GENERATION IV : Technological developments for Sodium, Gas, Lead, molten salt cooled reactors.

By Dr Christian Latgé,

CEA Cadarache, Nuclear Energy Division
Nuclear Technology Department,
13108 St. Paul Lez Durance (France)

Christian.latge@cea.fr
+33 4 42 25 44 71

CADARACHE

Content

French Nuclear policy
Generation IV concepts
Sodium cooled Fast Neutron reactors
Gas cooled Fast Neutron reactors
Other developments (Lead alloys, salts)

CADARACHE

French Nuclear policy

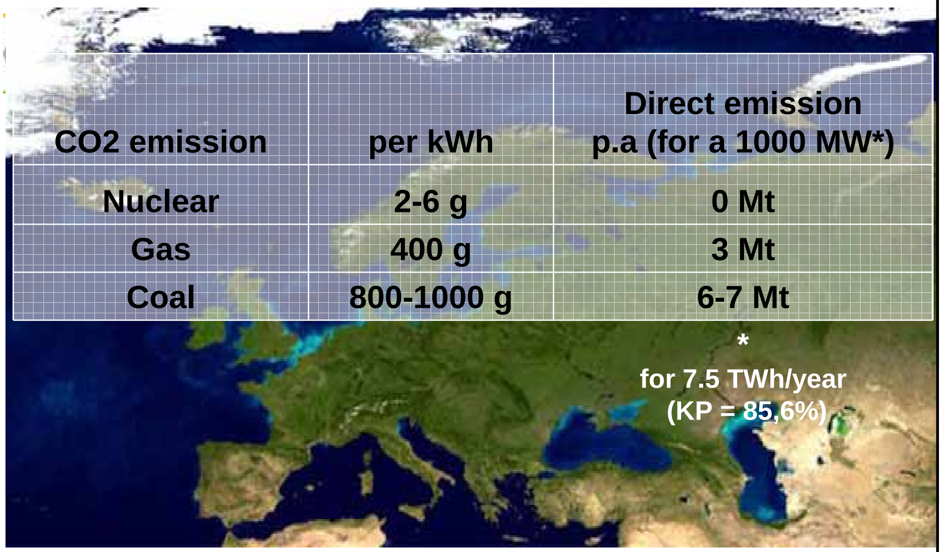
The climate challenge

Reduce CO_2 emissions

while

Producing more energy

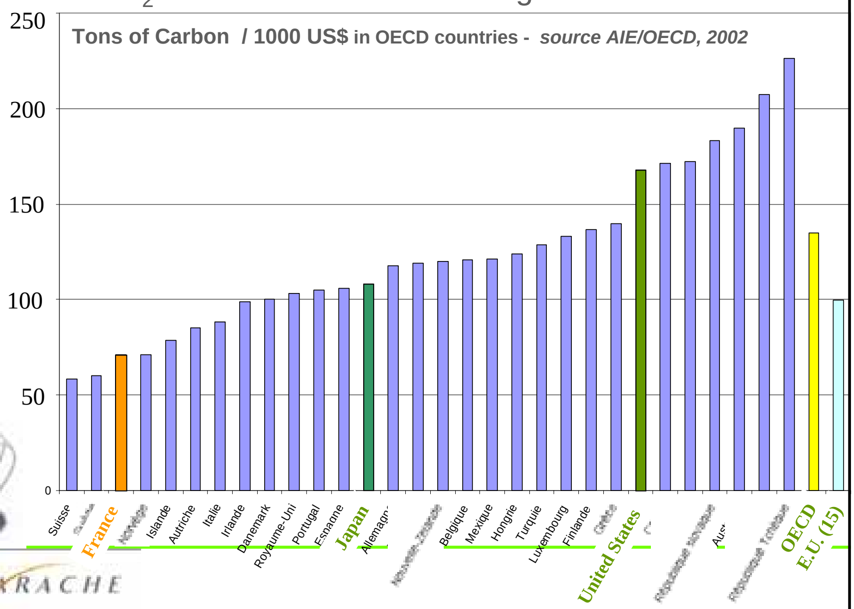
CO_2 emissions per energy source



CO2 emission	per kWh	Direct emission p.a (for a 1000 MW*)
Nuclear	2-6 g	0 Mt
Gas	400 g	3 Mt
Coal	800-1000 g	6-7 Mt

CADARACHE

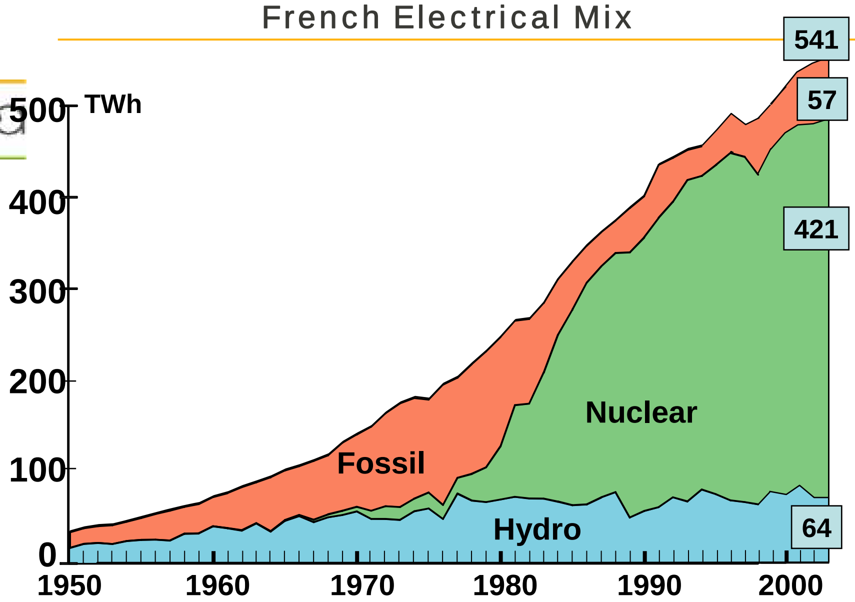
CO_2 emissions in 2002 relating to GDP



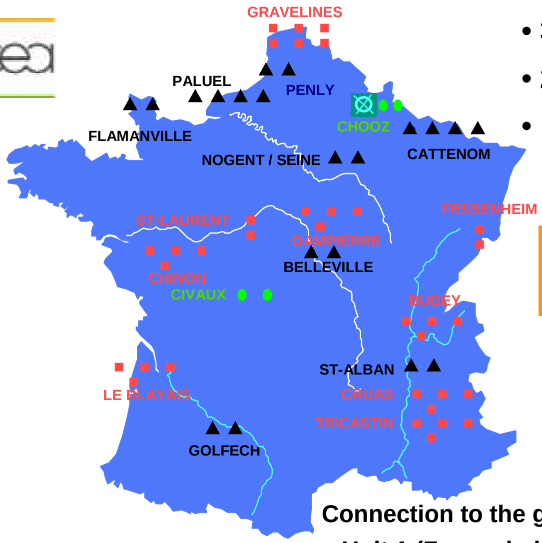
cea

CADARACHE

French Electrical Mix



The French Nuclear Program at a glance (1 / 2)



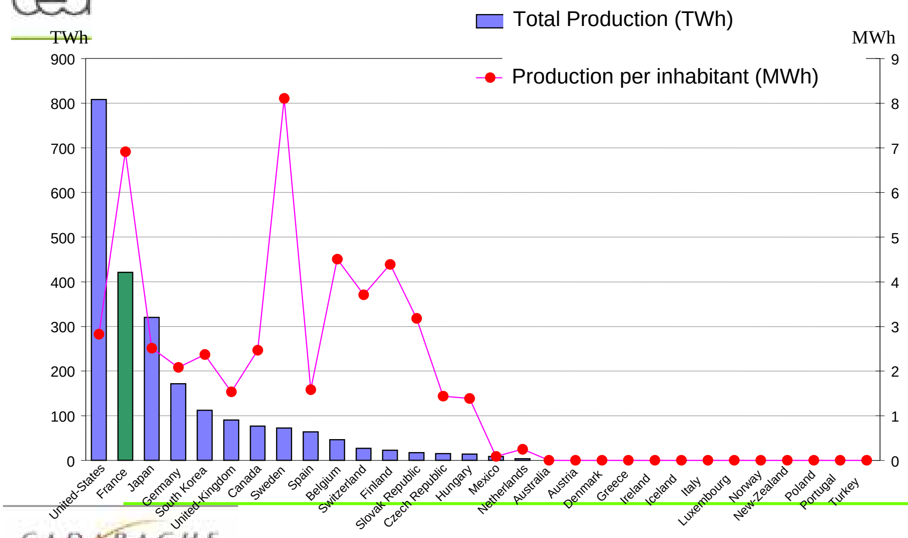
- 34 900 MWe units ■
- 20 1300 MWe units ▲
- 4 1500 MWe units ●

58 units
63184 MWe installed

Connection to the grid :

- **Unit 1 (Fessenheim 1) : April 1977**
- **Unit 58 (Civaux 2) : Décember 1999**

France is the second nuclear electricity producer in the OECD countries



(For 2001, source: IEA)

Today : Main features of the French energy status

- Energy import cost of 22,7 billions Euros in 2003, accounting for 1,4 % of French GDP (versus 5 % in the 80's) ;
- The rate of energy independence has considerably increased, from 26 % in 1973 to 50 % today.
- The fourth highest energy consumer in the OECD countries, but only ranked 27th for CO_2 emissions (2002, AIE).
- A competitive electricity supply for companies and households, characterised by **steady prices**.
- A self-sufficient national electricity production allowing France to be the **first electricity exporter in the world**.

The French nuclear policy : the main actors

Definition of the French nuclear policy : DGEMP (Direction Générale de l'Énergie et des Matières Premières, General Directorate for Energy and Raw Materials)

Research and development in the nuclear field : CEA (Commissariat à l'Énergie Atomique, Atomic Energy Commissariat), IRSN (Institut de Radioprotection et de Sûreté Nucléaire, Institute for Radiological Protection and Nuclear Safety)

Companies : AREVA (Framatome-ANP, COGEMA), Alstom

Utilities : EDF

Waste management : ANDRA (Agence Nationale pour la gestion des Déchets Radioactifs, National Agency for Radioactive Waste Management)

Safety control : DGSNR (Directorate General for Nuclear Safety and Radiation protection) (expert : IRSN)

The French National Debate on Energy

2003 : « National Debate on Energy », launched by the Ministry of Industry

2004 : First draft of the Energy Orientation Bill, adopted by the Council of Ministers on May 2004 and adopted on second reading by the National Assembly on the 29th of March 2005 and will be put to the Senate in May 2005

Reaffirms the necessity of nuclear power, authorizes EDF to build a first EPR and encourages R&D for the future nuclear systems.

Scenario for the renewal of French power reactors based on Gen III reactors (EPR) deployment with a transition to Gen IV fast neutrons systems as from 2040

The 3 challenges structuring French energy policy

First challenge : reducing our green house contribution by dividing by 4 our green house gases emissions by 2050

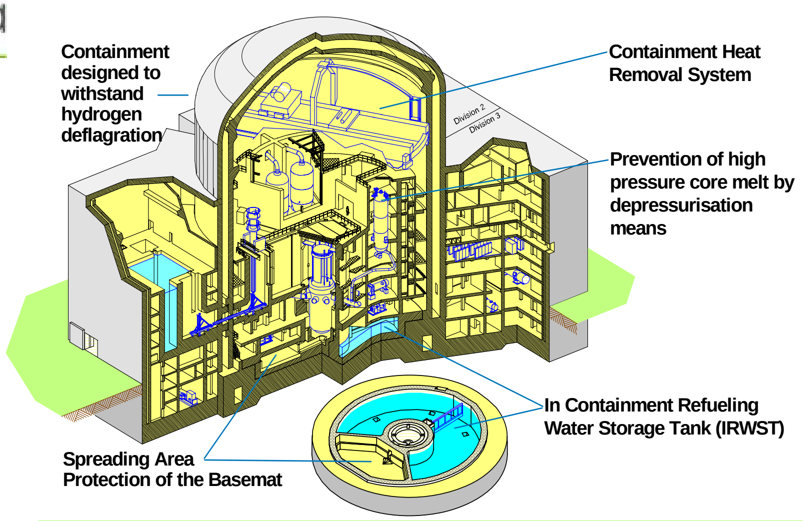
Second challenge : answering the gas and oil prices growing due to the increase of the global demand in the framework of ressources run out before the end of the century

Third challenge : facing the anticipated renewal of our nuclear fleet

- **2015 - 2020 :** beginning of current fleet renewal building based on evolved and mature PWR (EPR).
- **beyond (> 2030 - 2040 ?),** completing the renewal in using Generation IV reactors concept.

CADARACHE

EPR: a matured concept, based on experience feed-back of current PWRs

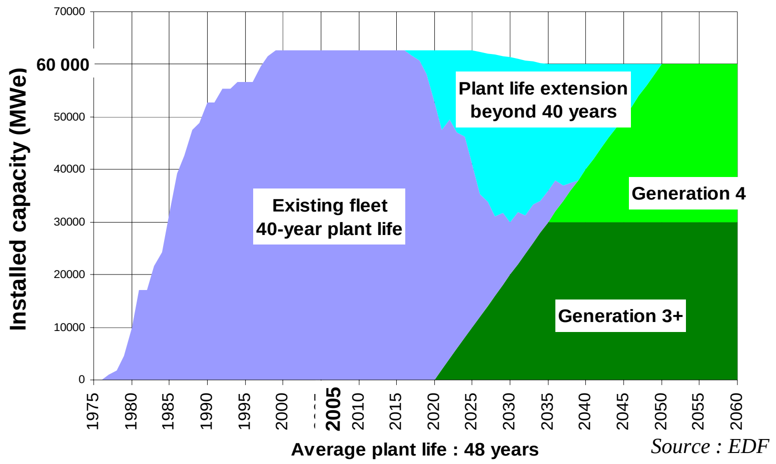


CADARACHE

Scenario for the renewal of French power reactors

Major role of LWRs over the 21st century

~2040 : Transition from PWRs to Gen IV Fast neutron systems



CADARACHE

R&D Strategy of France for Future Nuclear Energy Systems

Approved by the French Government in March 2005

1 – Development of Fast Reactors with closed fuel cycles, along 2 tracks:

- Sodium Fast Reactor (SFR)
- Gas Fast Reactor (GFR)
- New processes for spent fuel treatment and recycling

→ ***Industrial deployment around 2040***

2 –Hydrogen production and very high temperature process heat supply to the industry

- Very High Temperature Reactor (VHTR)
- Water splitting processes

3 – Innovations for LWRs ***(Fuel, Systems…)***

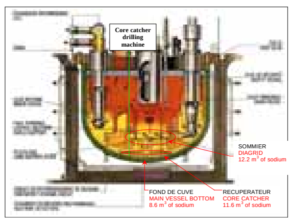
CADARACHE

GENERATION IV Forum

Gen IV : paves the way for a sustainable nuclear energy

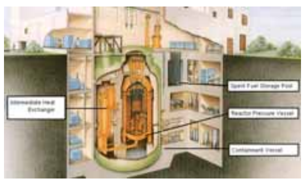
Ensure energy needs are met in the long term without emitting greenhouse gases

- **Gradual improvements**
  - Economic competitiveness
  - Safety and reliability

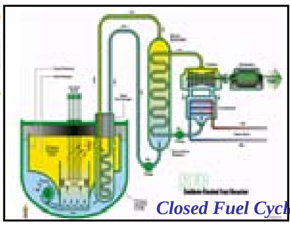


- **Significant steps forward:**
  - Saving of natural resources
  - Waste minimization
  - Security: non-proliferation, physical protection

- **An opening to other applications:**
  - High temperature heat for industry
  - Hydrogen vector
  - Drinking water

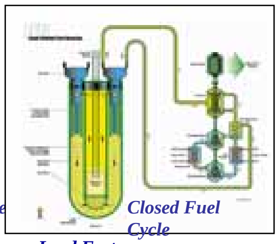


6 Innovative concepts with technological breakthroughs



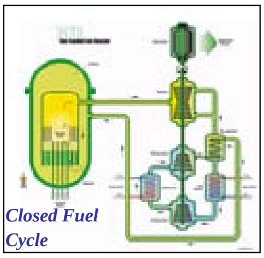
Closed Fuel Cycle

Sodium Fast reactor



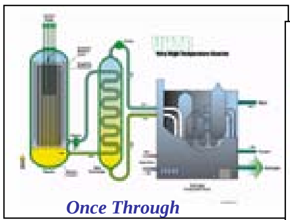
Closed Fuel Cycle

Lead Fast Reactor



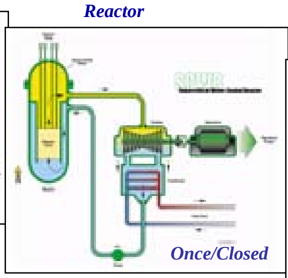
Closed Fuel Cycle

Gas Fast Reactor



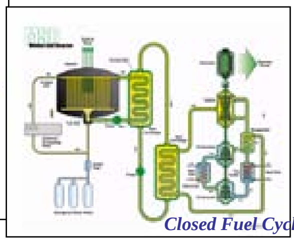
Once Through

Very High Temperature Reactor



Once/Closed

Supercritical Water Reactor



Closed Fuel Cycle

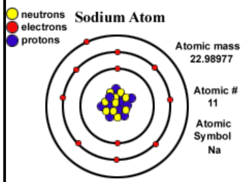
Molten Salt Reactor

Sodium cooled Fast Neutron reactors

Introduction to sodium :

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

قَلْوِيّ



	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						

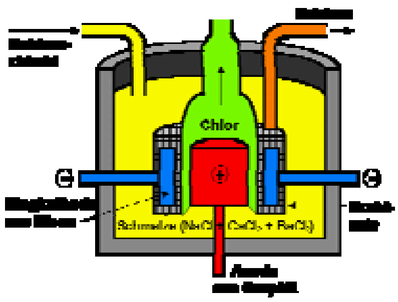
6	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
7	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Sodium manufacturing

→

Produced by electrolysis of eutectic NaCL/$CaCl_2$

Electrolysis battery in Métaux Spéciaux (France)



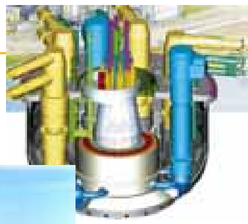
Sodium properties

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,…

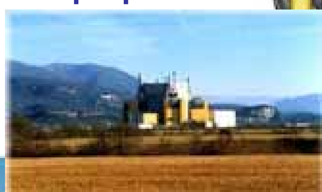
But high reactivity

From Rapsodie to EFR

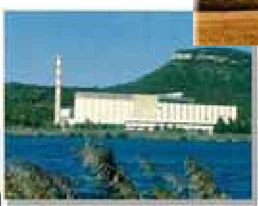


EFR

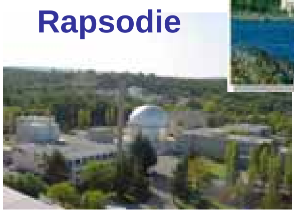
Superphenix



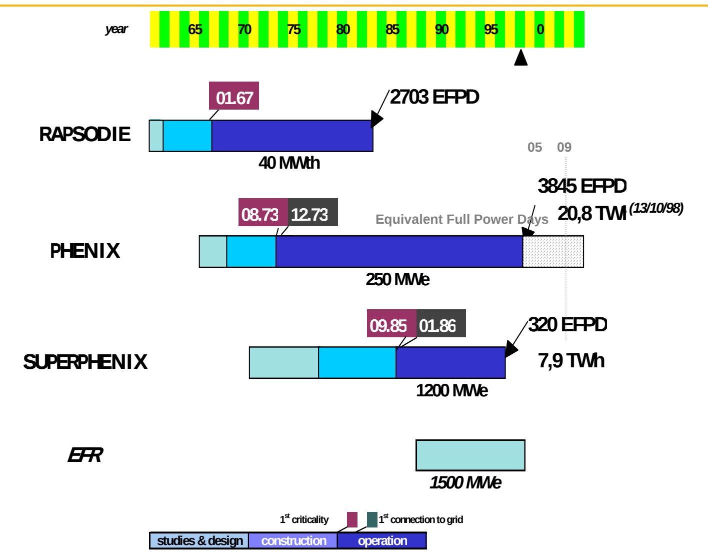
Phenix



Rapsodie

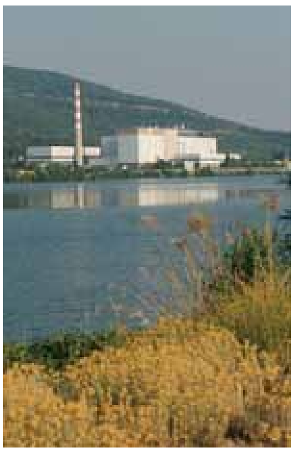


Fast reactors in France - Main data and milestones



CADARACHE

PHENIX Plant data



Objectives:

- Initially, demonstration of Sodium Cooled FBR technology for extrapolation to commercial size reactor
- After 1992, role of PHENIX as irradiation facility emphasised
- Maintain CEA expertise on sodium cooled FBR, one of the six concepts of future system selected by Generation IV forum

Nominal Power: 563 MWth (250 MWe)

- Since 1993 power limited to 350 MWth (145 MWe), on two secondary loop operation

Key dates :

- First criticality: 31st August 1973
- First connection to the grid: 13th December 1973
- Commercial operation: 14th July 1974

Total number of Equivalent Full Power Days: 3860

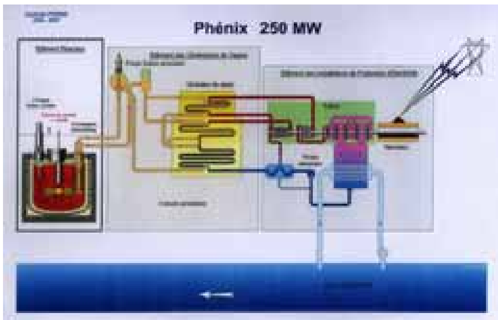
Total operating hours: 100 000 h (*reached 1/9/2003*)

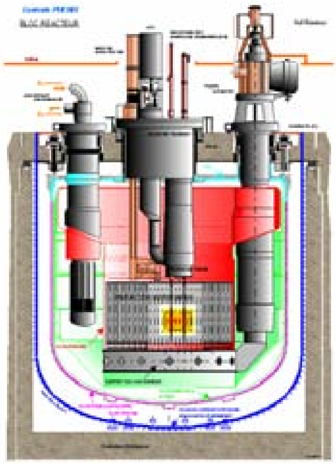
Gross electrical output: 22 424 087 MWh

Total staff : 280 people coming from CEA (about 80%) and EDF (about 20%)

CADARACHE

General design of the plant





Pool type primary circuit

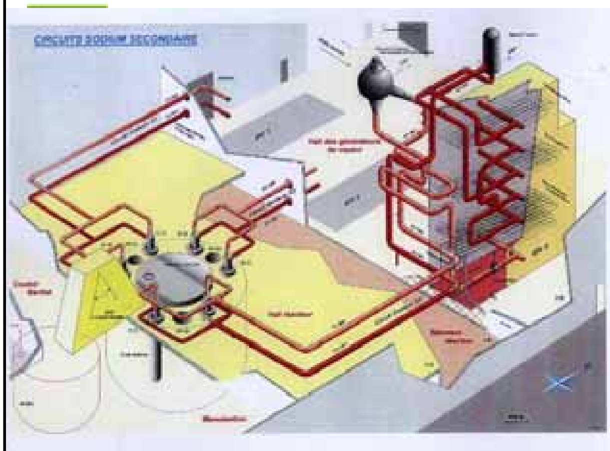
3 primary pumps

6 intermediate heat exchangers

temperatures : 400 - 560°C

Intermediate loops

- •3 secondary sodium loops
- •350°C - 550°C

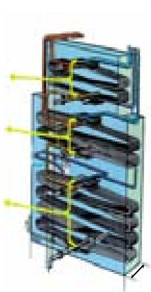


One steam generator per secondary circuit

3 modular stages :

- –evaporator (24 modules)
- –superheater (12 modules)
- –reheater (12 modules)

steam : 512°C, 16,3 MPa



Some incidents

sodium leaks

- from a few grams to twenty kilograms
- most of the leaks located of on welds of secondary loops and auxiliary circuits
- leak satisfactorily detected in an early stage (significant corrosion due to delayed detection on one occasion: lead to improvement of detection system)

5 small sodium-water reactions (4 in 1982 – 1983 and one in 2003)

- Efficiency of the hydrogen detection
- replacement of the modules
- Modification of the procedures

4 negative reactivity trips in 1989-1990

- Extensive studies and testing to identify the cause of the transient
- International Expert committee : 200 Man.Year - 500 documents
- Examination of all possible phenomena
- Safety analysis conclusions: no safety consequences for the reactor

CADARACHE

44

LIFETIME EXTENSION PROGRAMME

Core and primary circuit Safety up-grading

- Installation of one safety control rod
- SARA fast acquisition system
- Instrument devices in the hot and cold pools

Seismic reinforcement of steam generator building

Protection of the SG Building against sodium fires (Resistance to the reference earthquake, sodium fire of 1100°C degrees for 30 ‘)

Re-evaluation of damages to the block structures

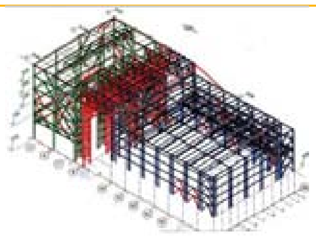
Major component repairs and replacements :

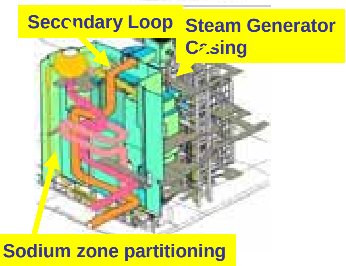
Repair of 321 steel components subject to delayed reheat cracking

- secondary loop hot legs
- SGU sodium headers
- SGU modules

Manufacturing of three new IHX

Primary and secondary pumps refurbishing,….





4 years of work and of requalification.

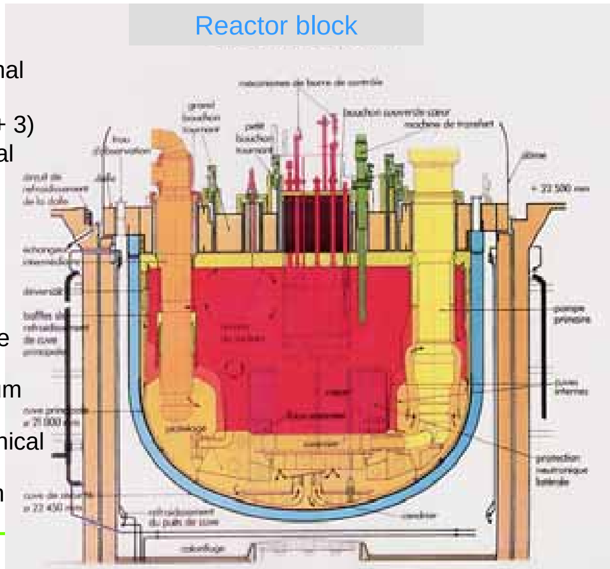
160 million € of studies and renovation works.

4000 contractors from 350 companies

CADARACHE

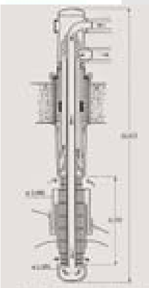
Superphénix plant brief description 1/2

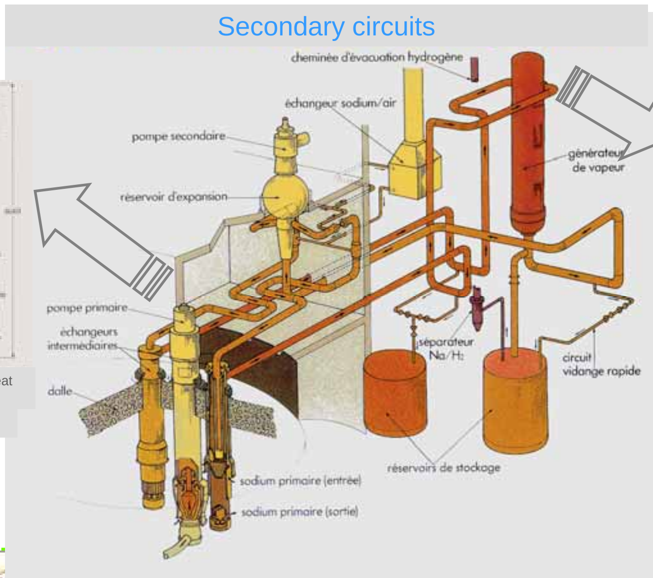
- 1 200 MWe (3 000 MWth). 2 turbines
- Pool type : ∅21 m primary vessel
- 364 $UPuO_2$ hexagonal fuel elements
- 24 control rods (21 + 3)
- 4 primary mechanical Na pumps
- 8 straigh tube heat exchangers
- 2 integrated Na purification units
- 2 rotating plugs
- Core catcher (severe accident)
- 4 intermediate sodium circuits
- 4 secondary mechanical Na pumps
- 4 helicoil tube steam generator units

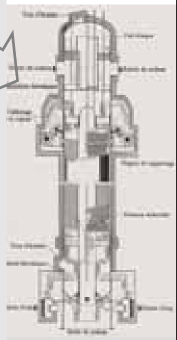


CADARACHE

Superphénix plant brief description 2/2





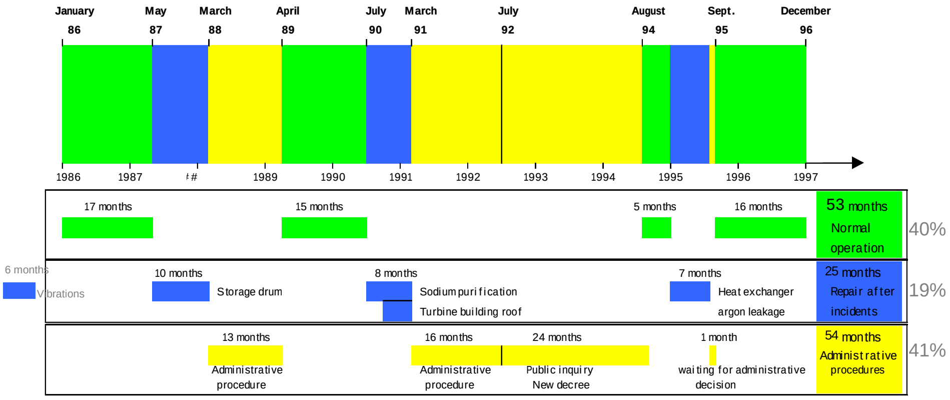


CADARACHE

2. Superphénix general operation balance

Super Phénix operation

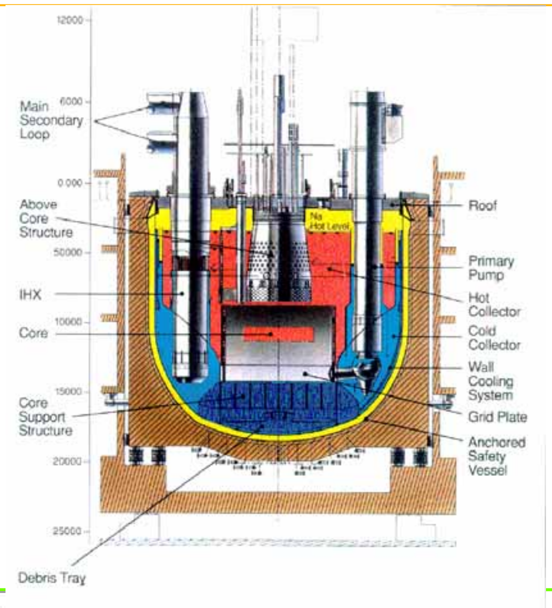
OPERATION BALANCE of CREYS-MALVILLE NPP



Output during operation period 7.9 TWh

CADARACHE

EFR



CADARACHE

Main objectives for the Sodium Fast Reactors 1/2

- improvement of safety :
  - severe accidents have to be mastered: potential initiators of accidents and subsequent energy release. Mainly : Core safety and notably problems associated with criticality control (void-effect, re-criticality)
  - specific risks due to Na must to be minimized (or avoided): Na fire, Na-water interaction.
- improvement of competitiveness in order to maintain the attractivity with regards to the existing operated reactors.
  - Reduce cost of investment by design simplification and improvement of efficiency : energy conversion, burn-up, systems&components reliability and reactor availability,…)
  - Improvement of In-service inspection and repair,
  - Life extension up to 60 years.
- advanced materials for structures and fuel
- saving of natural ressources : U

CADARACHE

Main objectives for the Sodium Fast Reactors 2/2

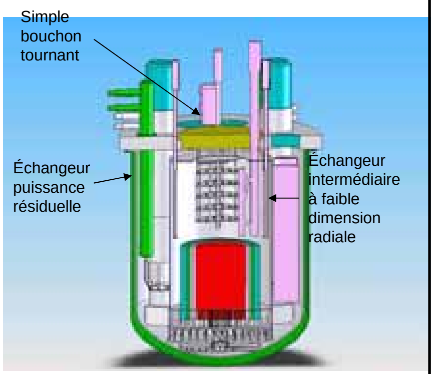
- non proliferation : systems which regenerates plutonium without lateral fertile fuel assemblies.
- waste management by transmutation and waste minimization (for irradiated fuel reprocessing and reactor operation and maintenance)
- minimization of environmental impact : liquid and gaseous effluents, operators dosimetry, decommissioning strategy,…
- definition of 3 to 4 concepts for a sodium cooled reactor :
  - to illustrate proposed innovations within a global design,
  - to evaluate resulting economics and associated risks,
  - to best target the most promising R&D paths,
  - to contribute to making a project come true.

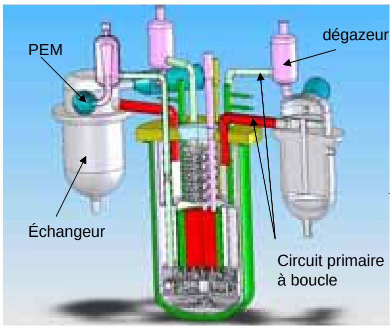
CADARACHE

Innovative SFR Sketches

Large pool type

1500 MWe optimized size





Modular concept with gas conversion system

Improvement of safety:

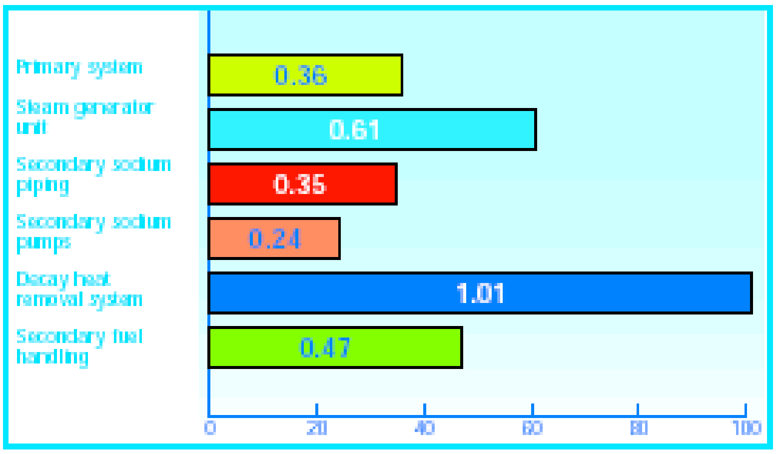
- **Reactor designed in order to reduce strongly the probability of core melting; nevertheless a reference accident involving a core melting event will be postulated, investigated and demonstrated as mastered.**
- **Protection against plane shut-down,…**
- **Elimination of environmental consequences outside the nuclear plant ; necessity to focus on incidents involving Na, (sodium leaks, release) :**
  - Sodium pipes and/or systems inertization
  - Sodium leak control systems : reliability improvement
  - Optimized In Service Inspection strategy
  - Efficient, safe and fast Repair operations.
  - Minimization of Liquid&gaseous effluent releases (« zero » release?),…

EFR : cost distribution

On site workshop	2,7
Reactor assembly structures	19,4
secondary handling	5,7
secondary circuit	9,0
DRACS	3,7
SGU	11,0
primary auxiliary system	48,6
	100,0

CADARACHE

EFR/SPX cost comparison (steel weight)



EFR vs SPX1 Comparison of the specific steel weight in t/kWe

CADARACHE

Improvement of competitiveness

Reduced cost by :

- design simplification :
  - intermediate loops : simplification, shortening or suppression,
  - ancillary systems (for cover gas control, sodium purification, measurements,…) : minimization of the number of circuits and/or simplification, after reassessment of functional specifications and operation feedback analysis.
  - fuel assemblies handling systems, after reassessment of functional specifications and operation feedback analysis.
  - …
- improvement of efficiency :
  - energy conversion
  - high burn-up,
- reactor availability increased by : systems&components reliability
  - improvement of systems&components reliability
  - reduction of fuel assemblies handling duration,…
- extension of life duration : up to 60 years.

CADARACHE

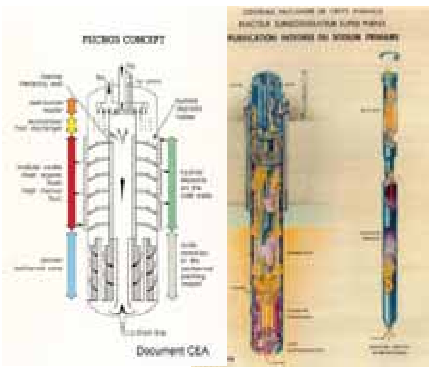
Ancillary systems : ex : Purification systems

- **Cost reduction is possible, thanks to :**
  - reassessment of functional specifications
  - feedback from reactors in operation and design studies (EFR,…)
- **Purification systems:**

– primary vessel:
  - SPX : 2 integrated cold traps
  - EFR : 2 external cold traps

– Intermédiate loops : 1 purification loop for each intermediate loop

– Ancillary Na systems : SPX and EFR : purification loop for each intermediate loop



CADARACHE

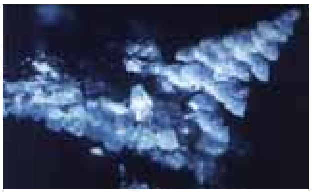
Primary purification system :

Requirement for [O] :

Two main options :

[O] < 3 ppm (<5ppm during 1 month) (strategy of « clean » Na) or

[O] < X ppm (X>3 : as exemple 10 ppm) (UK)



Consequences :

- improvement of tribological behaviour but :
- increase of dosimetry (due to activated corrosion products), increased radionuclides inventory in cold traps, increase of liquid effluents (due to cleaning/decontamination).

Corrosion rate depends on mainly [O], primary sodium and fuel pin temperatures, sodium velocity

→ necessity to compare PX and PFR feedback.

→ necessity to model oxygen behaviour and compare corrosion and purification kinetics: effect of reactor size.

→ options for purification systems :

→ continuous or non-continuous operation. Impact of : specification on [O], incidental pollution, tritium balance of the reactor, defueling?)

→ cold trap always in situ or removable

→ cold trap with cartridge or not (makes cold trap treatment easiest or not, and consequences on the size of the cold trap and building allocated to this system.

→ Other specific concepts

CADARACHE

Intermediate purification system

Case : Rankine Cycle (H_2O) :

Specifications on :

- nominal residual [H] : with regards to efficient fast water-sodium detection in SGU

- tritium release (EFR : difficulty to fulfill requirements due to choice of ferritic steel Steam Generator : aqueous corrosion increased→ continuous H source increased)

→ H trapping in intermediate cold traps allows to trap also tritium and to control release.

- incidental purification campaign : anticipated Na2O and NaH inventory.

→ options for purification systems :

→ continuous or non-continuous operation ? Impact of : specification on [H], incidental pollution, tritium balance of the reactor,)

→ cold trap always in situ or removable

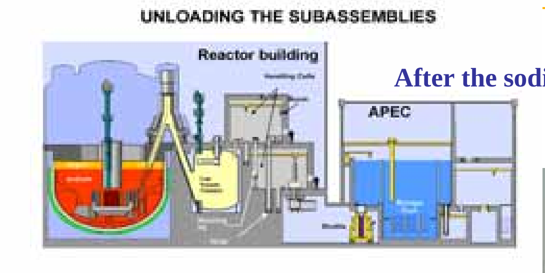
→ cold trap able to be regenerated or not, with cartridge or not (makes cold trap treatment easiest or not, and consequences on the size of the cold trap and building allocated to this system.

→ cold trap for continuous and incidental pollution or not (specific removable cold trap for incidental pollution, able to be installed on the involved loop)

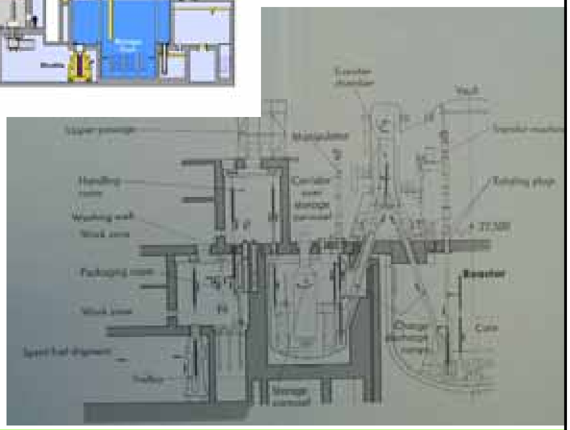
→ other concepts?

CADARACHE

Description of the defuelling route



After the sodium leak (1987)



CADARACHE

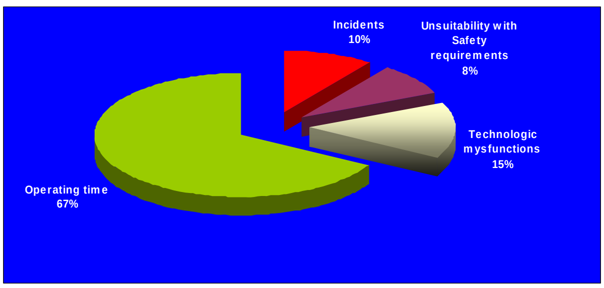
Before the sodium leak (1987)

Synthesis of the defuelling campaign

Technological dysfunctions: first defuelling operation as routine procedure, 15 years after SPX start-up. (delay sufficient to raise the probability of dysfunctions of instrumentation)

Unsuitability with the safety requirements : The first safety document was limiting the total residual amount of sodium to 300 grams. Assessment too restrictive : The cleaning pit has demonstrated it could treat greater amounts of sodium without any risk. This assessment had major consequences : loss of 16 weeks in the defuelling planning, modification of the future cleaning procedure that decreases the potential defuelling rate.

Average defuelling rate : 4.5 per week (Expected defuelling rate : 9 assemblies/week) → The defuelling procedure was not as efficient as expected because cleaning processes were too long and defuelling route for one assembly too complex. Absence of an EVST appears to be crucial.



CADARACHE

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 attractivity :

- 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.

CADARACHE

Design options and main consequences

Energy Conversion System (ECS) coolant : H_2O, CO_2, N_2,…
→ impact on :

➔ ECS thermodynamic efficiency
➔ heat exchanger design (efficiency, reliability, compacity, inspectability, reparability/modularity,…)
➔interaction between ECS coolant and structural material
➔interaction between ECS coolant and sodium or ECS coolant – intermediate fluid (Ga, Pb-Bi,…) in case of integrated IHX-SGU component.
➔ Behaviour of products from interactions : content, dissolved phase/particles,…)
➔ Leak detection systems
➔ purification (filters, limited effect of cold traps,…)
➔ Thermal/mechanical/chemical effect of ECS coolant (westage)
➔ transfer of tritium between primay circuit and ECS,…

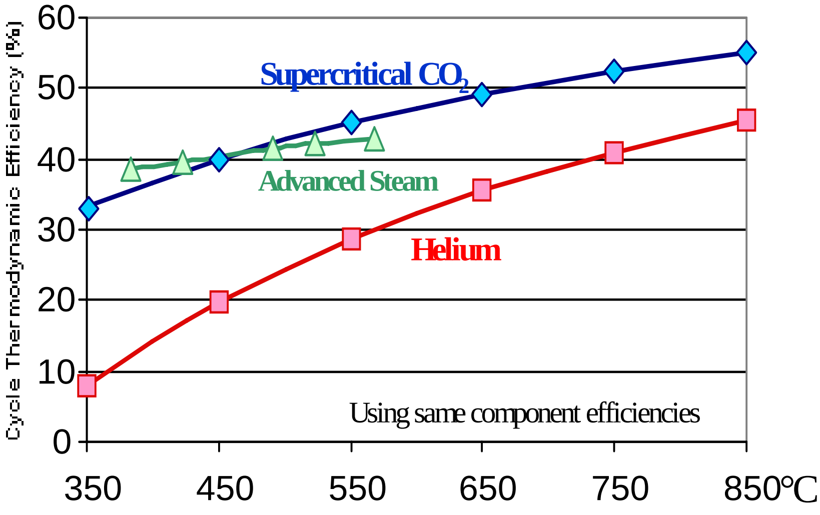
CADARACHE

Influence of various parameters on overall efficiency

- Tinlet core
- Toutlet core
- Gas : N_2, N_2-He, N_2-Ar, He, CO_2,
- Gas pressure
- Cycle structure
- Efficiency of single components (compressor, heat exchanger, recuperator, turbine,…

CADARACHE

Improvement of efficiency : energy conversion system

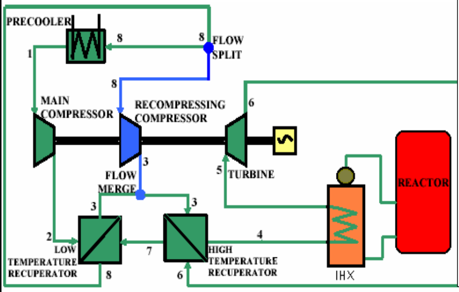


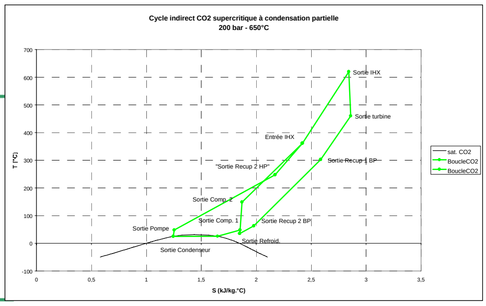
CADARACHE

Supercritical CO_2 cycle :

- With $_{SC}CO2$, high efficiency can be obtained with complex cycle structures
- Very compact turbines
- Na –CO_2 interaction acceptable (?)
- Assessment of other consequences : tritium transfer, purification,

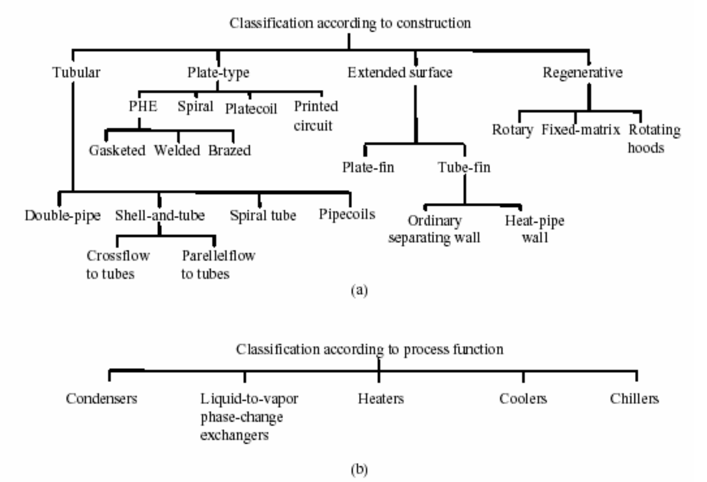
Net efficiency for Na at 550 °C : up to 42,50% (depends of various parameters





CADARACHE

SMFR : Heat exchangers for Na / gas exchange

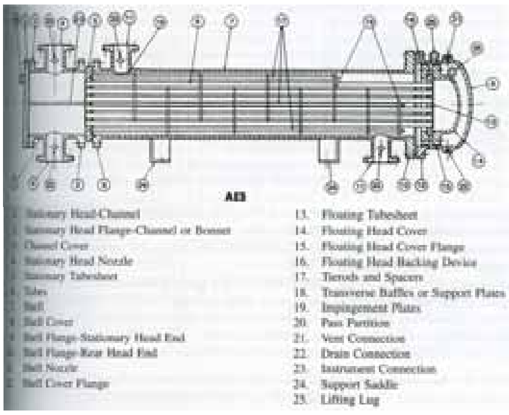


Necessary to compare various concepts. Parameters : Pmax, Tmax, fabricability, inspectability, reparability, compacity, thermal behaviour,….

CADARACHE

Shell and tube heat exchangers

- A shell and tube heat exchanger is essentially **a bundle of tubes enclosed in a schell** and so arranged that **one fluid flows through the tubes and another fluid flows across the outside of the tubes**, heat being transferred from one fluid to the other through the tube wall.
- Shell and tube heat exchanger have been constructed with **heat transfer areas from less than 0.1 m² to over 100 000 m²**
- for **pressures** from deep vacuum to over 1000 bar .
- for temperatures from near 0 to over 1400 K .
- for **all fluid** services including single-phase heating and cooling and multiphase vaporization and condensation.



CADARACHE

Plate-Fin Heat Exchangers

- Aluminium plate-fin heat exchangers (PFHE) were initially developed in the 40's to provide for the aerospace industry compact, light and high efficient heat exchangers for gas/gas applications.

The fins and the parting sheets are assembled by fusion of a brazing alloy **cladded to the surface of the parting sheets. The brazing operation is made in a vacuum furnace in which the brazing alloy is heated to its point of fusion.**

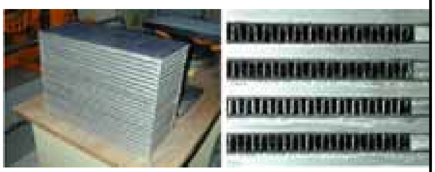
Numerous fin corrugations **have been developed, each with its own special characteristics.**

For higher temperature **applications stainless steel (temperature up to 700°C) or copper materials can be used.**

For very high temperature **(gas turbine heat recovery ; T > 1200 °C), a ceramic plate fin heat exchanger has also been developed**

Pictures of plate fin heat exchangers

Different fin geometry



Stainless steel brazed plate fin heat exchanger (courtsey of Nordon)

CADARACHE

Microchannels Heat Exchangers

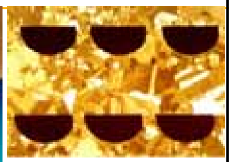
Microchannels heat exchangers refer to compact heat exchangers where the channel size is around or lower than 1 mm. (developed for severe environment such as offshore platforms)

New applications are also arising for nuclear high temperature reactors (Heatric Company)

To manufacture such small channels several technologies are available : chemical etching, micromachining, electrodischarge machining ...

The processing technique is as flexible as for plate-fin heat exchangers, and crossflow and counterflow configurations are employed.

The main limitation of microchannel heat exchanger is the pressure drop, which is roughly inversely proportional to the channel diameter .



Detail of the bonded plates

Printed circuit heat exchanger (courtesy of Heatric)

View of completed unit : A typical 24.4 MW unit operating at 70 bar

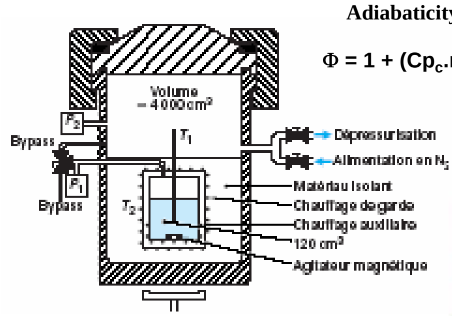
CADARACHE

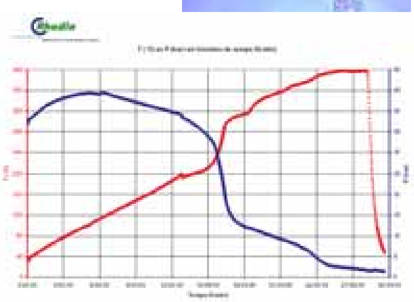
VSP for Na-CO_2 interaction study

VSP (Vent Sizing Package)

Adiabaticity factor Φ < 1,05

$$\Phi = 1 + (Cp_c.m_c) / (Cp_{sample}.m_{sample})$$





Apparatus developped by DIERS (Design Institute for Emergency Relief Systems) in order to obtain data for the calculation of relief systems in chemical industry.

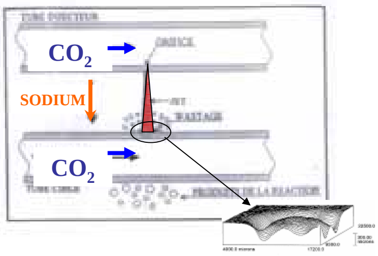
CADARACHE

Na-CO2 interaction

- Exothermal reaction Na + Na-oxalate and CO production
- then exothermicity due to Na + CO (with induction time) around 400 ° C over this temperature.
  → several by-products and complex exothermicity
  - Limited reaction Na + carbonate ?
- T> 500 ° C interaction producing directly carbonate
- T< 500 ° C more complex scenario

- Study going on ; (to be published in near future)

→ With the aim to check :
  - the absence of wastage,
  - the significative dissolution of carbona
  - the very limited effect of carbon,
  - The efficiency of detection systems



Comparison Na-CO_2, Na-H_2O (1/2)

Event	Water ingress	CO_2 ingress	Comments
Pressure (H_2O or CO_2)	168 bar	200 bar	Impact of pressure on heat exchanger design
ΔH (kJ/mol)	162	271.5	
Kinetics of reaction	Almost instantaneous	Order 2 / CO_2	For CO_2 to be investigated in realistic conditions
Products of reaction	NaOH, $O^=$, H^-	Na_2CO_3, C, and Na_2C_2, $Na_2C_2O_4$ as intermediate products	Necessity to investigate carbonate dissolution in sodium
Particulates?	Not	Yes (Na_2CO_3)	Necessity to foresee filters
Soluble products trapping	Cold trap, hot trap	To be defined	Necessity to foresee a carbon trap?
Non soluble products trapping	Not necessary	Filters,	Implementation has to deal with thermo-hydraulics

Comparison Na-CO_2, Na-H_2O (2/2)

Event	Water ingress	CO_2 ingress	Comments
General corrosion	Yes but very limited due to NaOH conversion with Na	Not	
Carburization	No	Yes at high temperature and high C content	Probably very limited consequences
Possibility of Leak detection	Yes (hydrogen-meter, acoustic detection system,...)	Yes (diffusion or electrochemical carbon meter, sampling then analysis,..)	Necessity to assess the response time for CO_2
Wastage	Yes	Probably not	To be investigated
Risk of strong reaction	Yes, if contact with oxygen	Not	Probability of loss of tightness of gas plenum to be investigated
Risk of combustion	Not	Yes	Operating conditions to be investigated

CADARACHE

ISIR : main objectives

In Service Inspection and Repair (ISI&R) is considered as one of the problems to be resolved for future liquid metal cooled reactors SFR.

Two main applications can be cited :

- Non Destructive Examination (NDE) of these structures
- Telemetry within liquid metal coolant (and also vision as a connected item)

What we are looking for?

Material failure

Loss of thickness (tribology, westage effect,…)

Fatigue/ creep/ local effect of temperature

Manufacturing defaults (dye penetration,…)

Horizontality of core

Right position of removable systems

Respective positions of systems/components

Loss of Tightness

Erosion/cavitation effects

Metal embrittlement,…

CADARACHE

Main difficulties for ISIR in Na

- Na opacity
- Impossibility to drain primary Na and unload core Fuel Assemblies
- High activation importante of internals structural material
- Temperature: 160 ° C-200 ° C, during cold shut-down
- Na chemical reactivity
- Necessity of confinement with regards to air and water
- Tribology for holders in Na or air
- Wetting characteristics (and criteria) of Na on traducers surfaces
- Dose rates in Na (up to 500 Gray/h) and possible contamination (Pu…)

CADARACHE

ISIR technologies

- Optic control (endoscope, periscope, dye penetration, chemical tests,
- Infra Red Camera,…
- Mechanical metrology
- Volumetric control by US
- Under Na US telemetry or in air telemetry
- Laser telemetry in gaz
- Acoustic detection (rotating machines, Na-water interaction, gas leak in Na,…)
- Main parameters monitoring : temperatures, Na level,flow-rates, pressure, rotating speed, neutronic parameters…
- Sodium leak detection systems, water-Na interaction detection systems,
- System/components tightness : He-Ar-N2 detection, pressure monitoring, activity monitoring,…
- Components or sampling devices dismantling and inspection and analysis in dedicated laboratories,

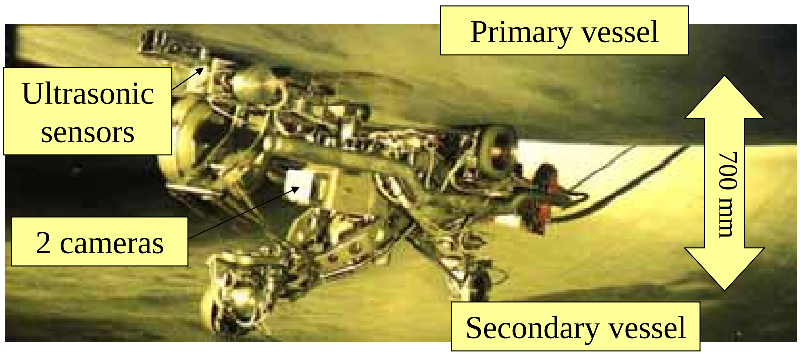
CADARACHE

Parameters impacting ISIR :

- tools and processes
- simplicity in the design
- easy access
- characteristics of structures
- size of structures
- modularity
- removability
- conditions for intervention

CADARACHE

Sodium cooled reactor feedback (1/2)

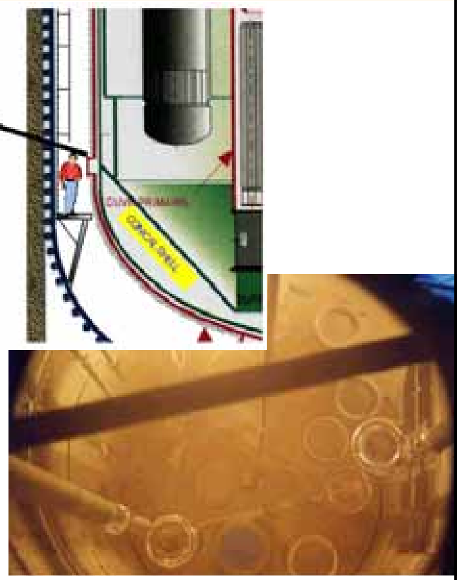


Inspection Engine

of Superphenix plant Primary Vessel

CADARACHE

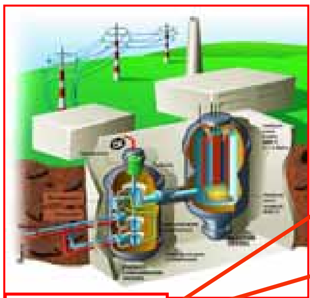
Sodium cooled reactor feedback (2/2)



Phenix plant inspection of core supporting structures

Gas cooled Fast Neutron reactors

GEN IV : R&D on Gas Cooled Reactors



➢Fast neutrons
➢Full Actinide recycling

GFR

R & D
- Fast neutron fuel
- Fuel cycle processes
- Safety systems

VHTR

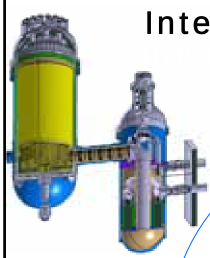
R & D
- VHT materials
- IHX for heat process
- ZrC coated fuel
- I-S cycle : H_2 production

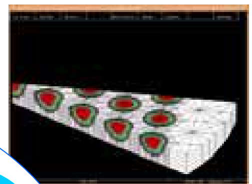
HTR

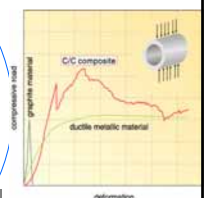
R & D
- Fuel particles
- Materials
- He systems technology
- Computer codes
- Fuel cycle

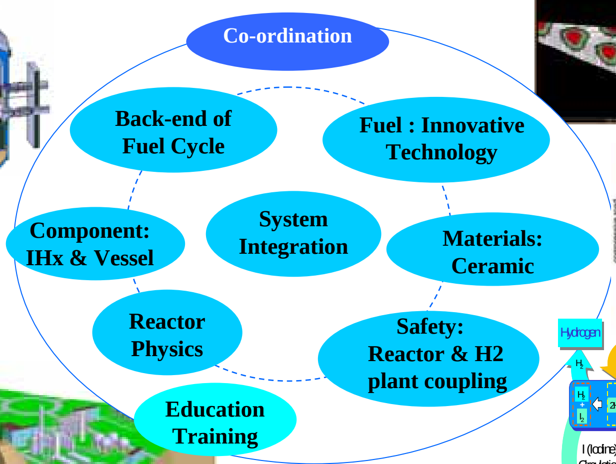
CADARACHE

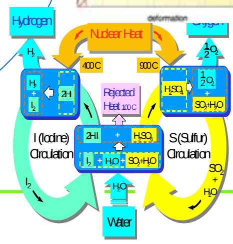
European R&D on VHTR concept: RAPHAEL Integrated Project scope



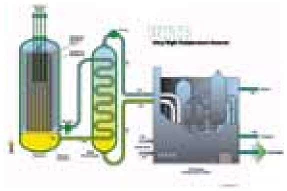








Very High Temperature Reactor – (VHTR)



Main goals :

Calculation system

Particle fuel

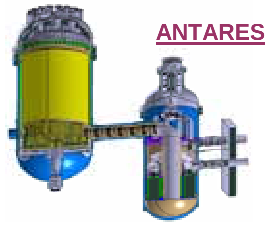
Very high temperature resistant materials (> 950°C)

High temperature helium circuit technology

Hydrogen production processes

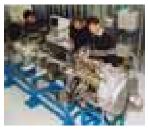
Conversion system

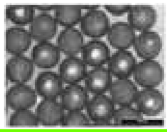
ANTARES



Main Milestones

- 2009: Feasibility
- 2015: Confirmation of performance

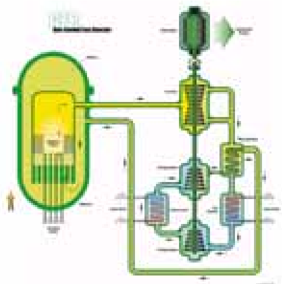




Tribology   Fuel

CADARACHE

Gas Fast Reactor (GFR)



Fuel and core materials

Choice of fuel reference materials (composite ceramic, ceramic cladding, etc.)

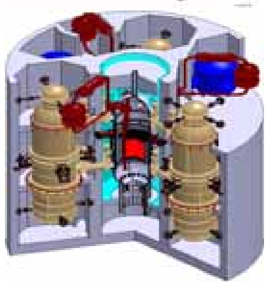
- Fuel cycle reference technology

Accident management (depressurisation, etc. ..)
High temperature helium circuit technology
Applications technology (Gas turbine, etc…)

GFR fuel

Main Milestones

- 2012: Feasibility
- 2020: Confirmation of performance
- 2025+: GFR 1st Demonstrator



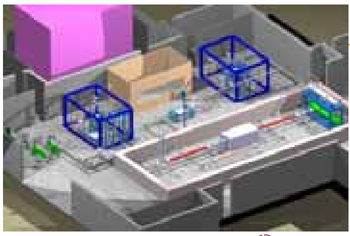
1.2 GWe GFR

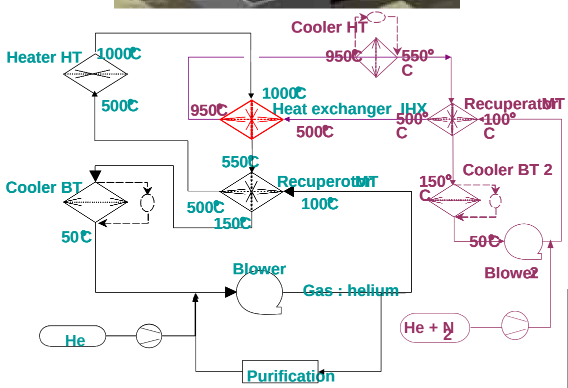
CADARACHE

Strategy for development

Objectives	*Experimental facilities*
Analytical validation : data base for codes	Analytical Benches : He Tribometer, ESTHEL (Heat transfer coefficient)
Technological qualifications at small scale in relevant conditions (T, P)	Technological Benches and Loop : HETIQ, HETHIMO, HELITE, HEPUR
Component validation in similarity at large scale	Large air flow loops
Qualification in helium relevant conditions at large scale	He Loop : Power : 10 - 20 MW

HELITE facility





→ Qualification of components
- § IHX and MT Recuperators with 2 different gases and/or 2 different pressures
- § Simulation of pressure and temperature transient

→ Qualification of purification process, decay heat removal systems, fuel assembly fluid dynamics,

Heat exchange up to1 MW

Gas : He and mixed He / N2 or CO2,..

MAXIMUM CAPACITY :
Max pressure = 100 bar
Max flow rate = 0,4 kg/s
Heat power » 1 MWth

R&D facilities for He technology in Cadarache

HEDYS : validation of He Dynamic Seals for rotating shaft

HETAP : functional and thermo-mechanical validation of high T heating elements

HETHIMO : Thermal insulation system qualification

HETIQ : Validation of tightness systems; qualifications of seals

OXYGRAPH : Kinetics of graphite oxidation in HTR reactor core

TRIBOMETER : Qualification of materials for junctions and contact surfaces

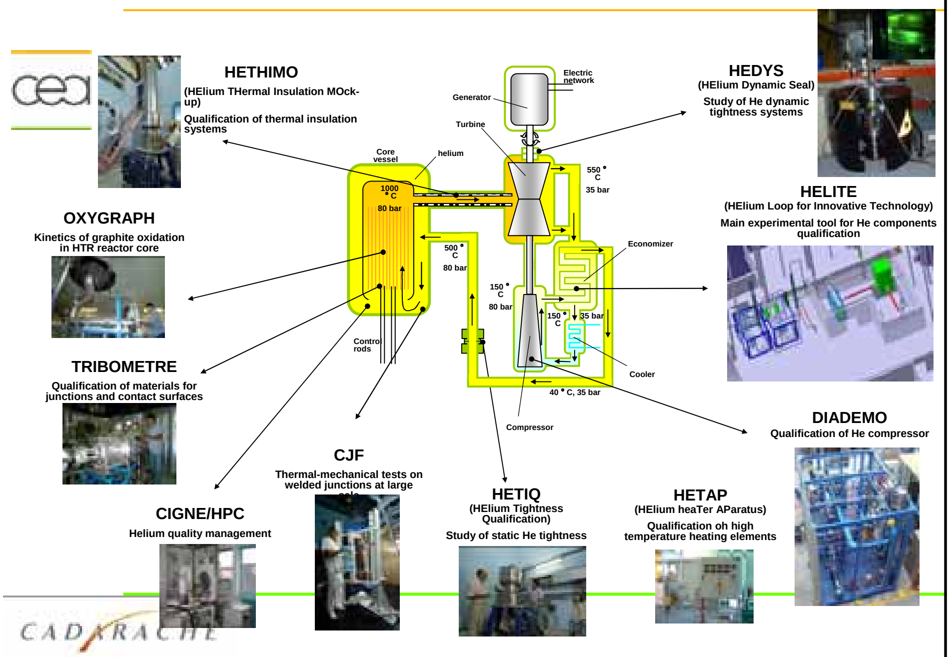
CIGNE/HPC : Helium quality management

DIADEMO : Qualification of He compressor

HEDYT : Generic qualification bench for He technology.

CADARACHE

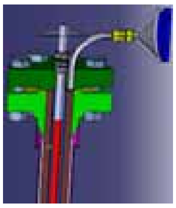
Platform for Gas Technology



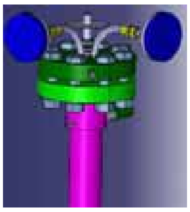
CADARACHE

HETAP : HE heaTer APparatus

CONTEXT : In the frame of the He technology development program for GCRs, the HETAP experimental facility is dedicated to the functional and thermo-mechanical validation of high temperature heating elements



Heating rod



Holes for instrumentation

PARAMETERS : Atmosphere : helium,

Pressure : up to 100 bar,

He flow rate : up to 300 Nl/min,

Temperature: up to 1000°C.

EXPERIMENTAL PROGRAM

Mechanical behavior of the sheath :
- Tests at 75% of full power,
- T sheath = 1050°C,
- P=100 bar,
- No He flow
- Thermal cycling and endurance tests

Limits of performance :
- Tests at full power,
- P=100 bar,
- He flow up to 1000°C
- Thermal cycling and endurance tests

CADARACHE

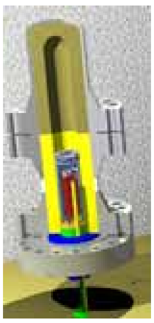
HETHIMO : HE THermal Insulation MOck up 1/2

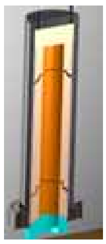
CONTEXT : Gas Cooled Reactors (GCR) use high pressure (100 bar) and high temperature (up to 1000°C) gas. In fact, no design code predicts this loading level with listed materials.

It is necessary to thermally insulate and/or to cool down the structural material in order to withstand such pressure load.

OBJECTIVE : Thermal insulation system qualification for GCRs

- thermal performance,
- mechanical behavior in case of high depressurization rate.

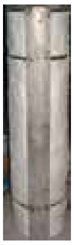




Thermal insulation mock-up

CADARACHE

HETHIMO : HE THermal Insulation MOck up 2/2



Thermal insulation mock-up

Experimental program :

- Endurance test,
- Thermal cycling,
- High depressurisation rate

Operating conditions :

- P = 100 bar,
- T = 1000 °C,
- $\Delta P / \Delta t$ = 20 bar/s
- He and He/N2

CADARACHE

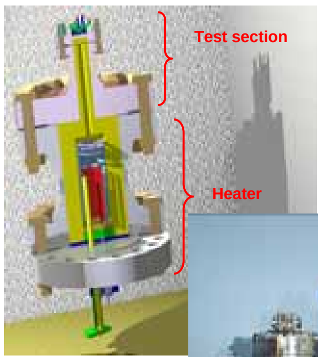
HETIQ : HE TIghtness Qualification 1/2

CONTEXT : Gas Cooled Reactors (GCR) use helium (up to 1000°C and 100 bar) as coolant. Due to its small molecular size, the helium gas easily leaks.

For GCRs, it is crucial to confine He circuit in order to :

- limit operation cost,
- reduce contamination level.

OBJECTIVE : Seals qualification in GCRs conditions. (100 bar, 1000 °C, thermal and pressure cycling)



Experimental measurements :

- He pressure and temperature,
- Tensile stress on bolts
- He leak flow rate with mass spectrometer

CADARACHE

HEDYS : He Dynamic Seals for rotating shaft 1/2

Context : Development of He component technology for GCRs (He pressurized circuits up to 100 bar and temperature up to 1000°C).

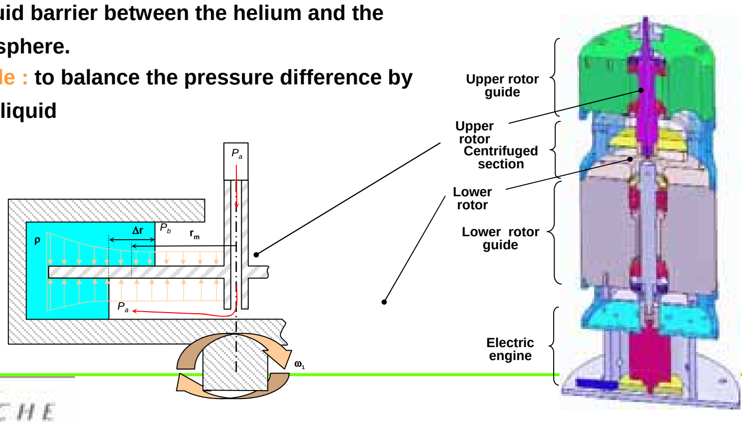
Technical issue : One of the reactor design solution is to place the generator out of the Power Conversion Vessel.

This requires to guarantee the tightness of the PCV.

Objective : To qualify a promising tightness system for rotating shaft. The dynamic seal is achieved by means of a liquid barrier between the helium and the external atmosphere.

Physical principle : to balance the pressure difference by the centrifuged liquid

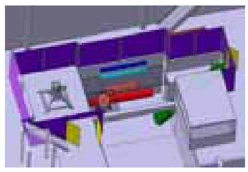
$$\Delta r = \frac{P_b - P_a}{\rho \omega_1^2 r_m}$$



CADARACHE

HEDYS : He Loop for technological tests

Main goal : Reduce design uncertainties and optimize the GCR design.ie produce experimental correlations for wear and thermal transfer foreseen in the core and heat exchangers.



HEDYT will be operated with :

-Helium, nitrogen, CO_2 or gas mixtures,

-In various conditions representatives of various situations of gas cooled reactors.

- channel of various sections,

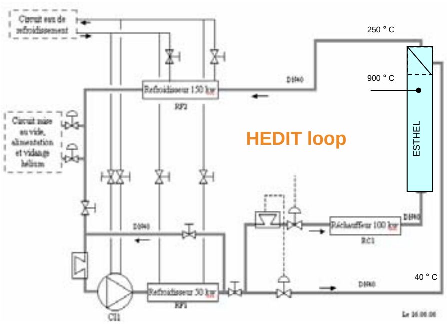
- Thermal flux up to 1.5 mW.m-2 generated by Joule effect

-Tmax at exit of channel : 900 ° C

-P up to 100 bar

-Gas velocity over 40 m.s-1

-Various hydraulic regime : laminar, turbulent,…



CADARACHE

Tribometry in helium 1/2

➢**Tribology :** generic subject for every new industrial equipment technical and economical aspect (life time, efficiency,..), safety (i.e. control rod operability), pollution (i.e. contamination by abrasion particules),...

- ➢Specificity of GCR conditions :
  - ✓**The atmosphere**, which can be a very reducing one depending on the impurities level, and so not in favor of oxide layers growing able to play a role of solid lubricant, risk of biding,
  - ✓**The temperature** level (up to 1000°C).

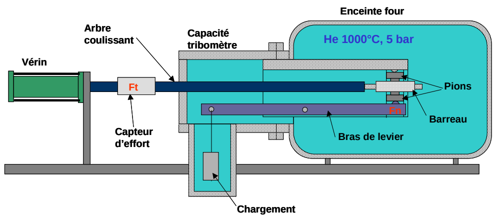
Description :

Pin/rail friction :

- ➢plane/plane contact,
- ➢Alternative motion,
- ➢Normal load : 0 – 20 MPa,
- ➢Displacement : up to 20 mm,
- ➢Frequency : up to 6 Hz.

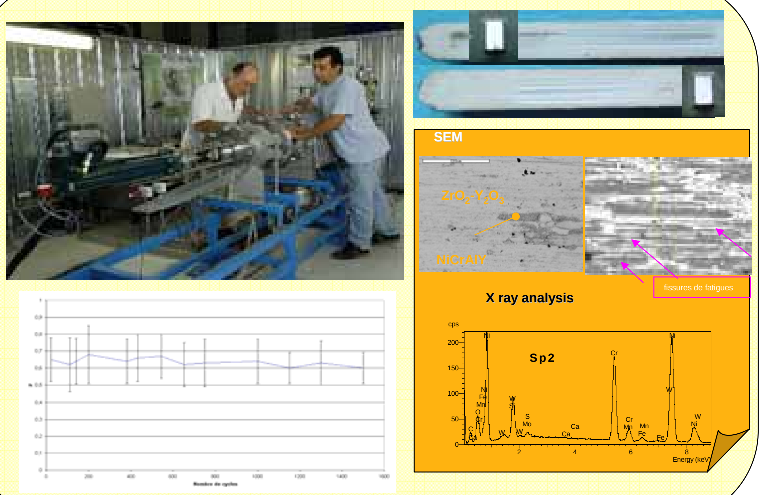
➢Environment parameters :

- ➢Temperature : up to 1000°C,
- ➢Atmosphere : impurities.



Tribometry in helium 2/2

Main results



He quality control and purification 2/3

Necessity to maintain impurities concentration at low levels and under some thresholds [1] ;

Determination of values from litterature and synthesis of constraints (material corrosion, maximum impurities concentration when circulating and eligible contamination threshold …) :

→ 1 For instance, concerning the Peach Bottom reactor and for a working pressure of 24 bar, concentration levels are :

- **CO < 10 ppm V**
- **CO_2 < 2 ppm V**
- **H_2 < 10 ppm V**
- **H_2O < 0.5 ppm V**
- **CH_4 < 2 ppm V**

- **→ 2 Resistance to corrosion. For example, to set an oxide film for protection of these type of material (supposing a chromium activity of 0.3) following conditions should be applied :**

- at 950°C : $a_{O2} > 2.10^{-23}$ µbar; i.e. $P_{H2O}/P_{H2} > 10^{-4}$ and $P_{CO} >$ ~150µbar

at 1000°C : $a_{O2} > 10^{-21}$ µbar ; i.e. $P_{H2O}/P_{H2} > 10^{-4}$ and $P_{CO} >$ ~500µbar

and necessity to adress also : graphite oxidation, fission products (poisoning due to Xe, radiological inventory in case of accident, dosimetry,…) and graphite aerosols (erosion, clogging,…).

[1], Helium purification at laboratory scale Conf. HTR 2006 Fanny Legros and all

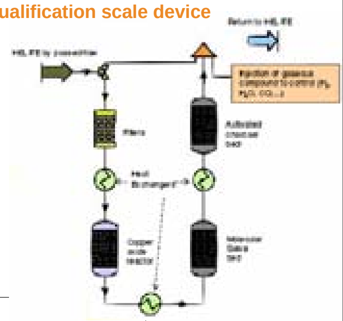
He quality control and purification 3/3

CIGNE : laboratory scale device :

- **•Oxidation of H_2 and CO on metallic oxide**
- **•Adsorption of CO_2, H_2O, NO, NO_2, CH_4 on molecular sieve at room T**
- **•Adsorption of oxygen and nitrogen on activated charcoal under cryogenic conditions.**

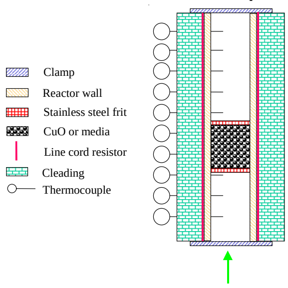
And regeneration as well as long term behaviour.

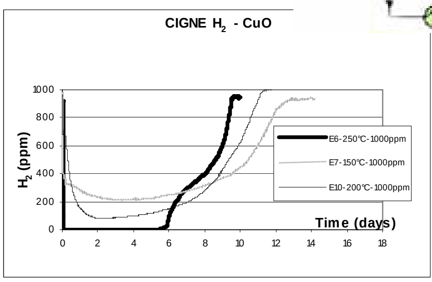
HPC : qualification scale device



Operating conditions :

- **•Temperature of the reactor from –190°C to 400°C**
- **•Pressure: 1.3 Bars**
- **•Concentrations of impurities: up to 1000ppmV**



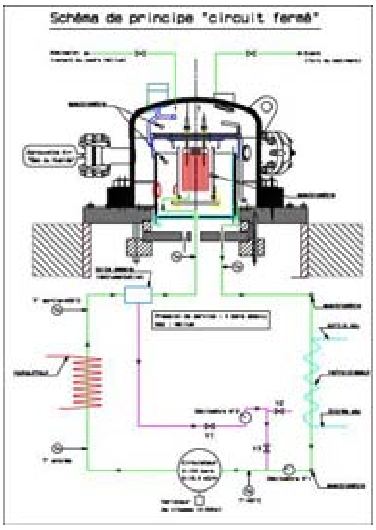


OXYGRAPH : High Temperatures Graphite Oxidation

General objectives :

To simulate in realistic conditions an air ingress on CGR graphite components.

-To supply and complete the existing data bases to validate the oxidation models and the related calculations.



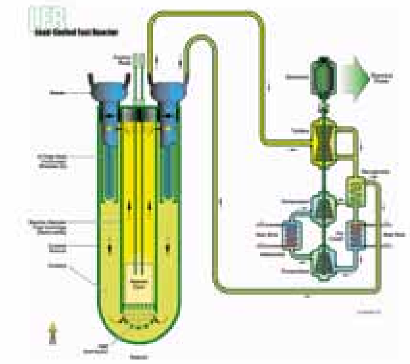
Experimental goals :

- Check the behavior of the selected nuclear graphite grades under oxidizing conditions.
- Define oxidation kinetics parameters f(T, %W He/air/H2O)
- Effect of the Oxidation on mechanical characteristics (compressive strength loss).
- Consequences from the safety point of view (carbon monoxide production, release of radioactive products formerly trapped in graphite…)
- Two configurations : Open loop (simulation of a massive and continuous air ingress) and closed loop (simulation of a limited air ingress) .

Lead cooled Fast Neutron Reactor

Lead cooled Fast Neutron Reactor

Reactor cooled by lead



Positive items:

- Safety (no reaction with air) except earthquakes, lead toxicity.
- Homogeneous recycling of M.A. >2.5% (to be validated)
- Efficiency > 42%

Main Drawbacks:

- Corrosion (O control)
- Behaviour/ earthquakes, lead toxicity)
- High melting point (SGU, material
- Density (pumps)
- Decommissioning (lead)
- Polonium (if Pb-Bi)

Key points for R&D:

- Corrosion, O control
- Fuel (nitride)
- Behaviour/Earthquake
- In Service Inspection and Repair

CADARACHE

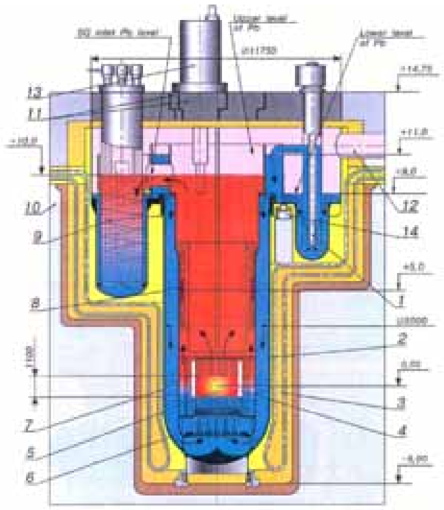
Some Heavy liquid metal properties :

Property		Pb	Bi	LME *	LBE**	Hg
Composition		elem.	elem.	Pb 97.5% Mg 2.5%	Pb 45% Bi 55%	elem.
Atomic mass A (g/mole)		207.2	209	202.6	208.2	200.6
Density (g/cm^3)	20°C	11.35	9.75			10.5
	liquid	10.7	10.07	10.6	10.5	13.55
Linear coefficient of thermal expansion (10^{-5} K^{-1})	solid	2.91	1.75			
	liquid (400°C)	4		4		6.1
Volume change upon solidification (%)		3.32	-3.35	3.3	0	
Melting point (°C)		327.5	271.3	250	125	-38.87
Boiling point at 1 atm (°C)		1740	1560			356.58
Specific heat (J/gK)		0.14	0.15	0.15	0.15	0.12
Thermal neutron absorption (barn)		0.17	0.034	0.17	0.11	389

* LME - lead/magnesium eutectic ** LBE - lead/bismuth eutectic

CADARACHE

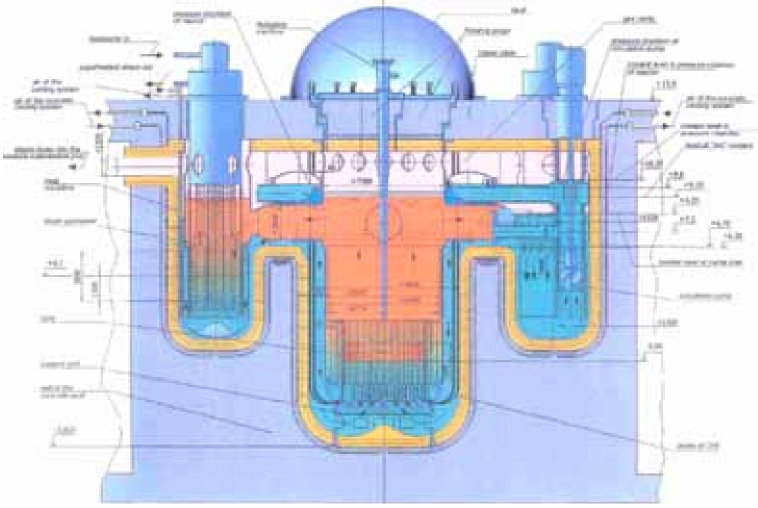
Lead cooled fast reactor : BREST 300 (RUSSIA)



1. Pump
2. Main vessel
3. Thermal insulation
4. CPS
5. Core
6. Matting
7. Internal vessel
8. Internal storage
9. SGU.
10. Concrete Pit
11. Rotating plug
12. Steam removal system
13. Handling machine
14. Support for internal vessel

CADARACHE

BREST 1200 (Russia)



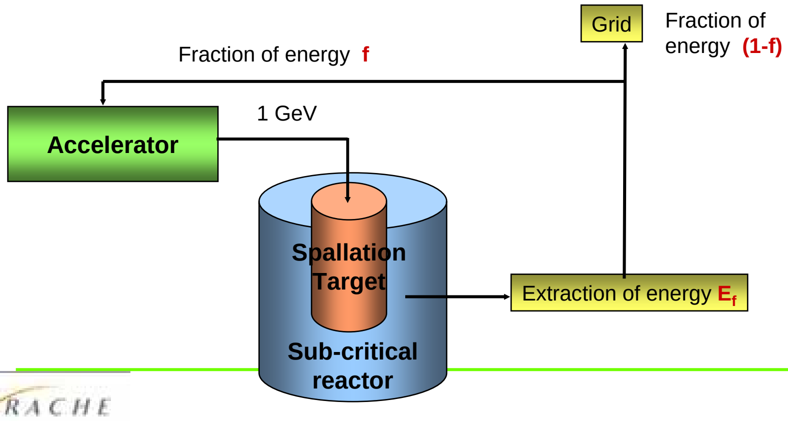
CADARACHE

ADS studies; target developments

General consensus :

- up to 1MW of beam power solid targets are feasible from a heat removal point of view.

- for higher power levels, liquid metal targets are the option of choice because of their higher heat removal capability, higher spallation material density in the volume, lower specific radioactivity,…



MEGAPIE experiment

A key experiment in the ADS roadmap :

→**MEGAwatt PIlot Experiment (MEGAPIE)** **(1 MW),** initiated in 1999.

Two main goals :

- to design and build a liquid LBE target, then
- to operate it into the Swiss spallation neutron facility SINQ at PSI .

It has to be equipped to provide the largest possible amount of scientific and technical information without jeopardizing its safe operation.

.

MEGAPIE-TEST

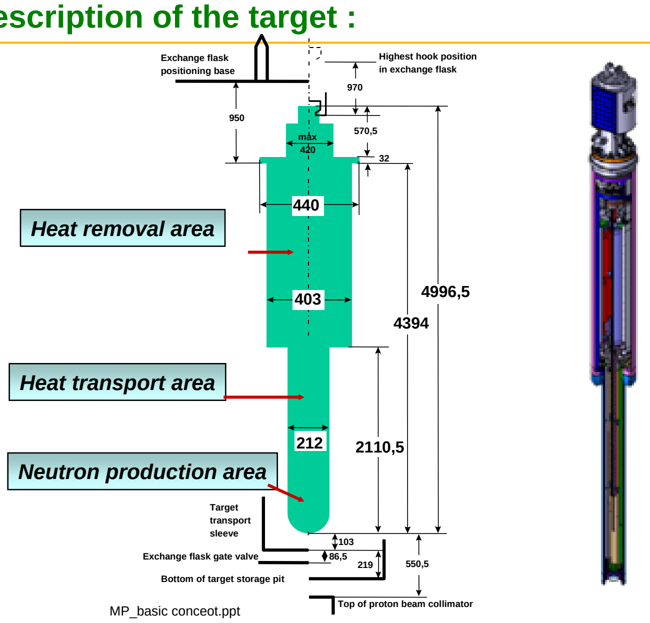
Choice of Lead-Bismuth

Lead bismuth eutectic (Pb44.5%-Bi55.5%) has been selected, due to its attractive neutronic and physical properties : heat transfer coefficient, low melting point (125 ° C);
nevertheless bismuth induces to the production of activation products i.e. polonium,...

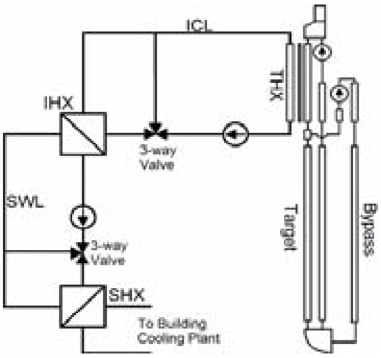
Property		Pb	Bi	LME *	LBE**	Hg
Composition		elem.	elem.	Pb 97.5% Mg 2.5%	Pb 45% Bi 55%	elem.
Atomic mass A (g/mole)		207.2	209	202.6	208.2	200.6
Density (g/cm^3)	20°C	11.35	9.75			10.5
	liquid	10.7	10.07	10.6	10.5	13.55
Linear coefficient of thermal expansion ($10^{-5}\ K^{-1}$)	solid	2.91	1.75			
	liquid (400°C)	4		4		6.1
Volume change upon solidification (%)		3.32	-3.35	3.3	0	
Melting point (°C)		327.5	271.3	250	125	-38.87
Boiling point at 1 atm (°C)		1740	1560			356.58
Specific heat (J/gK)		0.14	0.15	0.15	0.15	0.12
Thermal neutron absorption (barn)		0.17	0.034	0.17	0.11	389

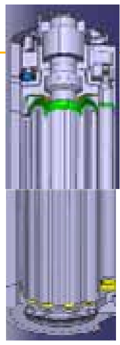
* LME - lead/magnesium eutectic ** LBE - lead/bismuth eutectic

Main description of the target :



MP_basic conceot.ppt





THX

Oil loop

Water loop

Heat Removal system with 3 cooling circuits :

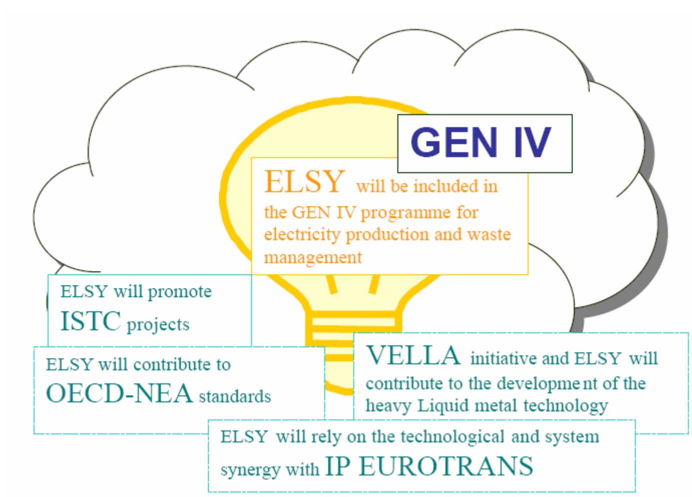
Primary loop : liquid LBE (target material), with 2 electro-magnetic pumps and one modualr heat exchanger (12 modules)

Intermediate loop (ICL): Diphyl THT (with low tension pressure, ~ 140 °C<T< ~ 240°C, stable under irradiation

Water loop (WCL):. This loop is cooled by the conventional cooling loop of the Building.

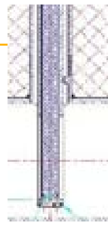
CADARACHE

Lead and Lead bismuth research in Europe



CADARACHE

Main R&D goals



Some tasks related to lead technology (often based on Lead Bismuth technology developped for ADS concepts and spallation targets) :

- Assessment of consistent data for chemical and thermo-physical properties (Hand Book of OECD NEA to be issued
- Investigations on secondary coolant with lead, experiments for supporting the accident scenario analysis (Lead water interaction)
- développment of corrosion resistant steel or protection coatings in lead at high temperature (500-550 ° C) for long term operation.
- development of erosion resistant pump impeller material.
- development of electrochemical oxygen-meters
- development of oxygen control systems (gaseous or lead oxide)
- development of purification systems (filters,…),…

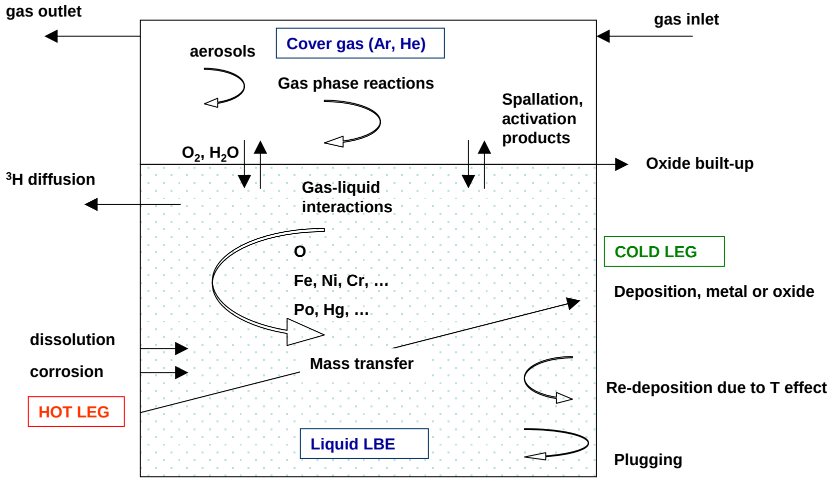
•($Bi_{1,23}\ Pb_{0,77}O_{2,62}$)

=Mixed oxide of

(PbO, Bi_2O_3)

Source of pollutions (potential effect)

$$\tfrac{3}{4}Fe_d + PbO_d \longrightarrow \tfrac{1}{4}Fe_3O_4 + Pb$$



STELLA Loop (Standard TEchnology Loop for Lead Alloys)

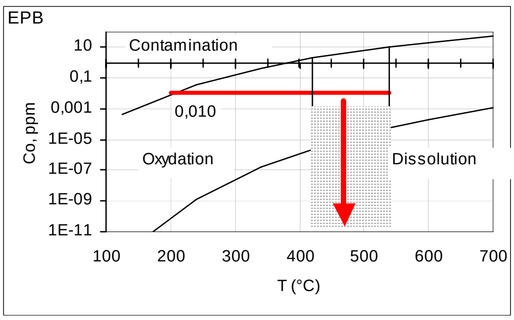
(max. temperature 550°C, SS316 aluminised, 32 liters, 0.1-1 m^3/h, ΔT = 150°C)

Contamination control

Co*, ppm weight :

	200°C	300°C	400°C	500°C	600°C	700°C
Lead	-	-	0.6	5.4	30	115
LBE	0.01	0.2	1.4	6.3	20	51
Na	12	97	415	1225	2821	5471

Lead : $\log C^*_{o(wgt\%)} = 3.2 - \frac{5000}{T_{(K)}}$ LBE : $\log C^*_{o(wgt\%)} = 1.2 - \frac{3400}{T_{(K)}}$



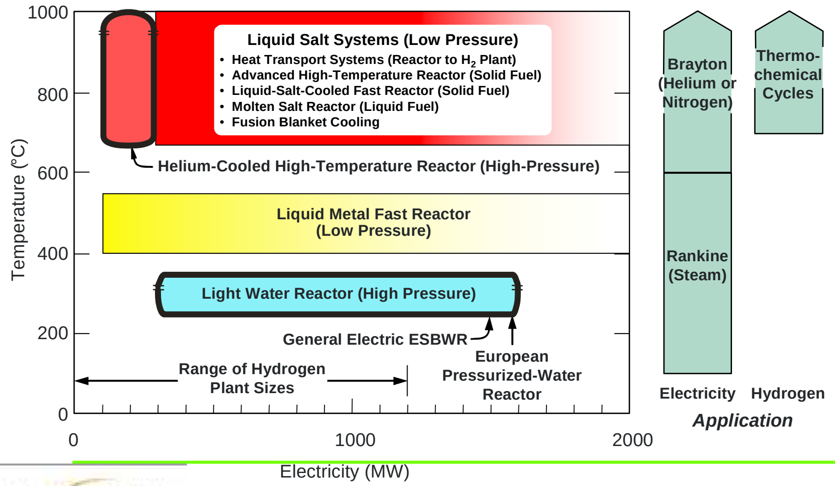
- Oxygen : 100 to 1000 times lower than for Na
- Operating consequences : any oxygen change can affect the concentration quickly, leaving less safety margins
- However, coolant oxides behaviour not well known : ability to clog or to stay in suspension, kinetics of coagulation and deposition, buoyancy effect on free surface, etc.

Molten Salt Reactor

LIQUID SALTS POTENTIAL APPLICATIONS

Salt coolants can be used
for high-temperature nuclear applications

(Liquid Salt Reactors: Clean Coolant with Solid Fuel or Fuel in Coolant)



MSR SYSTEM IN GENERATION IV

MSR R&D SCOPE IN GENERATION IV

1. DEMONSTRATION OF FEASIBILITY AND EVALUATION OF PERFORMANCE OF TMSR FAMILY (TH-U233 BREEDER) ACCORDING TO GENERATION IV CRITERIA

2. EVALUATION OF PERFORMANCE OF MSR FOR WASTE REDUCTION (LWR SPENT FUEL)

3. EXPLORATION OF THE POTENTIAL OF LIQUID SALTS AS EFFICIENT COOLANTS FOR SOLID FUEL REACTORS, AS AN ALTERNATIVE TO SODIUM AND HELIUM :
   - IN FAST REACTORS (LSFR)
   - IN THERMAL SPECTRUM REACTORS (AHTR)

4. UTILIZATION OF LIQUID SALTS FOR HEAT TRANSPORT :
   - SFR INTERMEDIATE LOOP
   - COUPLING FLUID REACTOR-H2 UNIT

CADARACHE

Molten salt Reactors

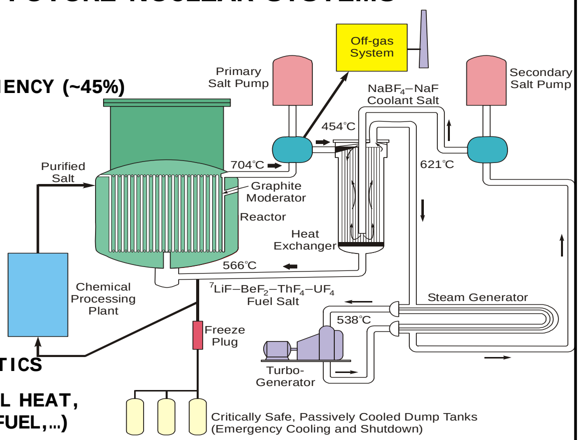
MSR : A PROMISING RESPONSE TO THE GOALS AND CRITERIA ASSIGNED TO FUTURE NUCLEAR SYSTEMS

✓ HIGH ENERGY CONVERSION EFFICIENCY (~45%)

✓ FLEXIBLE WASTE MANAGEMENT
(HIGH BURN-UP,
ON-SITE REPROCESSING)

✓ BREEDING POTENTIAL
IN THERMAL NEUTRON SPECTRUM
(IN Th-U233 FUEL CYCLE)

✓ FAVORABLE SAFETY CHARACTERISTICS
(LOW SOURCE TERM, SMALL RESIDUAL HEAT,
PASSIVE DRAINING OF THE LIQUID FUEL,…)



THE MSBR CONCEPT (ORNL, 1975)

CADARACHE

Molten salt as intermediate coolant for SFR

Selection criteria :

Low melting point and liquid between 200 (or lower)-700 ° C
Stable in a very large range of temperature
Good thermal properties (Cp, Pr number)
Compatibility with primary Na, water, CO_2, air,
Corrosion mastered
Relatively low pumping power
Low toxicity
Non flamable
Availability, low cost
Capability for structures to be cleaned and/or decontaminated
Low impact on decommissioning operations
Good wettability for US sensors (for In Service Inspection),…

CADARACHE

LIQUID SALTS POTENTIAL APPLICATIONS

Potential of liquid salts as coolants

	unit	helium 60 bar 500°C	CO_2 60 bar 500°C	water 150 bar 300°C	sodium 1 bar 500°C	FLiBe T > 450°C
ρ	kg/m^3	3.7	40.9	726	865	1940
c_p	kJ/kg.K	5.2	1.2	5.6	1.3	2.3
ρc_p	$kJ/m^3.K$	19.4	48.6	4066	1125	4540
λ	W/m.K	0.29	0.06	0.56	80	1.0
μ	10^{-5}*Pa/s	3.8	3.3	9.0	23.3	563
Pr	-	0.67	0.66	0.90	0.004	13.2
relative merit* (ref. Na)	-	0.001	0.003	51	1	14

*merit factor = $c_p^{2,8}\rho^2\mu^{-0,2}$

Good compatibility with water , air,…Non flamable, low toxicity, low cost,..

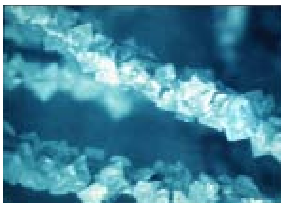
CADARACHE

Some other examples of salts :

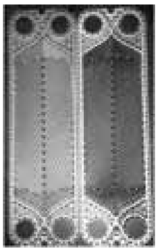
Sel	Composition	Tfusion	Tmax	Density at 300 ° C	Used for solar plants
Hitec	7%$NaNO_3$ 40%$NaNO_2$ 53%KNO_3	142 ° C	535 ° C	1,6	THEMIS (2,5MWe)
Drawsalt	46%- 60%$NaNO_3$ 54%- 40%KNO_3	220 ° C	600 ° C	1,9	SOLAR 2 (10MWe)

- **Salts at low melting point to be compared / criteria previously defined.**

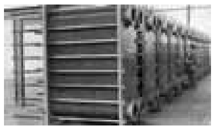
CADARACHE



Na chemistry



View of corrugated plates (courtesy of Alfa-Laval Vicarb)



View of plate heat exchanger (courtesy of Alfa-Laval Vicarb)

Minasama domo arigato gozaimashita !

Pb-Bi studies

ISIR US developments

Na school in CEA-Cadarache

CADARACHE