ESFR-SMART
sodium fast reactor safety

WP:	**WP3.1 "Dissemination, education and Training"**
Task:	3-1-3 Workshops & Seminars
Speaker:	Christian LATGE,
Affiliation:	CEA-Cadarache, Nuclear Energy Directorate, Department of Nuclear Technology
Event:	**Spring School (W6)**
When:	March 29th -31st 2021
Where:	UCAM Cambridge (United Kingdom) (Remote Meeting)

Overview of Sodium Fast Reactors in the world.

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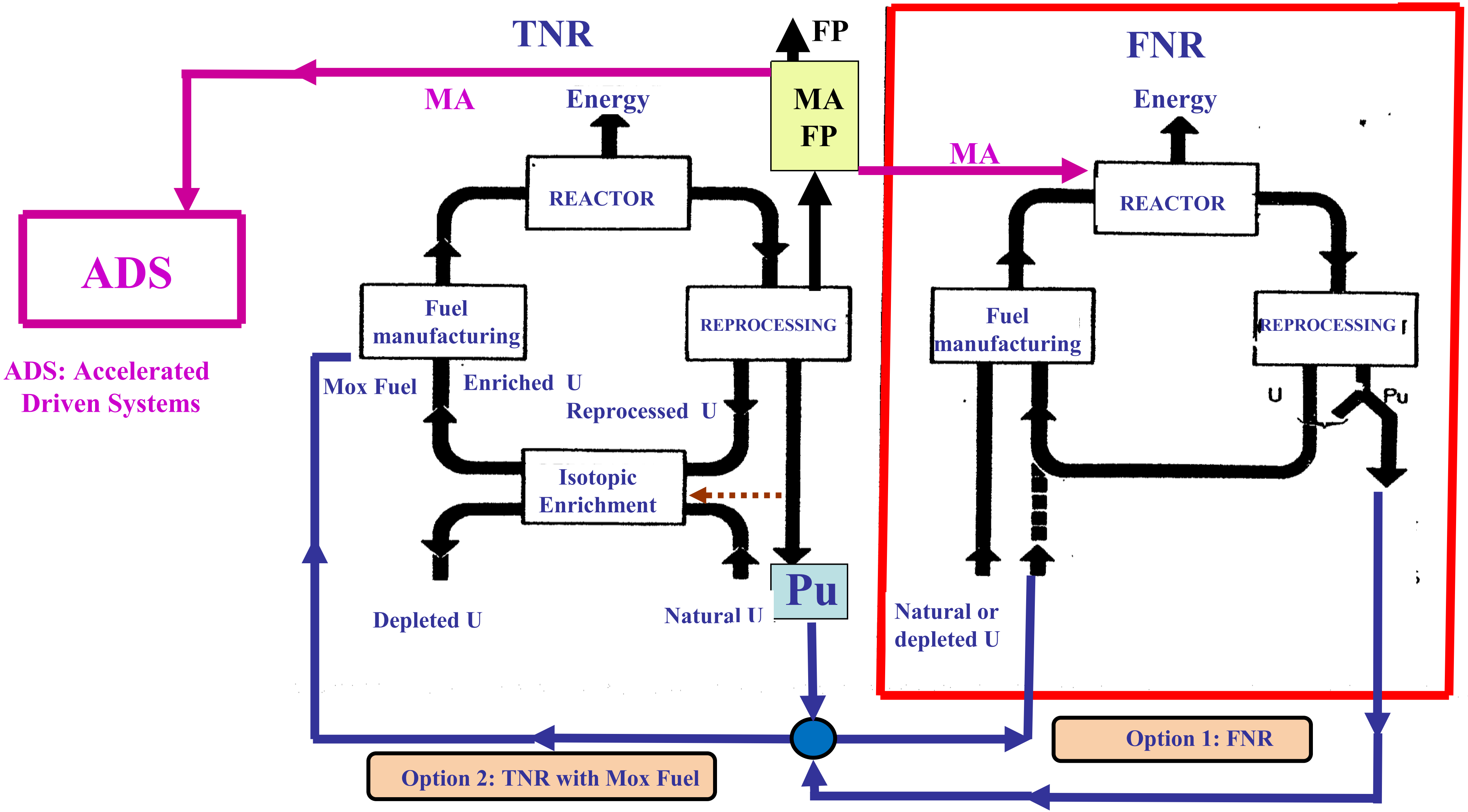
This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754501.

Fuel Cycle: Thermal Neutron Reactor and Fuel Neutron Reactor

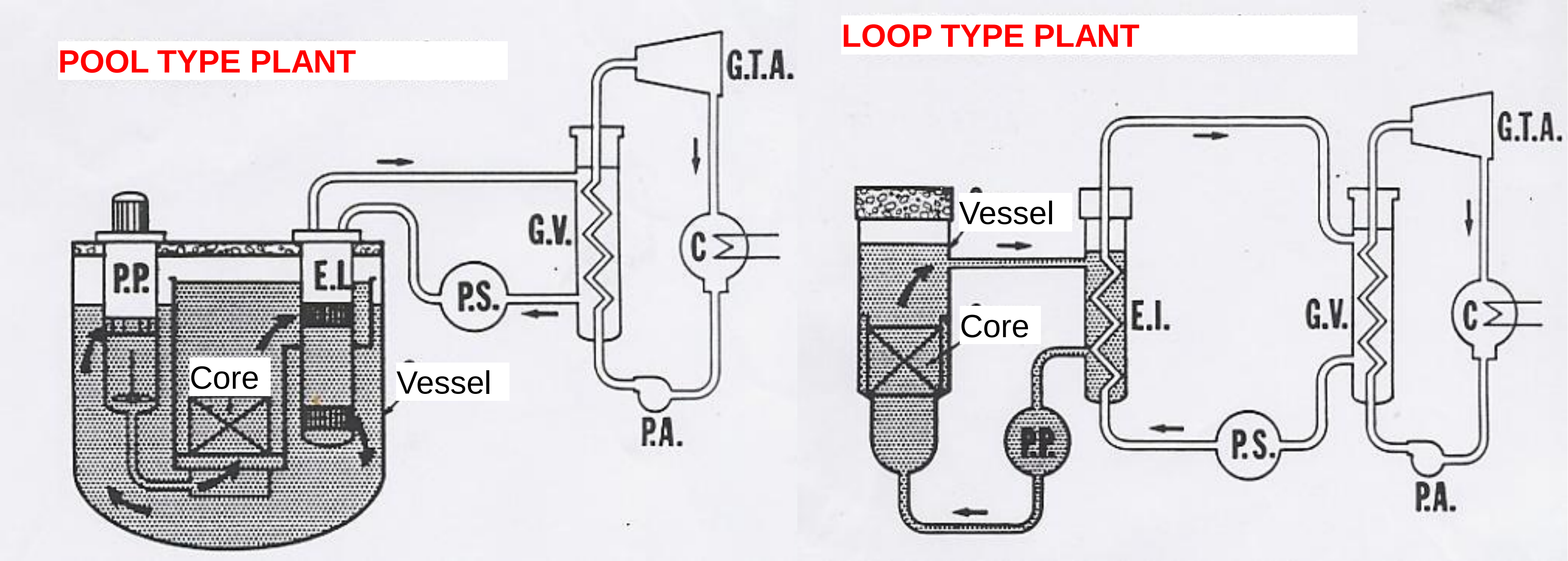
TNR= Thermal Neutron Reactors

FNR= Fast Neutron Reactors

MA= Minor actinides
FP= Fission Products

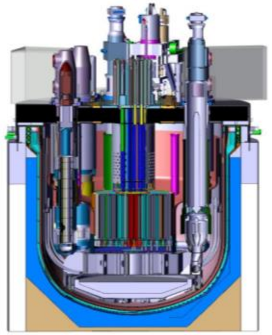


INTRODUCTION ON SFR (POOL OR LOOP CONCEPT)

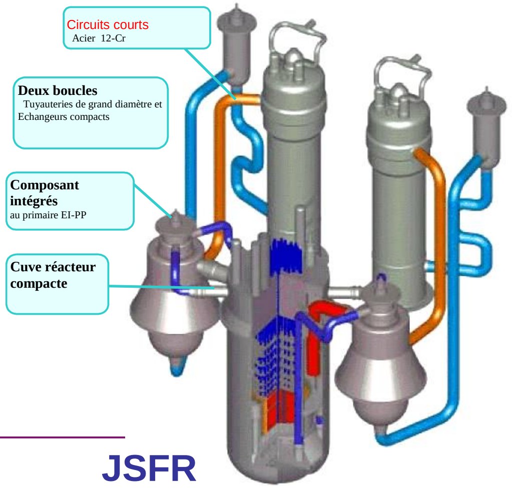


Two reactor designs

Four parts:
- Fuel
- Structures
- Coolant
- Instrumentation & Control systems



ASTRID



JSFR

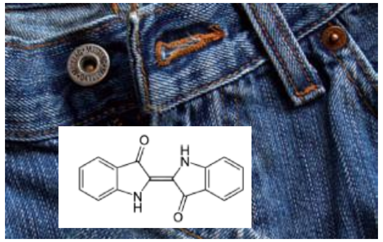
Coolants: Sodium (Na)

The so-called « natron » was already known from Aegyptians, as « **neter** », from ancient Aegyptian langage **nṯr(ĵ)**, word which means that this product was extracted from dryed lake, located in the desert of « Nitrie » **(Wadi El Natrun)**.

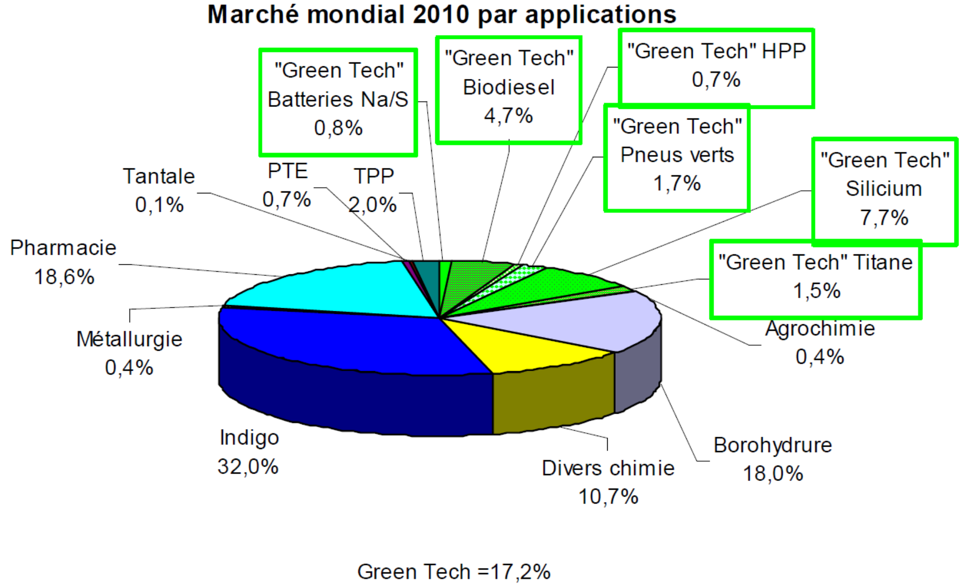
Wadi El Natrun

No specific toxicity (like lead) but irritation and local corrosivity
Biological utility: essential
Daily recommended consumption: 2 to 15g;
MNa in human body (70kg): 100g
- **Bones: 10 000 ppm**
- **Blood: 1970 mg/l**

Yearly output: c. 200 000 ton.year^{-1}

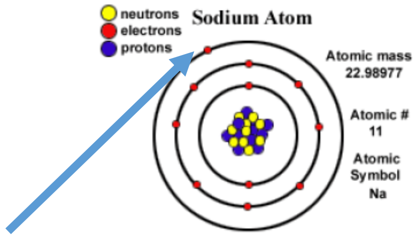


Some explanations:
-TPP triphenyl phosphine used for the synthesis of vitamin A
-HPP High Performance Pigment



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

قَلَوِىّ



	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: MAIN PROPERTIES

- a coolant which does not slow down the neutrons,

- a very limited activation, with short decay periods (^{22}Na: 2.6 years, ^{24}Na: 15 hours), and no α emitters (such as ^{210}Po)

- no specific toxicity (but corrosivity)

- large availability (used for many applications: chemistry, Dynamo, Solar Plants, batteries…) and cheapness

- Large temperature range (liquid): 97.8 to 882.8 °C

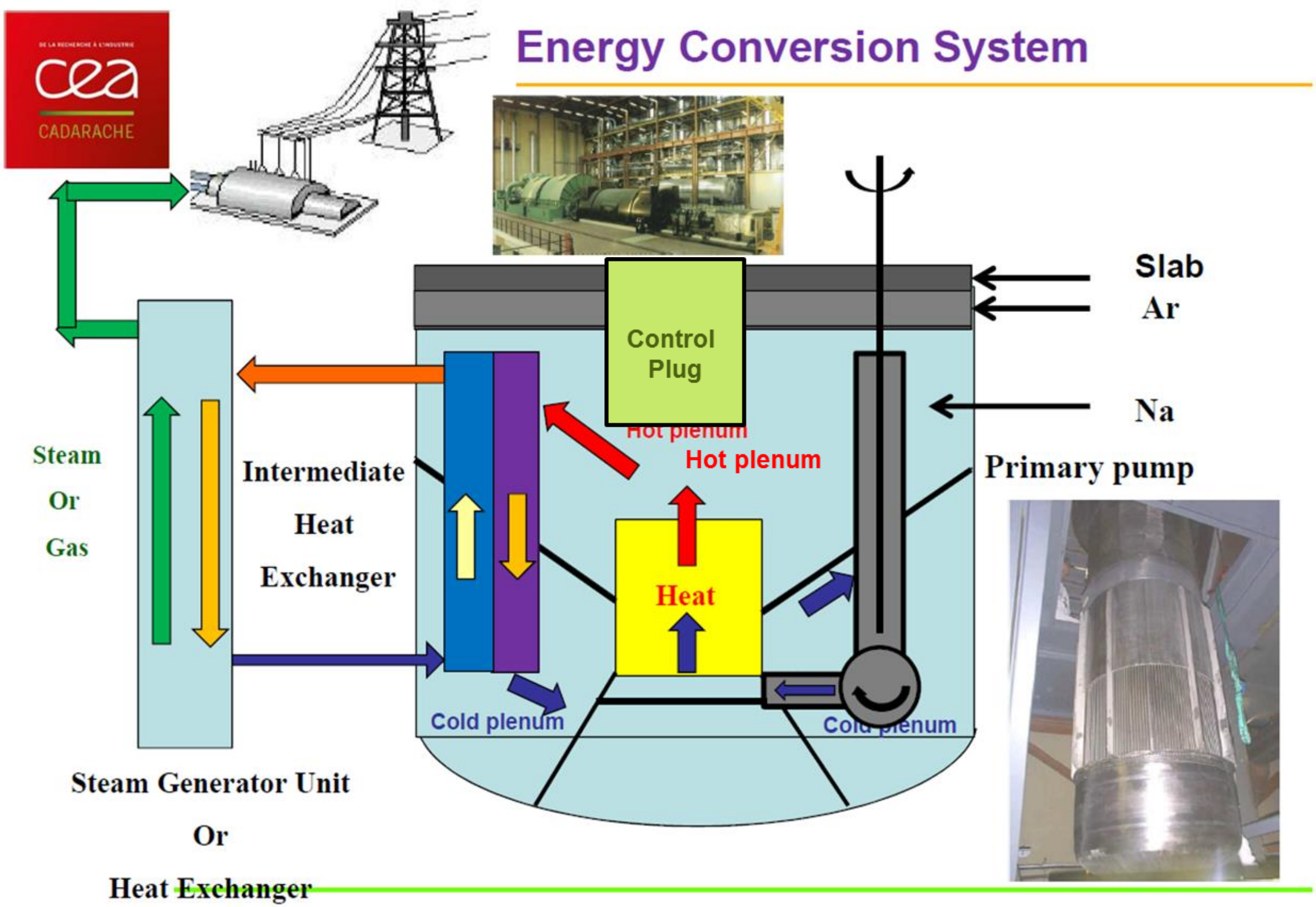
- a very good compatibility with steels: no liquid metal embrittlement and very low corrosion kinetics, limited mass transfer and consequently low dosimetry, demonstrated by years of operation.

- a very limited amount of particles in sodium, due to the instability of ternary oxides (except $NaCrO_2$) and high dissolution rates in Na, due to its reducing properties,

- low oxygen and hydrogen solubilities in Na, almost nil near the melting point, allowing its purification thanks to cooling below their saturation temperature (O and H), called “cold trap”

- a very important reactivity with water - possible deleterious effects in Steam Generator Units (SGU), in case of pipe rupture, but possibility to clean structures for maintenance, treat Na bulk during decommissioning phase

- an important chemical reactivity with air, which can induce Na fire.



CADARACHE
Energy Conversion System
Slab
Ar
Na
Primary pump
Control Plug
Hot plenum
Hot plenum
Heat
Steam
Or
Gas
Intermediate
Heat
Exchanger
Cold plenum
Cold plenum
Steam Generator Unit
Or
Heat Exchanger

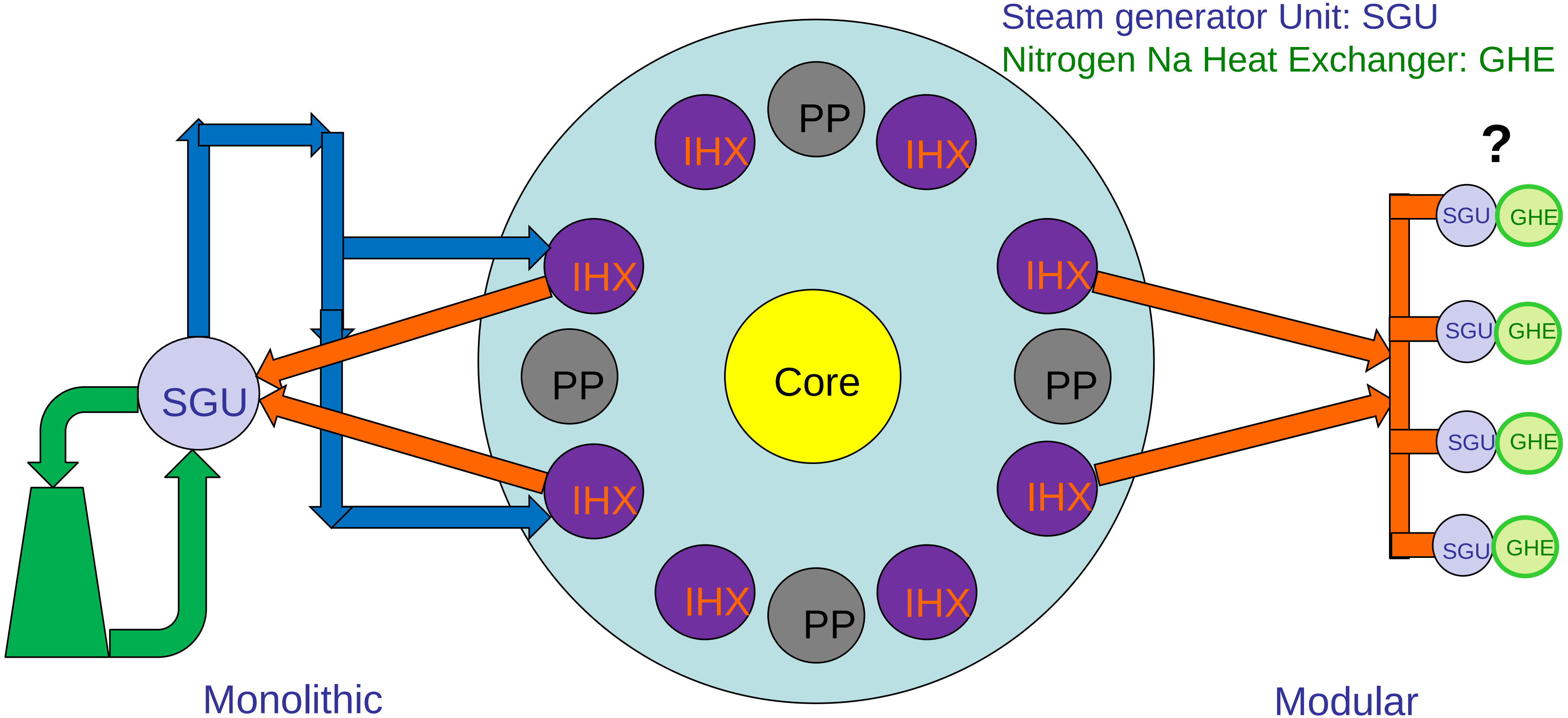
PRIMARY CIRCUIT OF SFR (POOL CONCEPT) 2/2

Primary pump: PP

Intermediate Heat Exchanger: IHX

Steam generator Unit: SGU

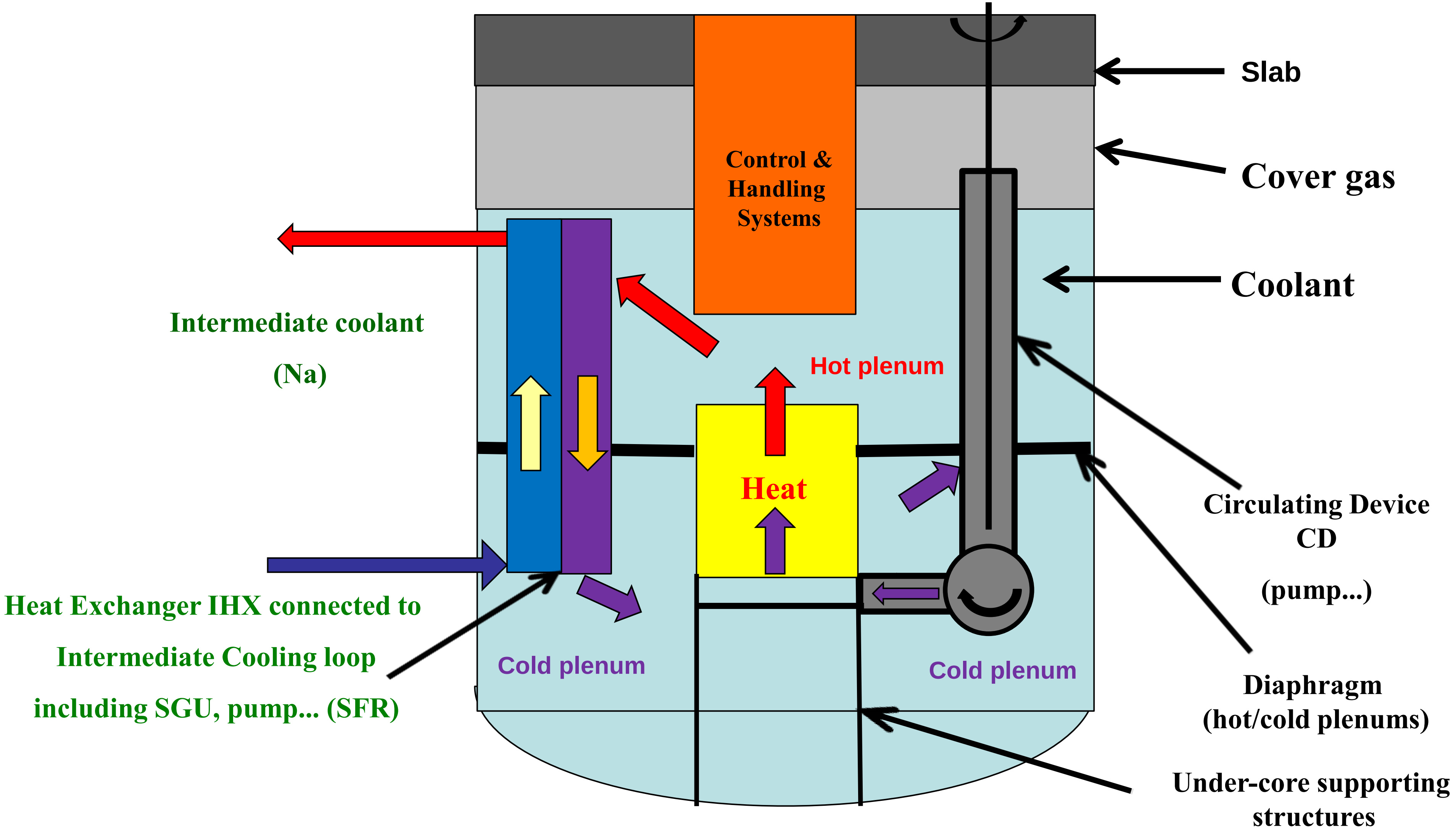
Nitrogen Na Heat Exchanger: GHE



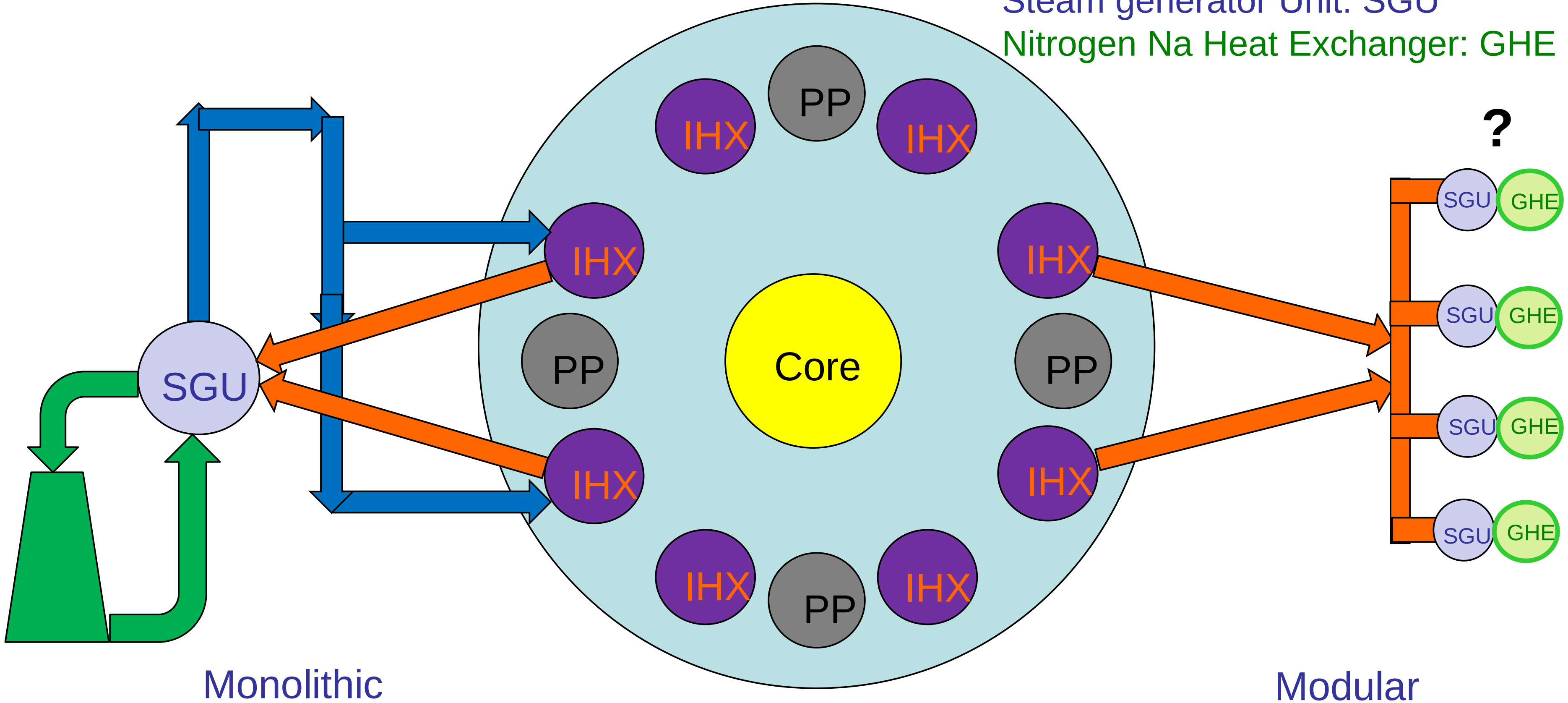
Monolithic
Steam generator

Modular
Steam generator
Or
Gas Heat Exchanger

PRIMARY CIRCUIT OF SODIUM FAST REACTORS (POOL CONCEPT)



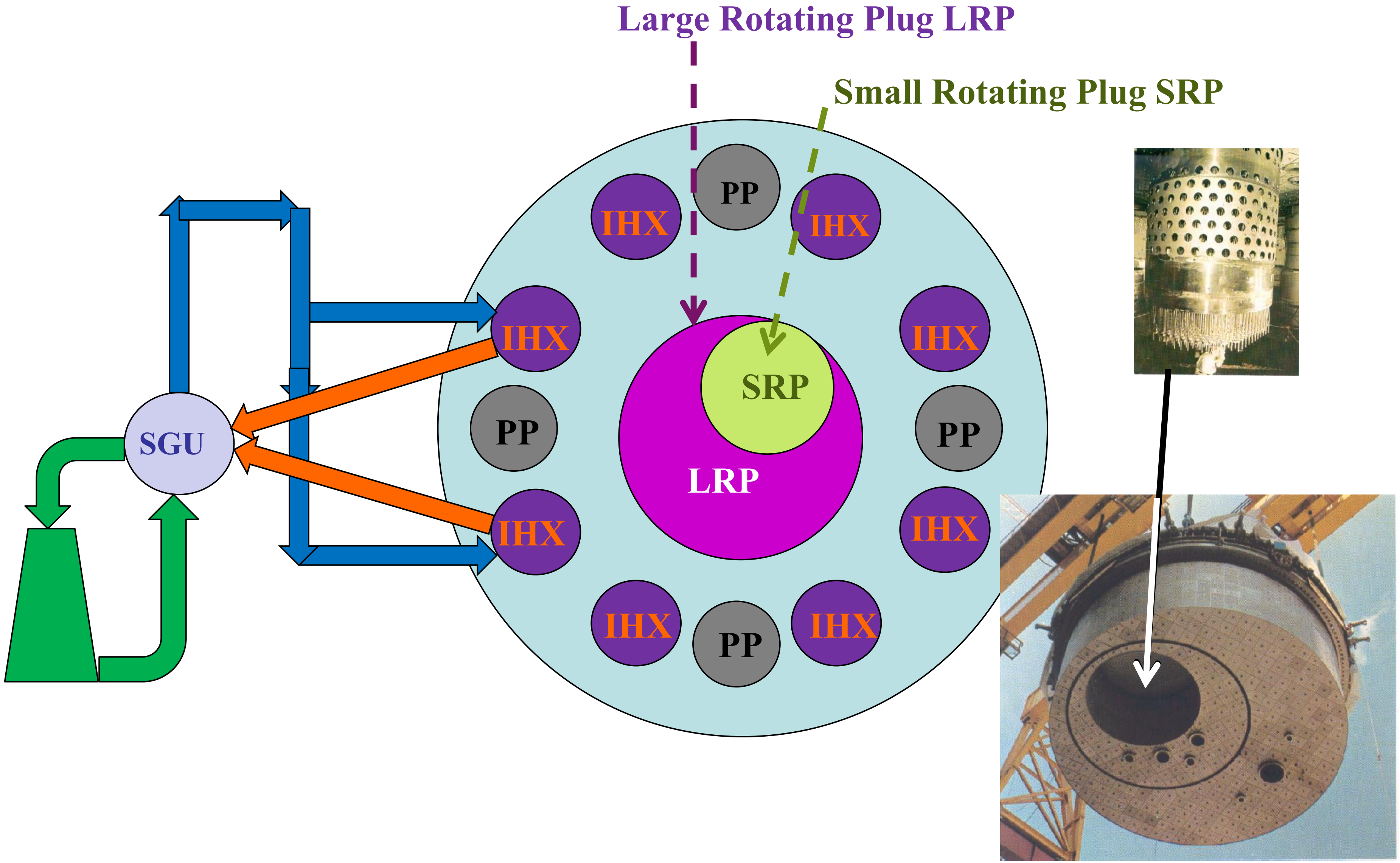
Primary pump: PP
Intermediate Heat Exchanger: IHX
Steam generator Unit: SGU
Nitrogen Na Heat Exchanger: GHE



Monolithic
Steam generator

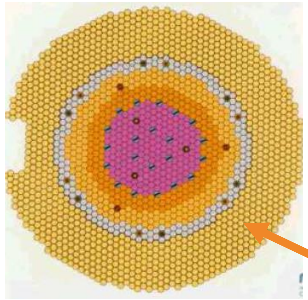
Modular
Steam generator
Or
Gas Heat Exchanger

ROTATING PLUGS



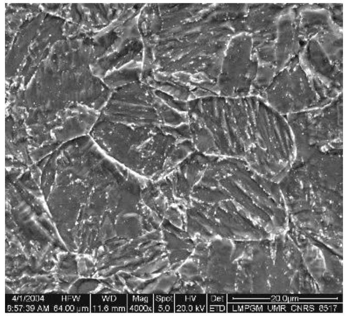
Sodium Fast Reactor:

Instrumentation



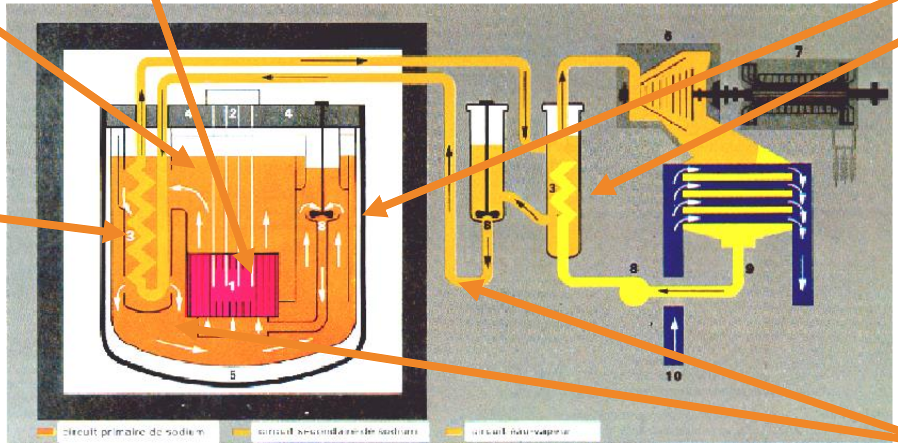
Core

Fuel



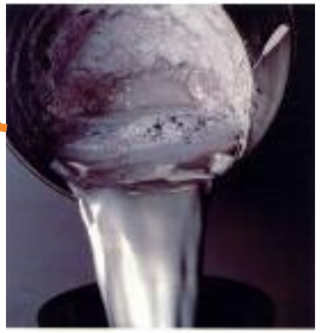
Structural Material

Components (IHX)



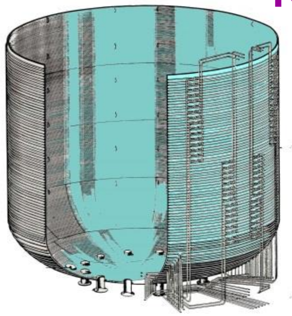
Reactor

Energy Conversion System

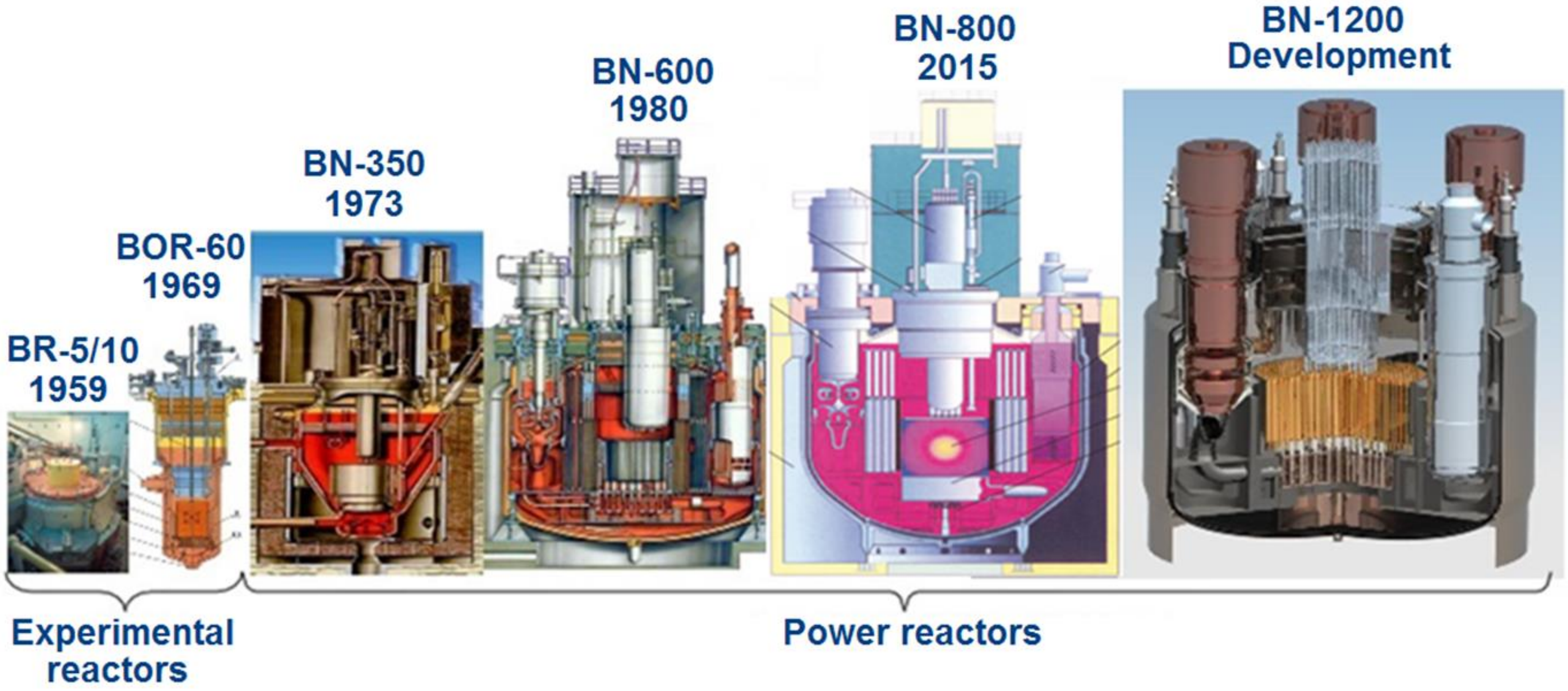


Sodium

Primary vessel



SFRs in Russia



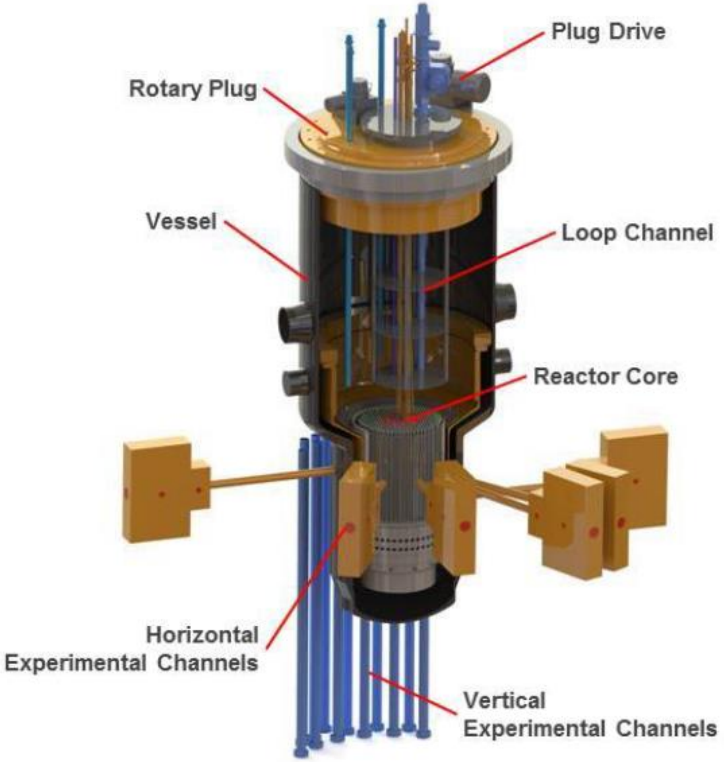
Courtesy IPPE

Unique research facility

ROSATOM

MBIR is a Multipurpose Sodium Fast Research Reactor

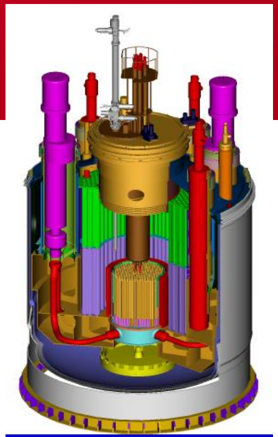
- 150 MW(t)
- Maximum neutron flux $5.3 \cdot 10^{15}$ n/(cm^2·s)
- Designed life time 50 years
- Upgradeable experimental capabilities: more loops, irradiation devices, channels, neutron beams, etc.
- Priority on research activities providing reliability and safety of operation
- Using of existing infrastructure (incl. fuel supply), the unique operation experience and staff resources of RIAR
- Closed fuel cycle



Top intended mission — enhancement of international R&D infrastructure

Courtesy IPPE

SFRs in China


CEFR Reactor Block

- Scientific certification
- Fuel and material study
- Training and experience feed back
- Engineering technology beginning

CEFR

CFR20

CDFR

CFR600

- Industry demonstration
- The system of the standard and rules for FR build and verification
- The power scale FR engineering experience accumulate
- Economic verification

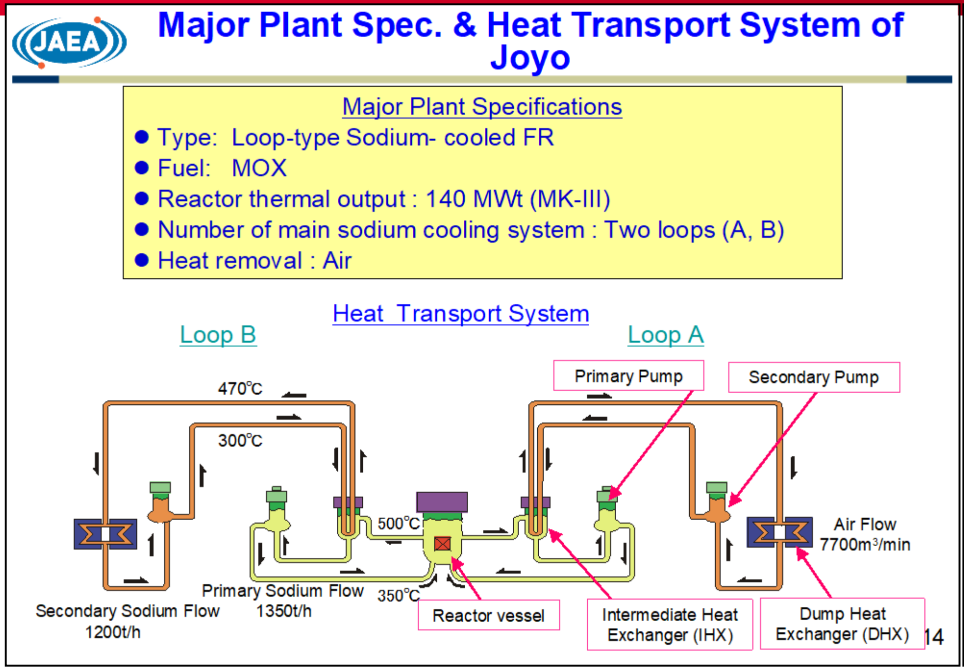
CCFR

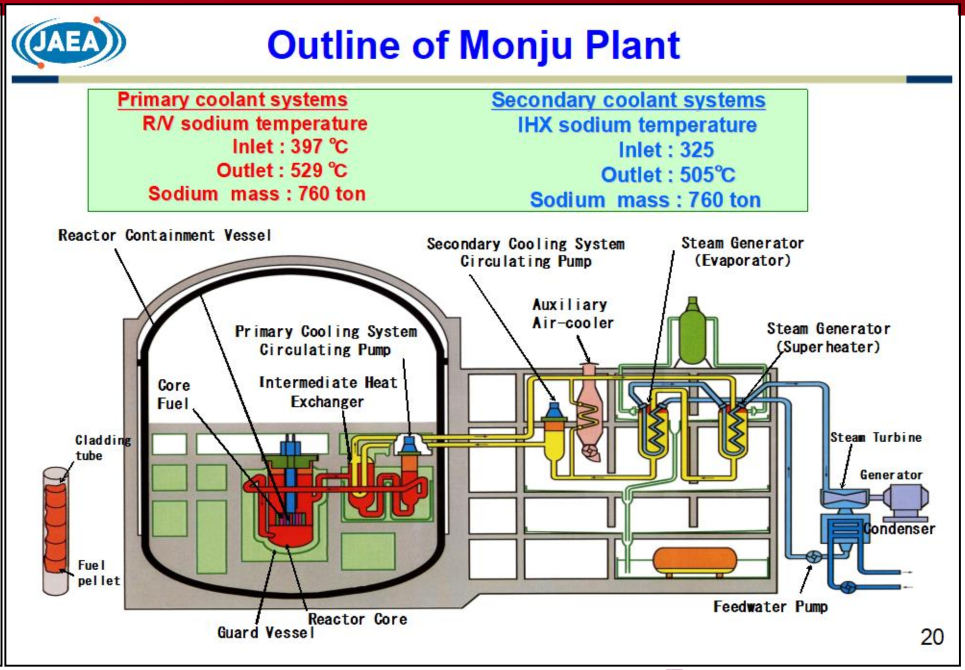
~CFR1200

- Commercial operation
- Support of the advanced fuel cycle system
- Serially developing
- Fit the GIF Requirement

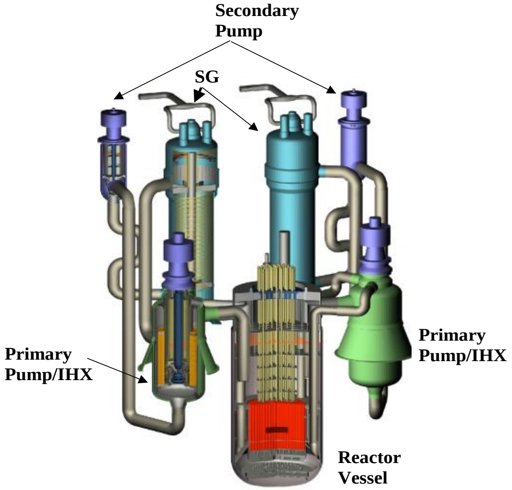
Courtesy CIAE

SFRs in Japan





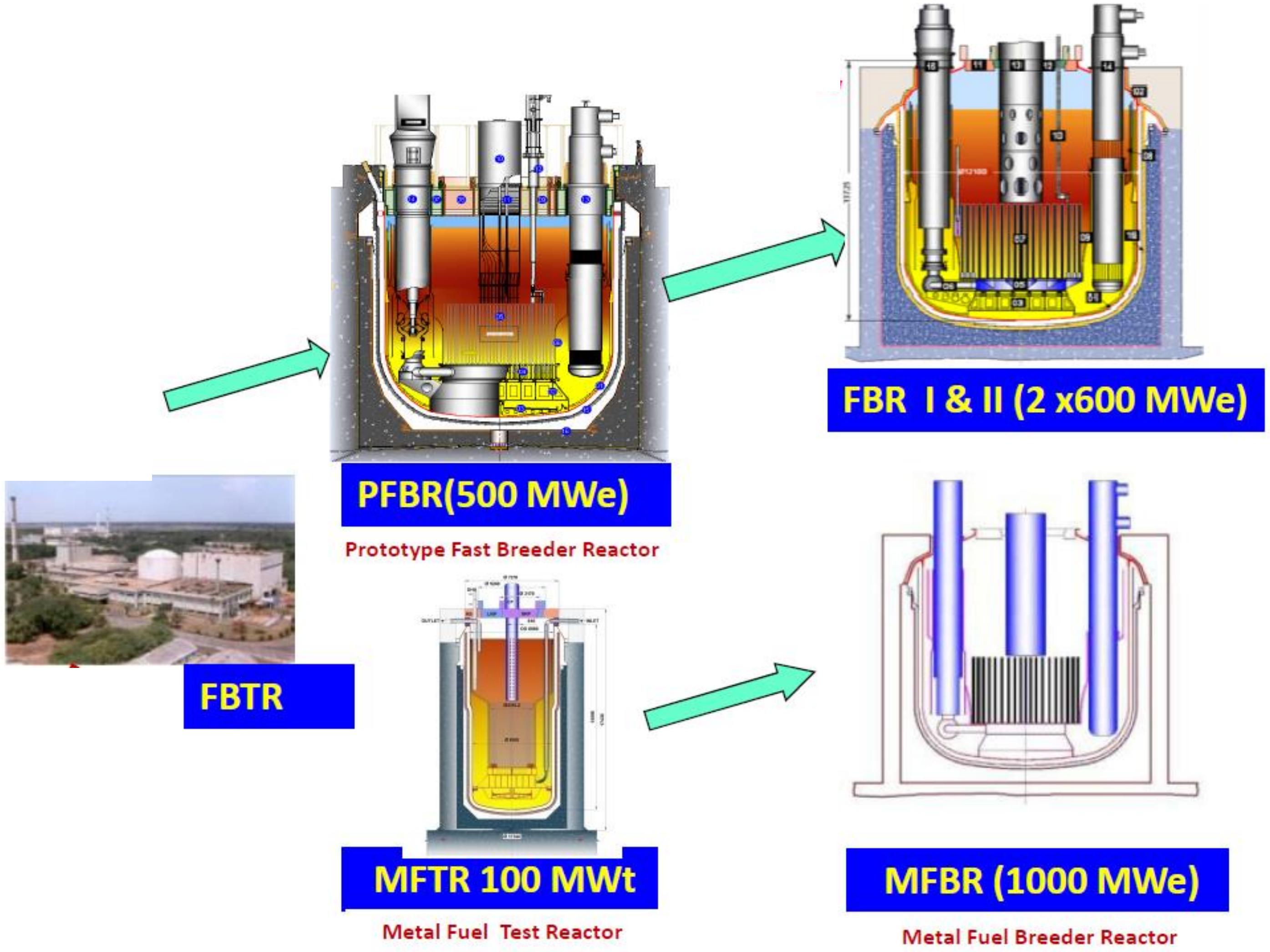
JSFR



Courtesy JAEA

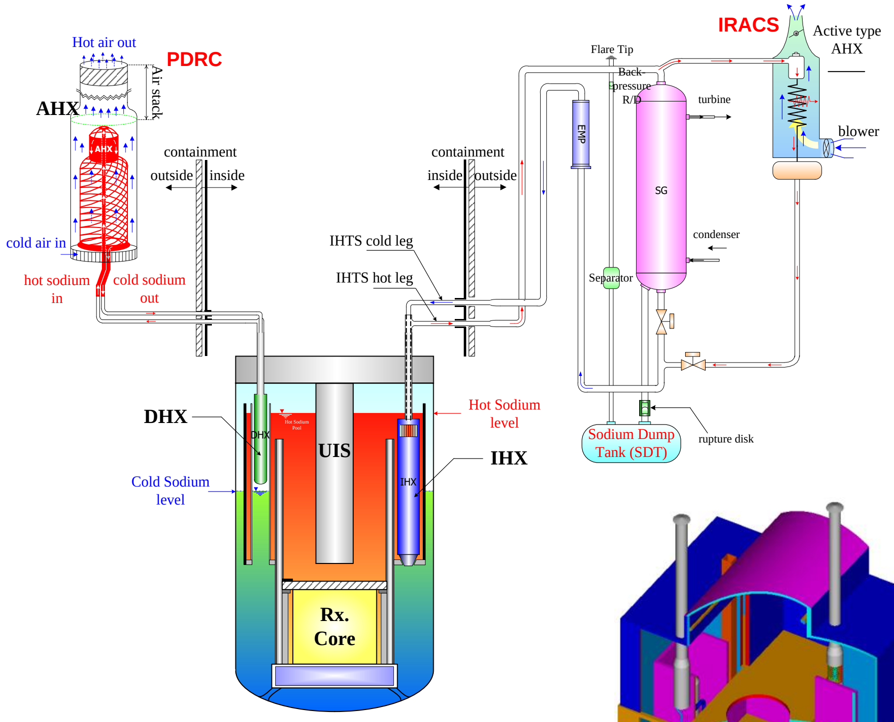
SFRs in India

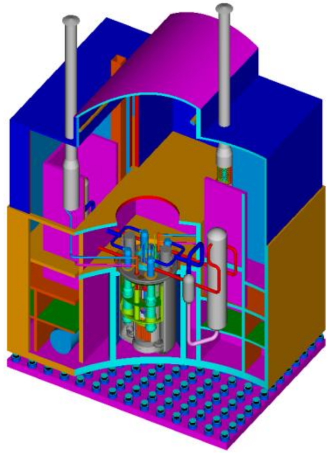
Courtesy IGCAR



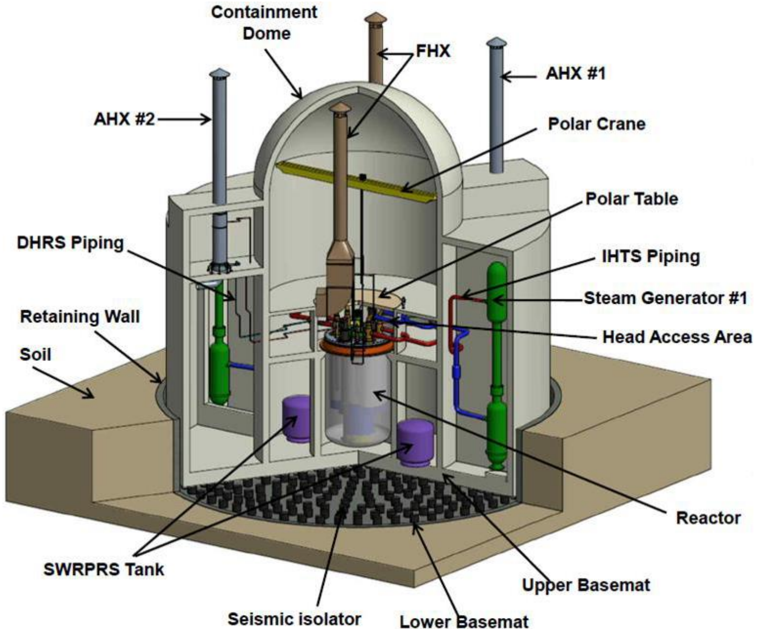
SFRs in Korea

Courtesy KAERI





KALIMER 600



PGSFR

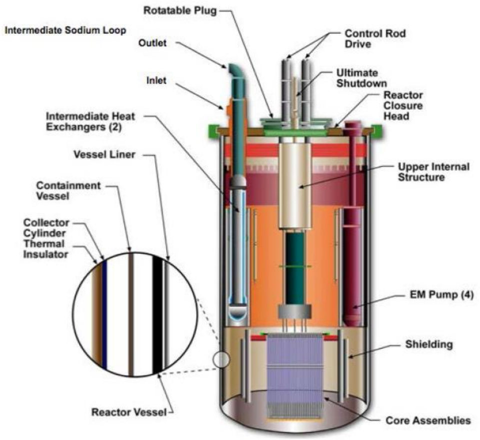
SFRs in USA

Courtesy US-DOE and INEL

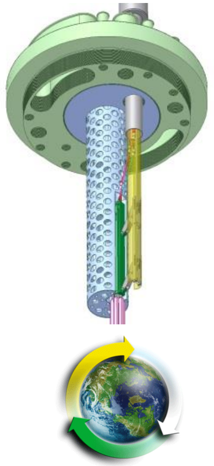
U.S. main operating experience

- **First usable nuclear electricity was generated by a fast reactor – EBR-I in 1951**
- **EBR-II (20 MWe) was operated at Idaho site from 1963 to 1994**
  - *Closed fuel cycle demo*
  - *Passive safety tests*
- **Fast Flux Test Facility (400 MWt) operated from 1980 to 1992**
- **FERMI, ….**

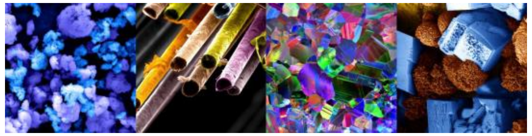
Recent U.S. project experience



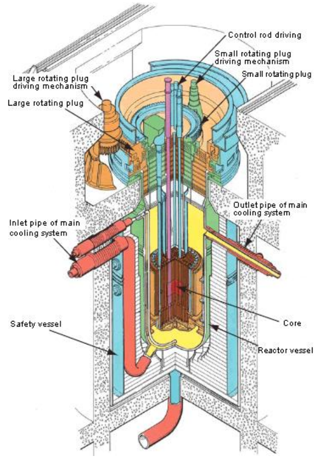
PRISM



ABR

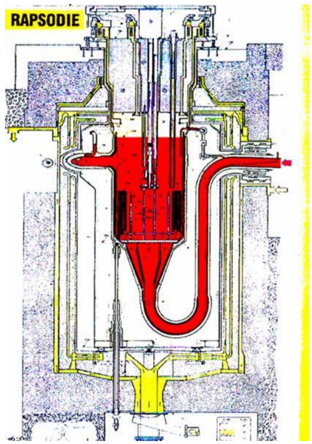


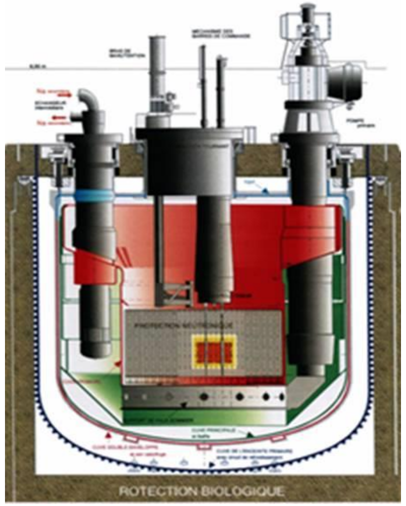
GAIN – Gateway for Accelerated Innovation in Nuclear Enabling a Nuclear Energy Future

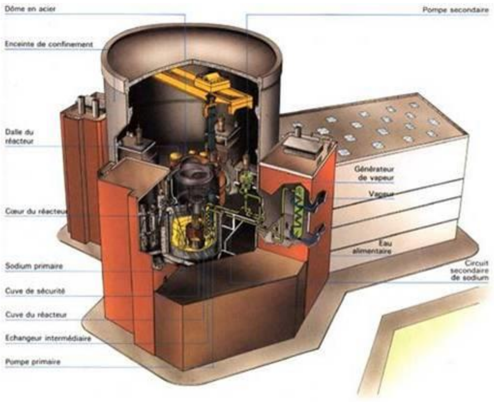


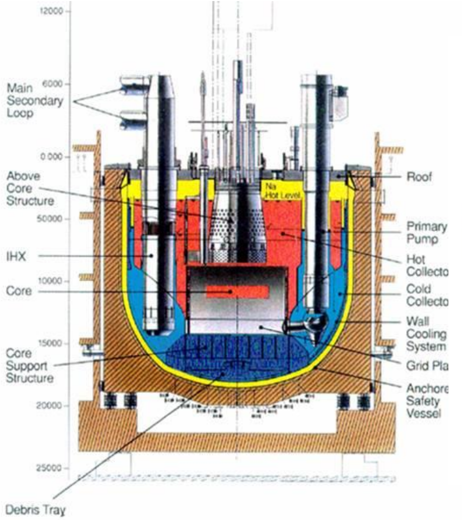
VTR – Versatile Coupled Test Reactor

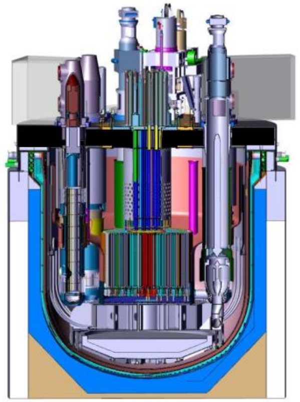
SFRs in France

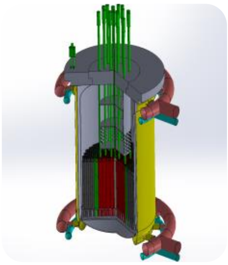












EFR (I, F, DeBeNe, UK)

ASTRID (F, Japan & EU)

SFR Research & sketches

RAPSODIE

PHENIX

SuperPhenix (DeBeNe, I, F)

RNR-1500
SPX2

6 SFR REACTORS IN OPERATION IN THE WORLD

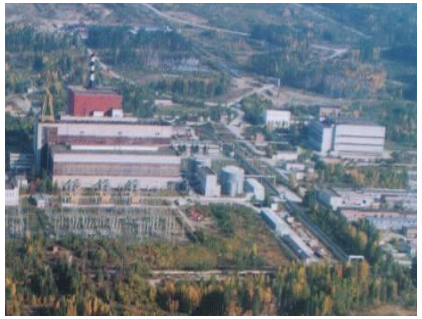
JOYO

FBTR

CEFR

BOR 60

BN600



BN800

SFR REACTORS IN CONSTRUCTION OR COMMISSIONING PHASE

Reactor in construction phase

MBIR (Russia)
Multifunctional fast neutron sodium-cooled research reactor
150 MWt

Courtesy ROSATOM

CFR 600 (China)
(2 Units)
600 Mwe
Xiapu 1
(Start-Up foreseen in 2023)

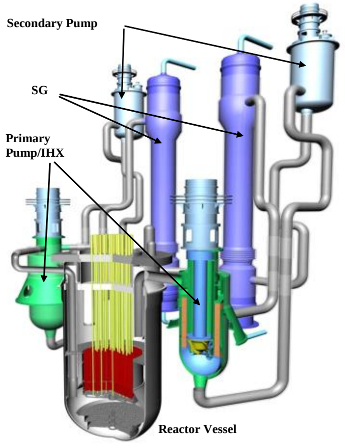
Reactor in commissioning phase

PFBR (India)
5OO Mwe
Kalpakkam
(Start-Up foreseen in 2022)

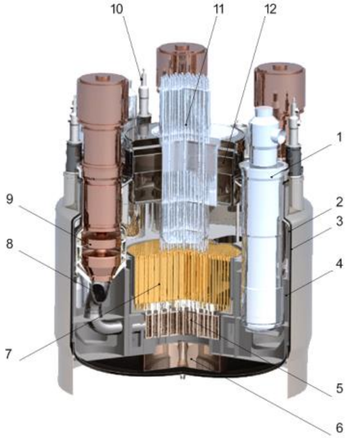
Courtesy Bhavini & IGCAR

DE LA RECHERCHE À L'INDUSTRIE

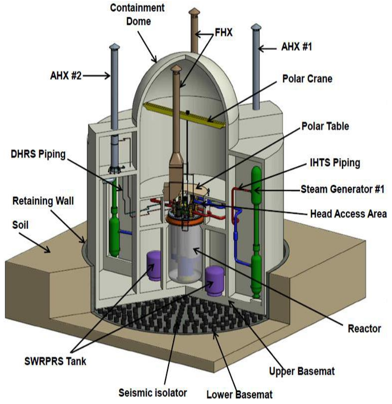
AND SFR PROJECTS



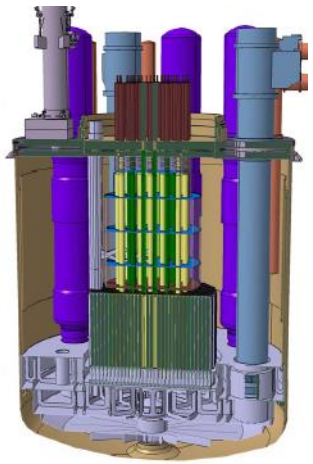
JSFR
(Japan)



BN 1200
(Russia)

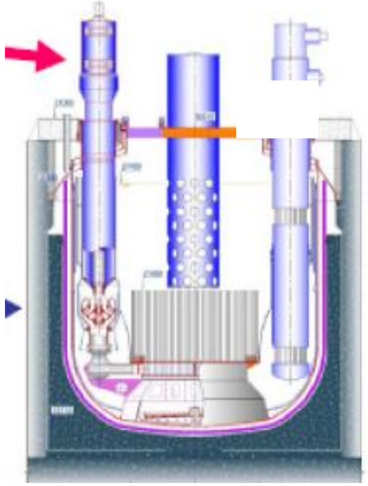


PGSFR
(Rep of Korea)



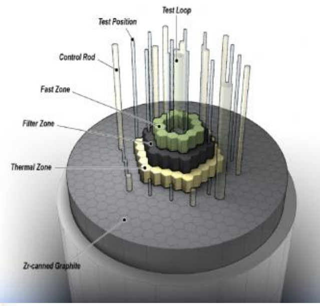
Astrid
(France EU
Japan)

Now SFR R&D



FBR-1-2
(India)

CCFR
(China)



VTR
(USA)

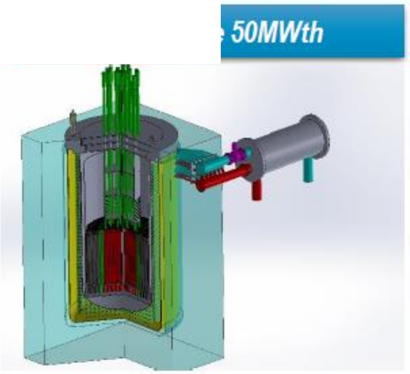
SMR, AMR : NEW TREND FOR NUCLEAR REACTORS

■**Small ModularReactor: concept of low-medium power reactor (< 500 MWe max, often 50 et 200 MWe) which often bases its economical model on the following characteristics:**

- ❑Size effect => modularization and factory manufacturing
- ❑Design simplification effect induced by the reduced power
- ❑Serial effect, reduction in construction time and associated cost effect (borrowing rate…)
- ❑Geographic niches, sometimes non-generators applications (calogen)

■**Advanced ModularReactor: Type of SMR whose design uses significant innovations and often dedicated to reactors using Gen-IV coolants ie Na, Pb, molten**

These reactors can be terrestrial or for naval propulsion



Atrium Reactor CEA

and several other concepts LFR, MSR….

PARTNERSHIPS AROUND ASTRID PROGRAM

R&D
generical

GEN IV International Forum

SEVENTH FRAMEWORK PROGRAMME

EERA European Energy Research Alliance

SNETP Sustainable Nuclear Energy Technology Platform

ESNII European Sustainable Nuclear Industry Initiative

Steering by CEA

around
600 people

ARDECo

EDF R&D, PSI,
Sweden (KTH, Chalmers, Uppsala), HZDR,
IPUL, KIT, ENEA, *JRC/ITU, NNL, CIEMAT,*
...
CNRS (NEEDS), universities (PhD...)

NEA-OECD, IAEA multilateral actions

AIRBUS SAFRAN LAUNCHERS

GE AREVA

Industrial

partners

EDF

TOSHIBA

ONET TECHNOLOGIES

ALSTOM

Rolls-Royce

PNB LE PÔLE DE L'INDUSTRIE NUCLÉAIRE

BOUYGUES CONSTRUCTION SERVICES NUCLÉAIRES

SEIV ALCEN

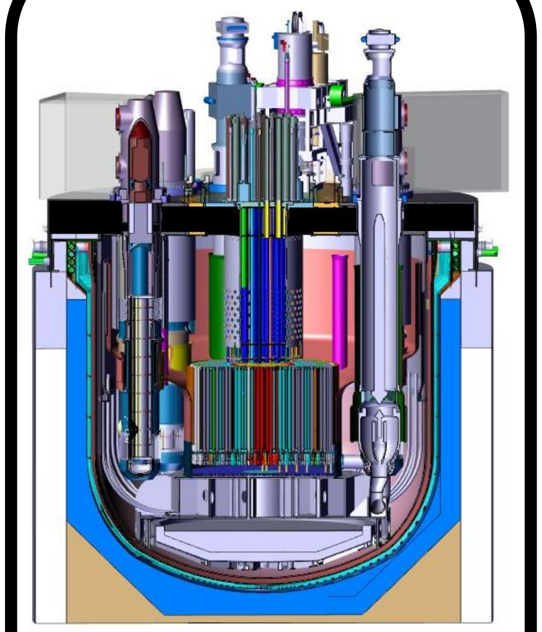
JAEA MFBR Systems, Inc. MITSUBISHI

VELAN

CNIM IMAGINER ET AGIR

NOX GROUP

Technetics GROUP



STRATEGIC CONTEXT OF CEA PROGRAMS DEDICATED TO THE CLOSURE OF THE FUEL CYCLE

- Industrial players, CEA and the State conducted a review of fast neutrons reactors (FNR) and fuel cycle strategy in 2018. This is now translated into the Multiannual Energy Program (PPE) and in the Strategic Contract for the Nuclear Sector concluded between the State and nuclear industry (CSFN)

- The review concluded that the perspective of industrial deployment of Fast Reactors is more distant. Yet it has been concluded to keep this option open, requiring to:

  - maintain competences,

  - progress on technological barriers and

  - further develop know-how.

- The strategy for complete closure of nuclear fuel cycle (meaning complete recycling of recoverable materials) is maintained as a long-term sustainability objective.

- Challenges for achieving full recycling in the long term:
  - Need to use FNRs,
  - The sodium technology, the most mature, to be consolidated, but interest in evaluating other technologies.

- Shorter term stakes :
  - Management of the decrease in the UOx flow in factories by closing 900 MW reactors and use of MOX fuel in 1300 MW reactors
  - Investigation of nuclear fuel multi-recycling in PWR as a possible intermediate step

Post ASTRID, a new program for FNR developments
=>R&D on the reactor technologies

A multi-year work-program with 2 main tracks :
- **R&D on SFR technologies,** needs identified during the ASTRID program (the major ones) +
- **exploratory design studies** (reactor sketches)
  and **survey on all Gen IV reactor technologies**

R&D adressing the main issues of the SFR

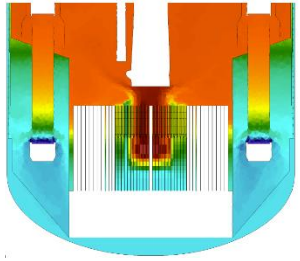
Improving the economy and the operability
- To increase the **UPuO2 fuel performances**
- To justify **the lifetime of reactor structures** immersed in the sodium (60 years lifetime)
- To make the **"inspection"** of submerged structures possible

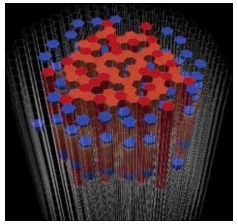
Progress in safety and security
- Confirm the strategy of prevention and mitigation of severe accidents through studies and tests **+ multi-scale and multi-physics** modeling and simulation
- Consolidate the **sodium risk** mitigation strategy

Exams performed in hot cell

long duration swelling test

Core cooling by sodium natural circulation postulating failure of all forced circulation means



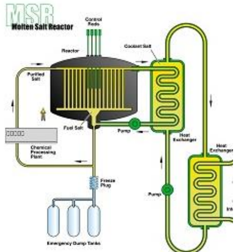


Coupling N / TH

Exploratory design studies *->new concepts*

AMR/SFR (sketch studies, identification of cost reduction solutions)

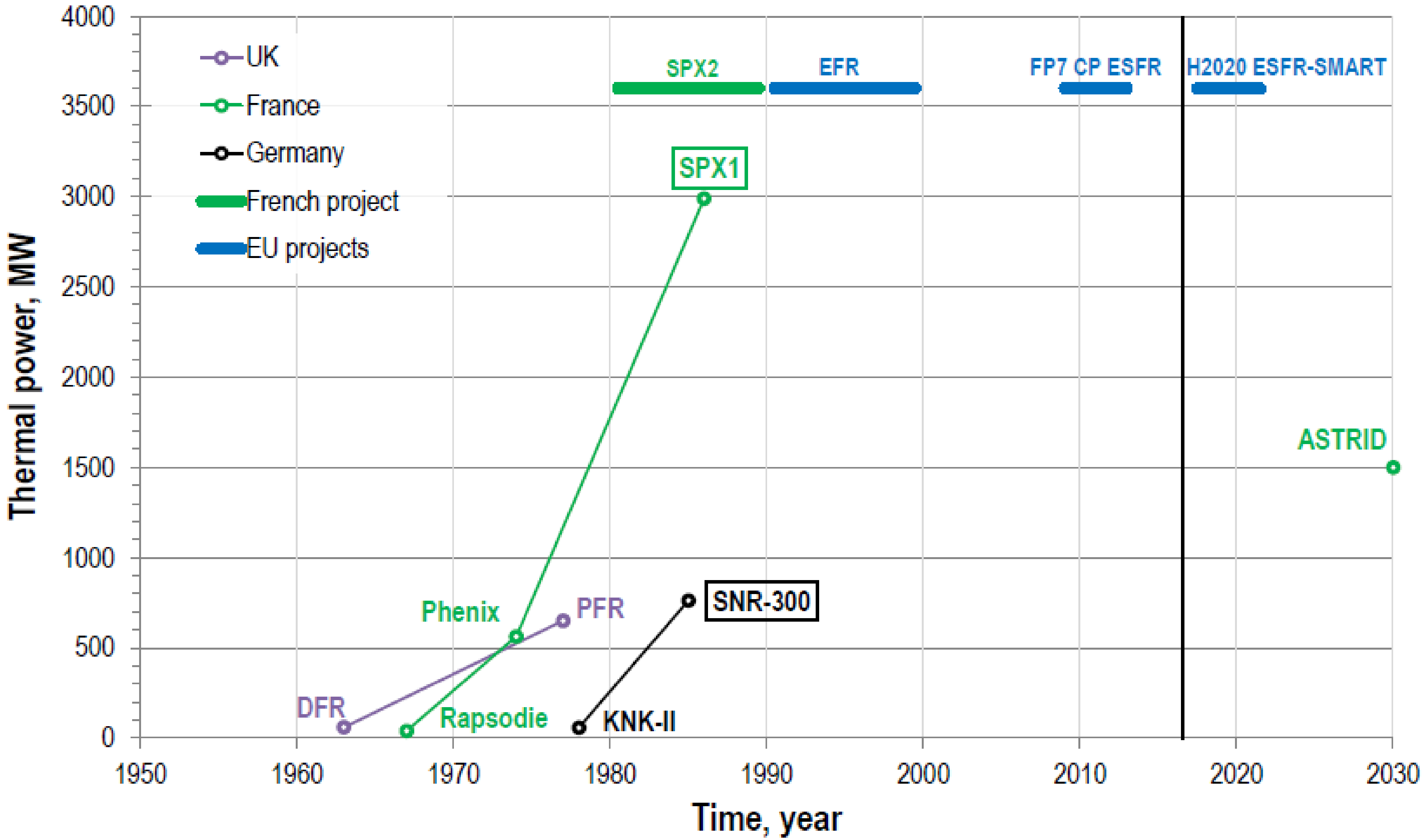
MSR (faisabilility, identification of technological barrier)



Molten Salt Reac

Thank you for your kind attention

Synthesis on European SFR Reactors



Summary of SFR operational experience and selected SFR projects in EU (framed are reactors stopped before end of their lifetime);