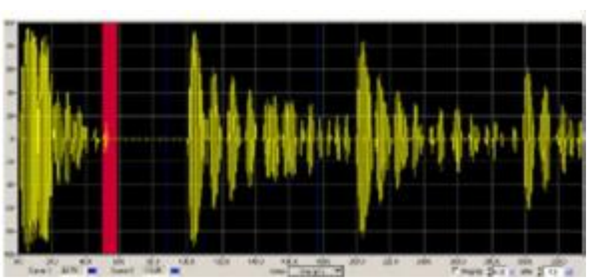
- With magnetic field : a specific technology can be used simplifying its use like Electro Magnetic Pump, sodium flowmeter (Eddy current flow meter), sodium level indicator.
- With electricity : sodium leak detector, sodium spark plug.

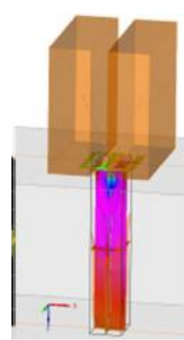
Sodium is not an agressive material in contact with steel if it is correctly purified on line =>

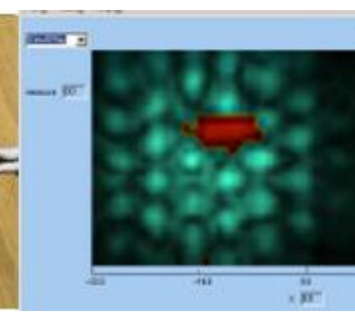
- Use of rather standard steels (316, 304, T91)
- No major risk of corrosion compared to other liquid metals (PbBi, Ga)

Sodium is well propagating sound =>

- Will be largely used in the ISI&R field thanks to Ultrasonic or EMAT sensors







These properties are positioning sodium as a very useful fluid for a coolant,

SODIUM : POSITIVE ASPECTS REGARDING SAFETY

- Large thermal inertia
- Diversified cold source
- Ability to perform natural convection
- A Pool type is by design limiting the risk of loss of 1^{ary} coolant inventory

	REP	RNRNa
M_{fluide} primaire (tonnes)	300	3300
Cp_{fluide} (J/Kg/C)	5200	1265
$M_{structures}$ (tonnes)	1700	3000
$Cp_{structures}$ (J/Kg/C)	650	650
M . Cp (MJ / °C)	2 700	6 100
ΔT (°C)	30	300
Δt (h)	**~ 1 h**	**~ 18 h**

Fluid

Structures

Margin to boiling

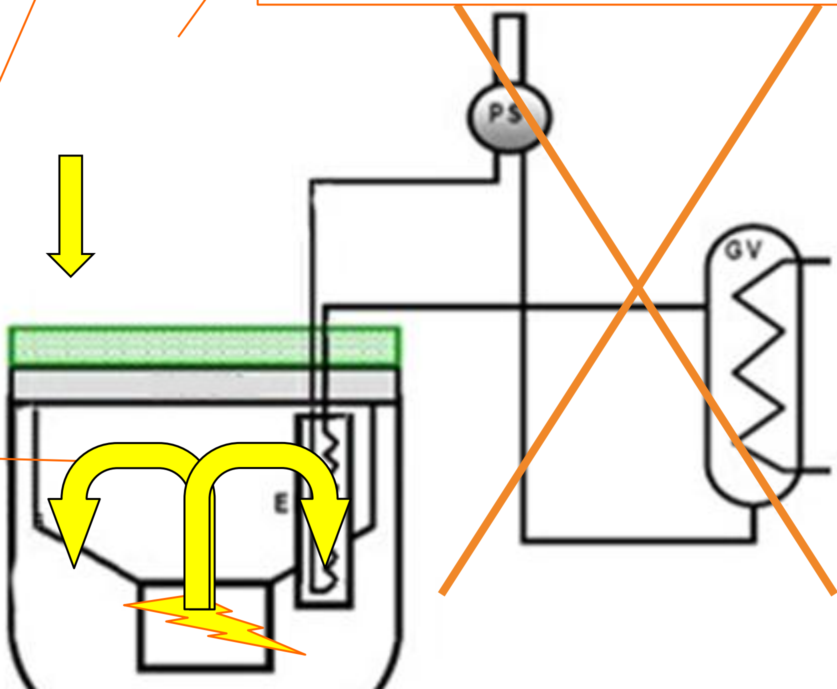
Heating at 1% PN

SODIUM : POSITIVE ASPECTS REGARDING SAFETY DECAY HEAT REMOVAL APPROACH IN A SFR

Thermosyphon in the DRACS circuit

Sodium – air HX

Cold source : atmosphere



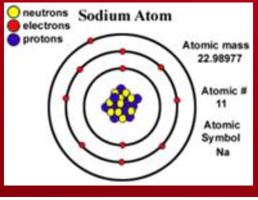
Primary natural Convection

Primary pumps inertia

In this whole sequence, the 1ary circuit temperature is increasing and in that situation the large thermal inertia, the margin to boiling plus the large volume of 1ary coolant in a pool configuration are very significant assets regarding safety demonstration (3300 tons of sodium in the Reactor Vessel).

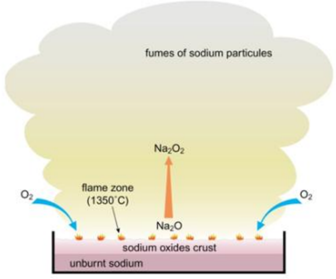
1. Loss of power = Loss of primary pumps, secondary circuits, reactor scram
2. The inertia of primary pumps is allowing the cooling during the first tens of seconds the fuel assembly residual power.
3. After the primary pump shut down, **natural convection** of the 1ary circuit is starting
4. Design of a **thermosyphon** in the decay heat removal circuit DRACS systems (Direct Reactor Auxiliary Cooling System)

THE METALLIC SODIUM : SIGNIFICANT DRAWBACKS OF SODIUM AND CONSEQUENCES (1/2)



Metallic sodium is one of the strongest chemical reducer

$$Na \rightarrow Na^+ + e^-$$



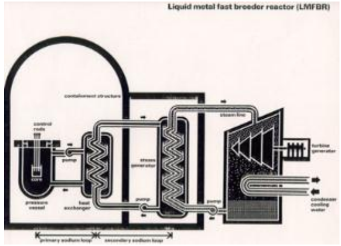
Mechanism of a sodium fire

As a consequence it will reacts very easily (vigorously) with all oxidants :

- most known from all : water and air

Consequences and impacts on reactor design are wide :

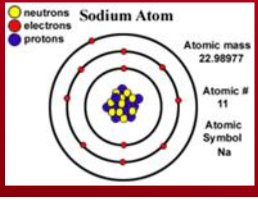
- use of secondary circuits to avoid of Na1ary/water reaction
- safety circuits design & containment
- large development of specific instrumentation & monitoring
- accurate surveillance of the hydrogen early detection in case of SGs
- and, need a lot of effort to communicate on this coolant for its social acceptation
  - many movies on the web are showing the "worst" of Na + water, or Na + air
  - any Na incident can lead to major consequences to all Na technology users (ALMERIA (large na fire), MONJU (Na leak), ILONA (large Na fire))



Some large sodium/water reactions leading to hydrogen explosion (experiments)

The protected operator can operate close to the sodium pool fire. The smoke is dense

THE METALLIC SODIUM : OTHER SIGNIFICANT DRAWBACKS OF SODIUM AND CONSEQUENCES (2/2)



Metallic sodium is opaque and liquid at 98°C => no visual testing, instrumentation must be used in T° (200°C or 550°C)

- ISI&R methodology must have to take into account these parameters
- A very significant effort have been carried on in that field to reach the same inspection level as PWRs. It is feasible thanks to the good US transmission

Metallic sodium must be kept hot to remain liquid => impact on design (trace heating on pipes + leak detectors)

Metallic sodium is not a material commonly used in industry or chemistry => need a specific teaching of operators with particuliar knowledge regarding safe handling, good practices, companionship

- Important role has to be played through knowledge transmission & preservation
- Sodium school (Natl & Intl) + IAEA specific role (Sodium Knowlegde Preservation Init)

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FINALLY HOW COULD WE POSITION SODIUM ?

Thus **METALLIC SODIUM** can been considered as the the most suitable heat coolant with some very significant assets regarding safety for the 1^{ary} system due its thermal properties.

The weakest point relies in the chemical reactivity. So a question raises :

Is it feasible to manage, to master to limit or even to suppress the effect of the sodium chemical reactivity ?

Can it be applied on 2^{ary} sodium circuits were the occurrence of a chemical reaction is the most probable (SWR, Na leaks)

This approach can be splitted in categories

- Cat. 1 : Physical elimination of sodium / water reaction.

- Cat. 2 : Practical exclusion of sodium / water reaction.

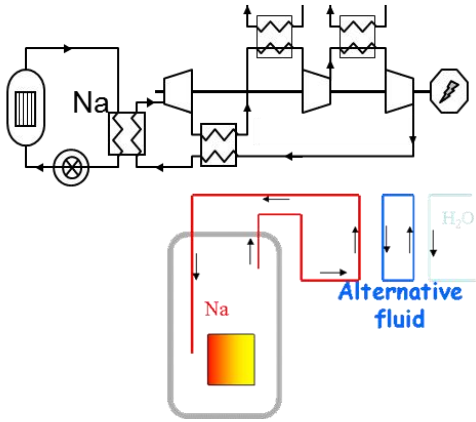
- Cat. 3 : Intrinsic limitation of the magnitude and consequences of the largest sodium / water reaction.

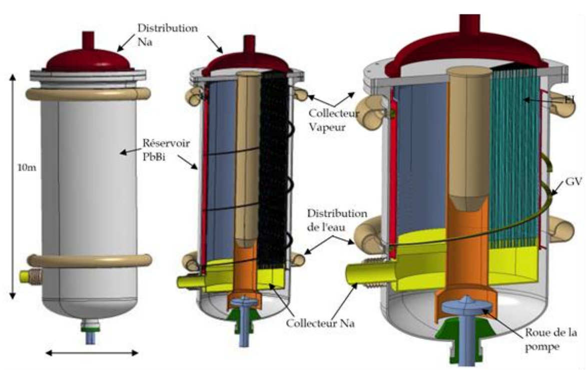
- Cat. 4 : Investment protection with respects to small leaks including : high manufacturing quality/ISI, early, robust and reliable leak detection, protective measures, simplification in the component replacement.

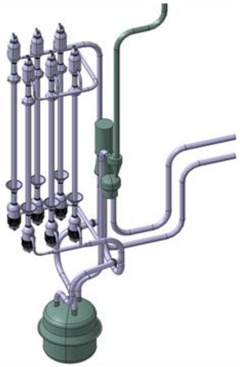
CONCEPTS IN RUPTURE

SEARCH FOR INNOVATIVE SYSTEMS

CONCEPTS IN IMPROVEMENT







THE APPROACH ON THE MITIGATION OF THE SODIUM/WATER REACTION (CAT. 1)

- Cat. 1 : Physical elimination of sodium / water reaction

  - Use of a gas brayton system instead of steam rankine cycle
    - Nitrogen cycle
    - SuperCritical CO_2 cycle

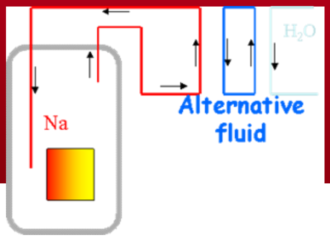
  - Replace sodium by another fluid in the secondary circuit
    - Search of an alternative fluid (2008-09 study)

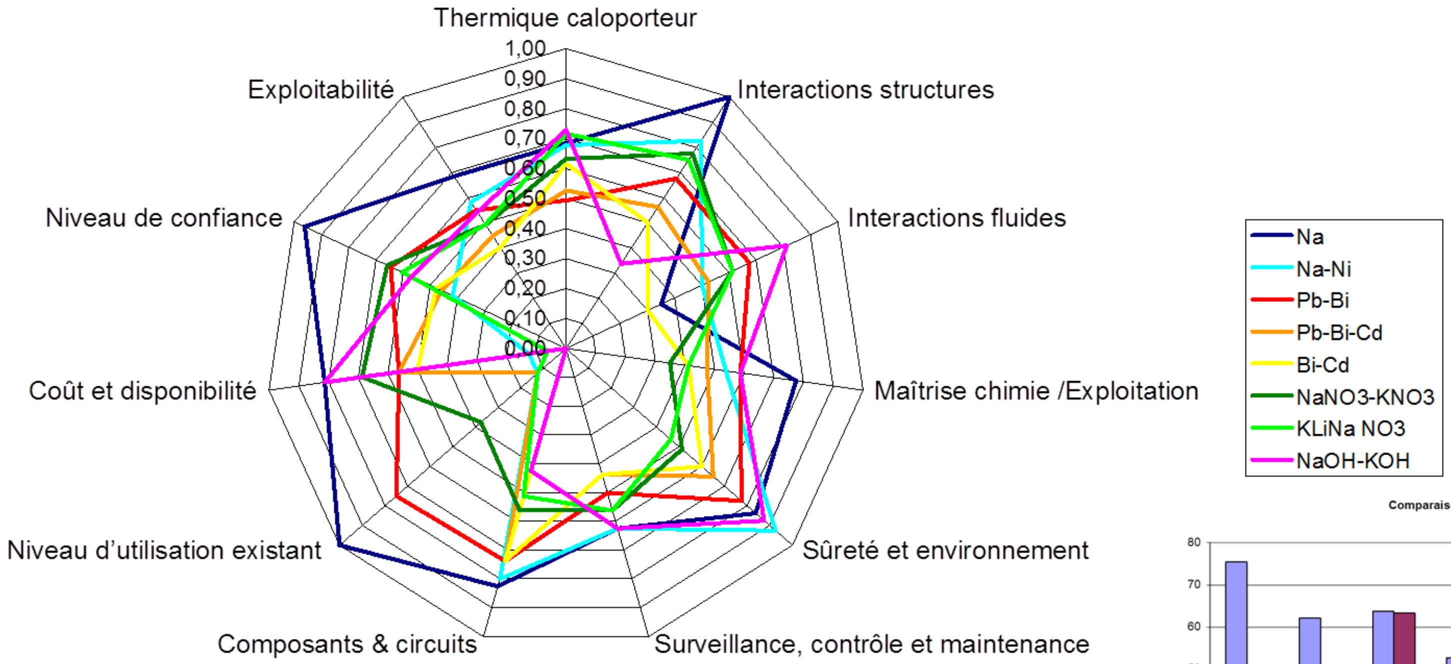
CONCEPTS IN RUPTURE

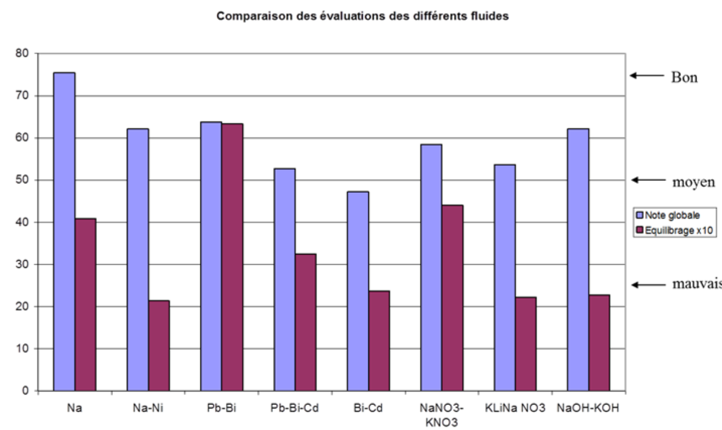
SEARCH FOR INNOVATIVE SYSTEMS

CONCEPTS IN IMPROVEMENT

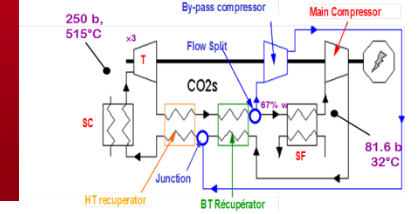
SEARCH OF AN ALTERNATIVE FLUID (2008/09 STUDY)







- **Na** coming first to all fluids in all domains except for fluid interaction (and even in fluid interaction, 2ary Na do not react with 1ary Na !!)
- **All the other fluids are presenting important weaknesses**
- **Pb-Bi is not showing major weakness**, but no big asset

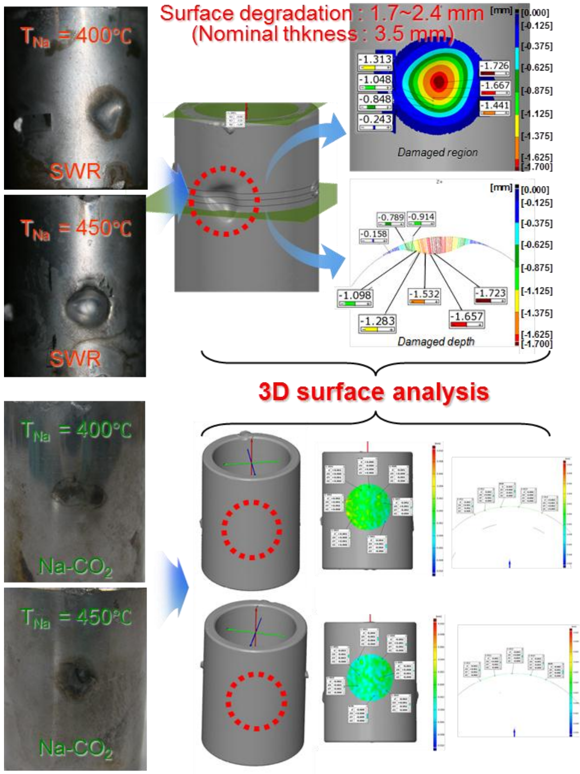


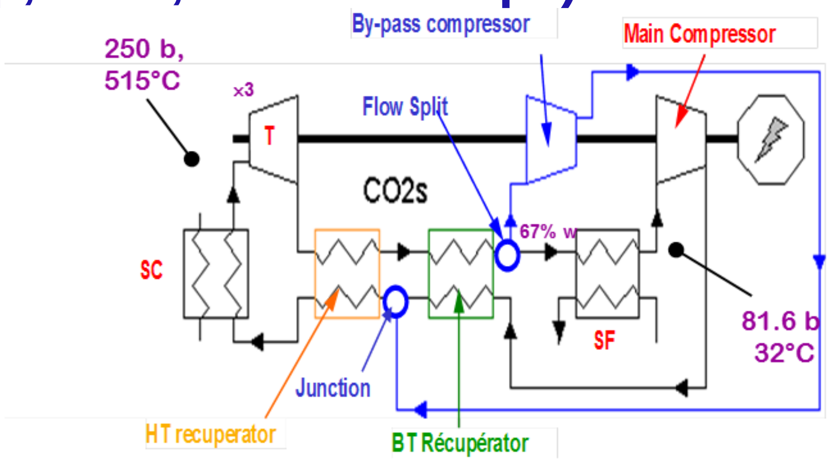
DESIGN OF A S-CO_2 CYCLE

With this system we replace Na / water reaction by Na / CO_2 reaction : less aggressive, with other difficult by-products (CO), but the gain in safety demonstration is significant (no wastage)

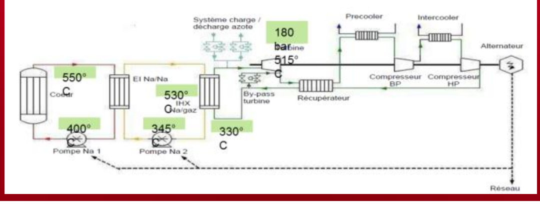
This system can achieve 42 to 44% yield. But the view for a correct maturity level is far

We try to extensively share the development of this cycle internationally through GENIV / SFR (USA, Jp, ROK, Fr and Europe)





DESIGN OF A N_2 CYCLE

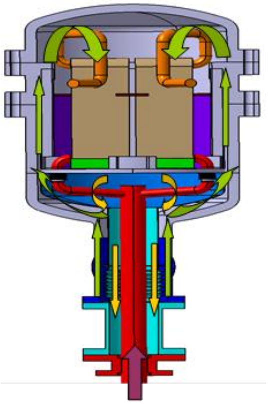


With this system Na / water reaction is *de facto* eliminated => the safety demonstration is simple

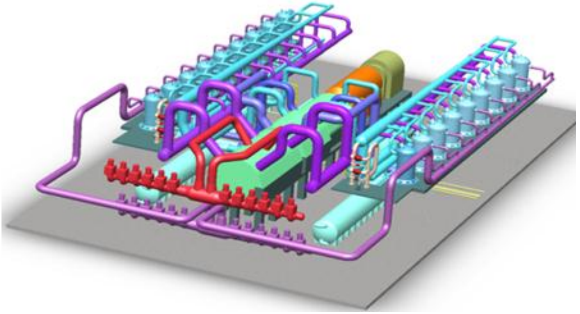
This system can achieve 37.5% to 38% yield (with realistic data).

Today we have demonstrated that there is no technological impossibilities but some technical challenges to overcome (Na / gas HX, codification, demonstration of this cycle at large scale)

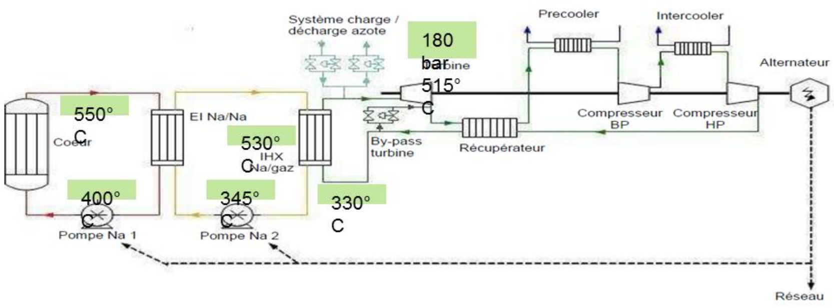
This cycle is extensively studied in the frame of ASTRID reactor



Sodium gas HX design



N_2 gas cycle plant layout



N2 gas 180 bar Brayton cycle

THE APPROACH ON THE MITIGATION OF THE SODIUM/WATER REACTION (CAT. 2)

Cat. 2 : Practical exclusion of sodium / water reaction.

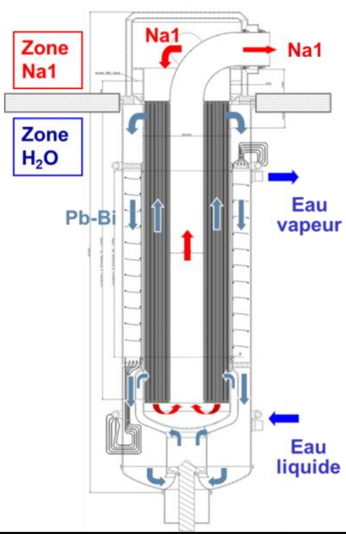
Use of a hybrid component where 1ary Na and steam are separated by a coupling fluid (PbBi) – Studied 2007-end 2009 then abandoned

But PbBi is giving other constraints (materials) and with this loop type config. we are loosing maturity level & safety assets of the pool design (DHR, loss of coolant,…)

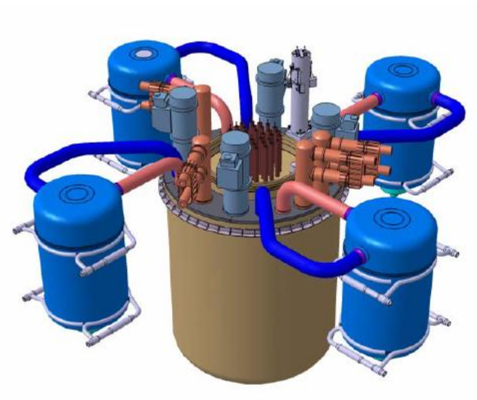
CONCEPTS IN RUPTURE

SEARCH FOR INNOVATIVE SYSTEMS

CONCEPTS IN IMPROVEMENT

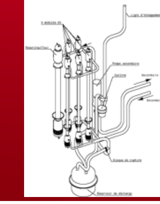


IHX/SG HYBRID component



IHX/SG HYBRID component

THE APPROACH ON THE MITIGATION OF THE SODIUM/WATER REACTION (CAT. 3 & 4)



Cat. 3 : Intrinsic limitation of the magnitude and consequences of the largest sodium / water reaction.

- **Design of modular steam generators which allows a very robust safety demonstration (no impact of the 1ary containment even if all the pipes of a SG are rupted in less that 1 sec)**

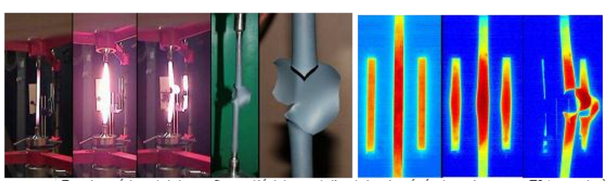
Cat. 4 : Improvements in :

- **Na / water knowledge and associated safety codes (with demonstration tests)**
- **H detection instrumentation (Indian Hmeter, acoustic)**
- **Complete overview of all SG designs (straight tubes, helicoidally tube, inverted SG, double-wall tube) + feedback analysis of Px & SPX**

CONCEPTS IN RUPTURE

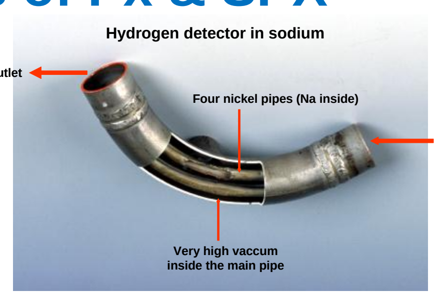
SEARCH FOR INNOVATIVE SYSTEMS

CONCEPTS IN IMPROVEMENT

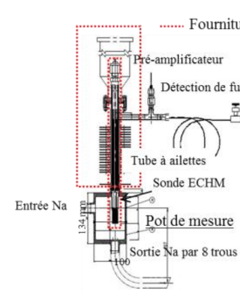


Essai expérimental de gonflement/éclatement d'un tube de générateur de vapeur T91 soumis à une surchauffe en palier à 1000°C (p = 150 bars).

Hydrogen detector in sodium



Hydrogren diffuses through the nickel membrane by permeation – Temperature > 400°C



Sonde ECHM

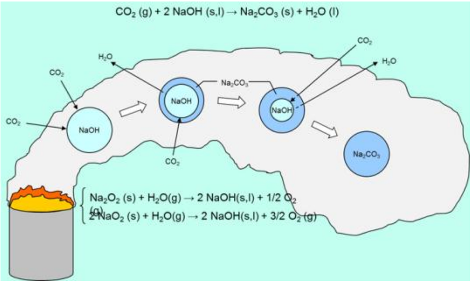
Ligne de l'ECHM en cours d'installation

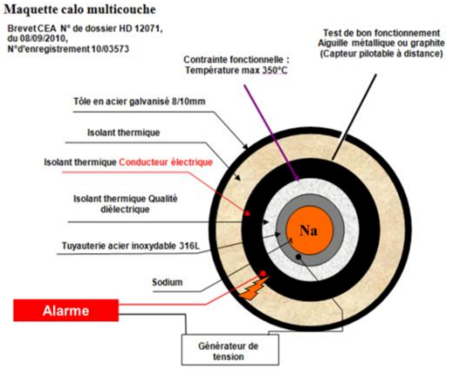
THE APPROACH ON THE MITIGATION OF THE SODIUM/AIR REACTION

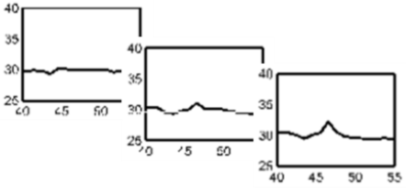

Positionnement du détecteur à perles en partie basse de la tuyauterie

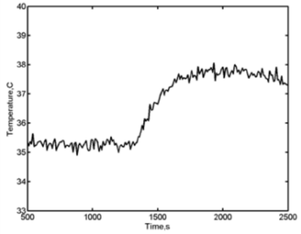
Several fields are under investigation to improve the safety related to sodium leak and sodium fire generation and aerosols releases :

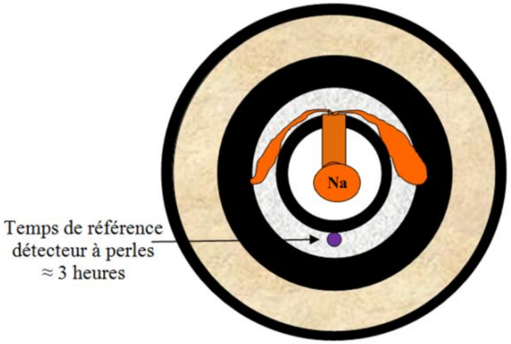
- **Take the feedback of the previous reactor to improve the already existing detection systems (reduce the number of false alarms)**
- **Search of improvement in heat insulator (multilayer heat insulator) or smoke detectors**
- **Search of innovative methods for detection with Raman optical fibers (better position of the leak)**
- **Definition of improved codes for aerosols release with exp. tests in support**











Thank you for your attention

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