DE LA RECHERCHE À L'INDUSTRIE

Candidate Coolants & Fast Reactor Types

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Outline

1 – Early Fast Reactor Projects: from Hg & NaK to sodium

2 – Strengths and constraints specific to sodium

3 – Non-sodium cooled fast reactor concepts

4 – Current prospects for future Fast Neutron Reactors: medium term projects and longer term research

5 – International cooperation *(Gen IV Forum, EU SNE-TP…)* Challenges & Perspectives

History of Fast Reactor Coolant Selection

Criteria

- ***Low effects of neutron moderation*** and absorption → « Heavy » liquid metals
- ***Range of operating temperature*** & Heat removal capability
- ***Chemical stability*** *(element, eutectic alloys…)*
- ***Availability and cost***

Coolant	Melting point	Boiling point
Mercury	- 38.8 °C	356.7 °C
NaK eutectic	-11 °C	785 °C
Sodium	97.7 °C	883 °C
PbBi eutectic	123.5 °C	1670 °C
Lead	327.5 °C	1749 °C

- Interaction with materials *(corrosion, stress corrosion, embrittlement…)*
- Impact on reactor operation and in-service inspection & repair
- Reaction with air and Nuclear Power Plant working fluids and nuclear fuel

Fast Neutron Reactors in the World

Year	Reactor	Country	Power	Coolant
1946	Clementine	USA	25 kW	Mercury
1951	EBR-1	USA	1,4 MW	NaK
1956	BR-2	USSR	100 kW	Mercury
1959	BR-5	USSR	5 MW	Na, NaK
1959	DFR	Great Britain	60 MW	NaK
1962	EBR-2	USA	62 MW	Na
1963	Enrico Fermi	USA	300 MW/60MWe	Na
1967	Rapsodie	France	20-40 MWe	Na
1969	BOR-60	USSR	60 MW	Na
1973	BR-10	USSR	8 MW	Na
1973	BN-350	USSR	1000 MW/250 MWe + Water	Na
1973	Phenix	France	250 MWe	Na
1974	PFR	Great Britain	250 MWe	Na

Fast Neutron Reactors in the World

Year	Reactor	Country	Power	Coolant
1977	Joyo	Japan	140 MW	Na
1978	KNK-II	Germany	20 MWe	Na
1980	BN-600	USSR	600 MWe	Na
1980	FFTF	USA	400 MW	Na
1985	SNR-300	Germany	300 MWe	Na
1985	FBTR	India	40 MW/13.2 MWe	Na
1986	Superphenix	France	1200 MWe	Na
1995	Monju	Japan	250 MWe	Na
2010	CEFR	China	65 MW/20 MWe	Na
2013	*PFBR*	*India*	*500 MWe*	*Na*
2014	*BN-800*	*Russia*	*800 MWe*	*Na*

→Convergence on sodium for NPPs so far

- Availability, cost, neutronic properties, operating temperature, heat removal capability, low corrosion… + ***Interest in high power density (~250 MW/m^3)***
- Specific technologies developed for sodium systems & nuclear fuel management

Fast Reactors for Nuclear Submarines

USS Seawolf (1957-1959)

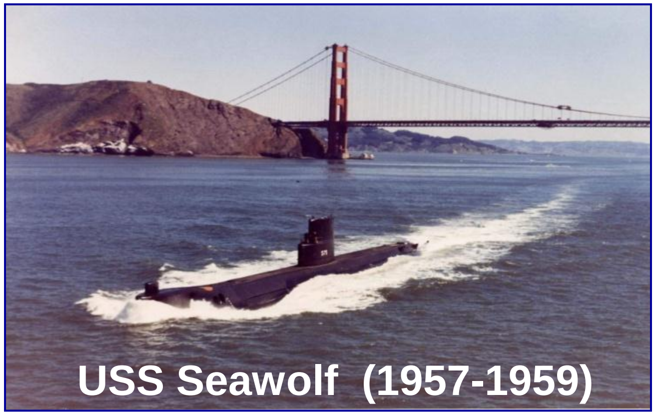
- #2 after Nautilus, followed by PWR subs
- ***Sodium cooled Fast Reactor***
  - Conversion with super heated steam
  40% gain in NSSS compactness

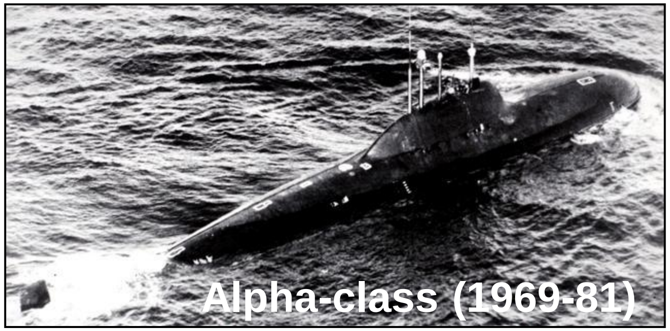
USSR November-class Submarine K-27 (1963-1968)

- ***Two VT-1 PbBi cooled Fast Reactors***
  Prototype for Alpha-class submarines
  - Loss of reactor power accident &
  Releases of radioactive gases

USSR Alpha-class Submarines 7 Lira-class units (1969-1981)

- ***155 MW PbBi cooled Fast Reactor***
  > 74 km/h & > 800 diving depth
  + Compactness, long lifetime

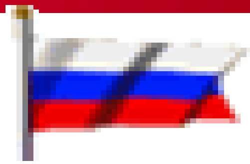




SVBR-100 Pb-Bi Reactor System *(2017)*

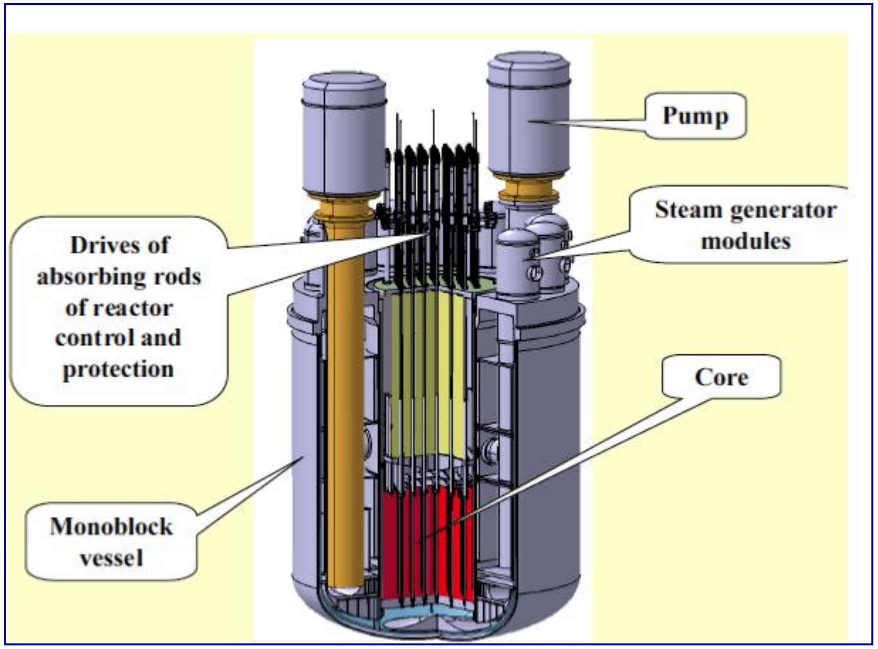
свбр - 100

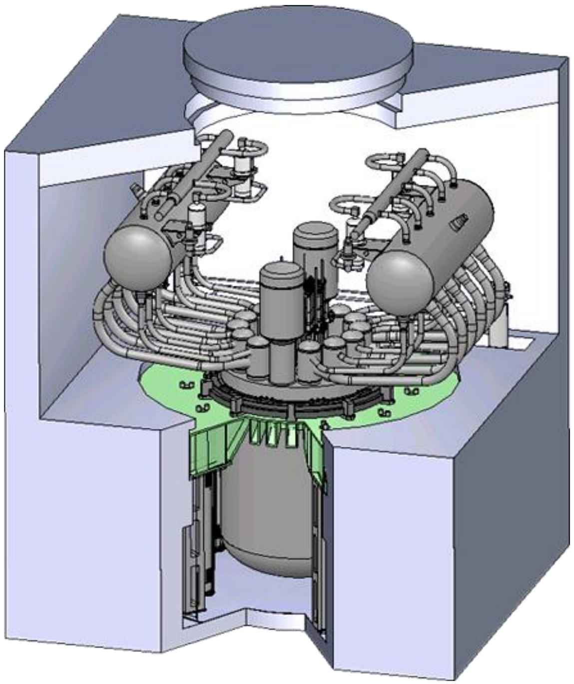
Rosatom / Irkutskenergo / Gidropress / IPPE Obninsk…

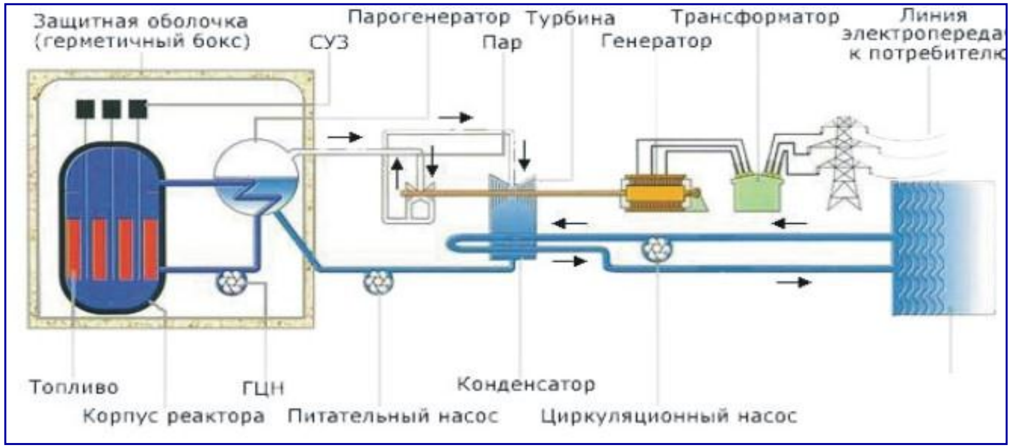


Russia

- ***100 MWe PbBi Eutectic cooled* reactor**
- **Integral design of primary system**
- **Steam turbine**
- **Strong supporting structure**



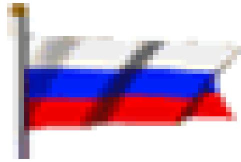




BREST-300 Pb-cooled Reactor *(2020)*

BREST-300

RDIPE Project at Tomsk
Siberian Chemical Combine



Russia

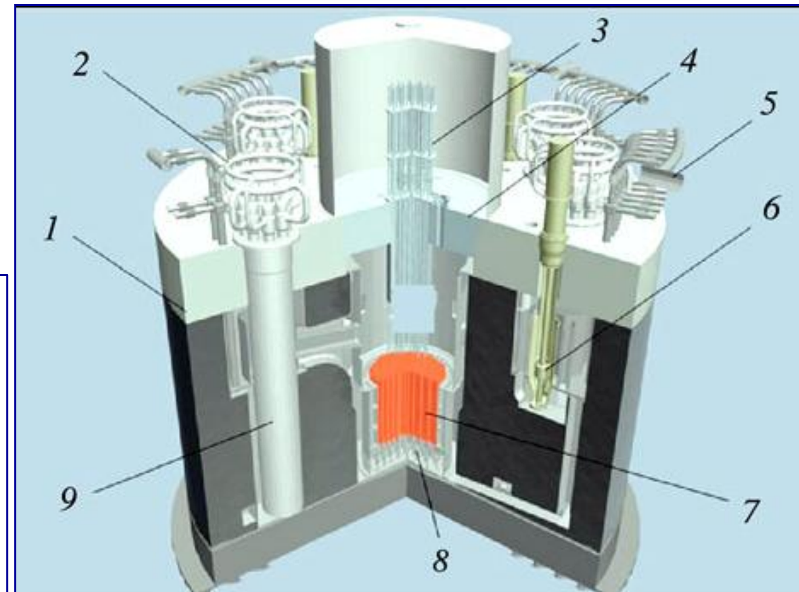
ROSATOM

- ***700 MW /300 MWe***
- **Integral design of primary system**
- **Nitride fuel, Bi-free coolant *(no Po)***
- **Steam turbine @ 505 °C, 17 MPa, η ~ 43%**
- **Strong supporting structure**

→ Demo plant towards BREST-1200

Strengths and limitations of Lead

- ***Low pressure, thermophysical properties***
- ***Non-flammability in operating conditions***
- ***High inertness to water and air***
- ***Moderate coolant void reactivity effect***
- ***Low activation, high radiation resistance***
- ***Weight, seismic events, T_{melt}~ 327°C***
- ***Control of steel corrosion***



Reactor block: *1) Vessel; 2) Steam–water collectors; 3) Safety-and-control rod* system; *4) Rotary plugs; 5) Channels of the emergency cool-down system; 6) Main circulation* pump; *7) Core; 8) Core barrel; 9) Steam generator.*

Gas Breeder Reactor (GBR) Projects *(1970s)*

→ *No project ever built*

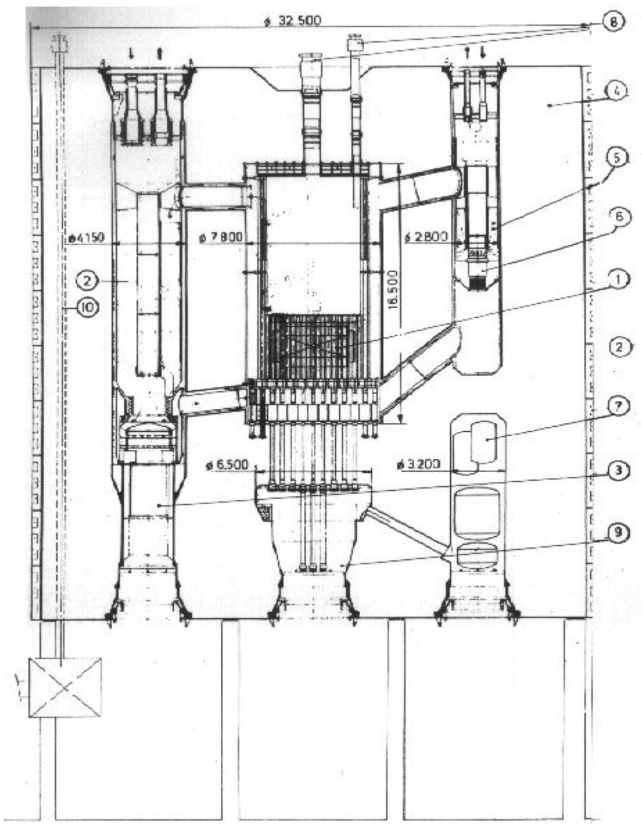
GBR Program *(1970s – Europe)*

- **LMFBR derivative** *(steel clad fuel) (< 550°C)*
- **Helium preferred to CO_2 & steam**
- **Prestressed concrete reactor pressure vessel**
- **Steam turbine**

GBR-1	1000 MWe	Helium	Pin fuel
GBR-2/3	1000 MWe	He/CO_2	Coated particle
GBR-4	1200 MWe	Helium	Pin fuel

Strengths and limitations of Helium

- *Potential for higher breeding capability*
- *Single phase & Optically transparent*
- *Very low coolant void reactivity effect*
- *Chemical inertness of coolant*
- *1[ry] system at 7 Mpa & Pumping power*
- *Blowdown accident & Low thermal inertia*



1 REACTOR CORE
2 MAIN STEAM GENERATOR
3 MAIN CIRCULATOR SET
4 PRESTRESSED CONCRETE VESSEL
5 EMERGENCY COOLER
6 EMERGENCY CIRCULATOR SET
7 FUEL VENTING PLANT AND He PURIFICATION WELLS
8 REFUELLING STANDPIPES
9 LOWER CAVITY
10 SPENT FUEL TRANSFER TUBE

GBR-4 *(1974)*

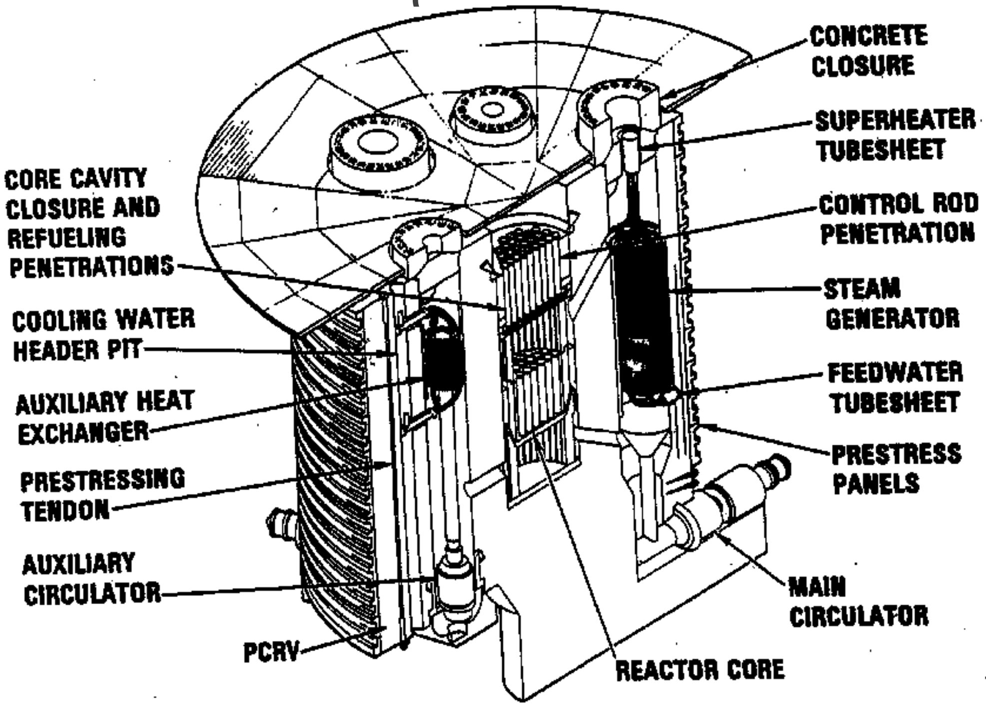
- ***He 260/565°C, η ~35%***
- ***12 MPa, Wp ~10%***
- ***$UPuO_2$/SS-clad pins***
- ***BG ~ 0,42***

Gas-Cooled Fast Reactor Project *(1982)*

GENERAL ATOMICS

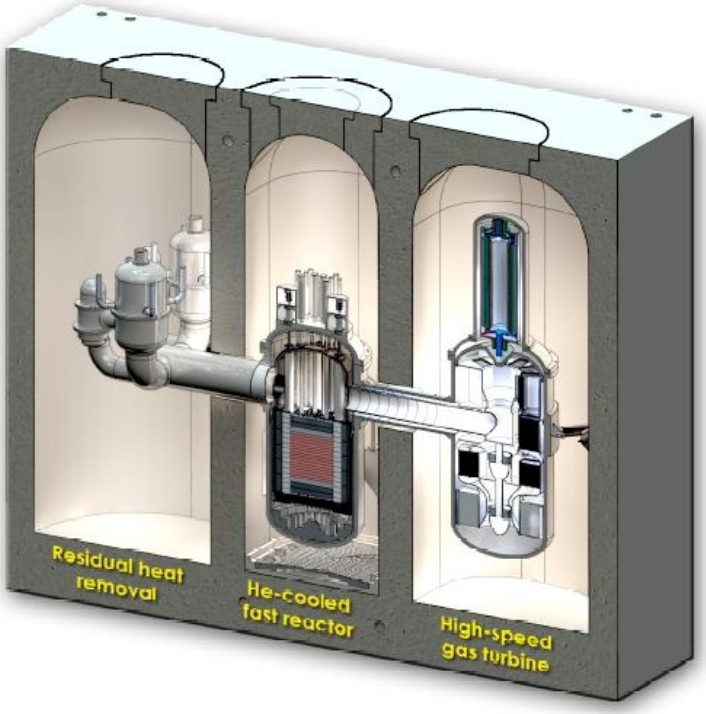
GCFR Project *(1974 – USA)*

- 835 MW/375 MWe
- Helium 323/550 °C, 10.7 Mpa, Wp ~6 %
- $UPuO_2$ SS-clad pins, Breeding gain ~0.4
- Prestressed concrete RPV
- Steam turbine η ~33%



EM² Project *(2007 – USA)*

- 500MW/240 MWe
- Helium 850 °C
- Direct conversion
- UPuC SiC-clad pins



Experience in Sodium cooled Fast Reactors

18 experimental or prototype Sodium Fast Reactors so far
~400 Reactor x Years of cumulated operation in 2012

United States

- *EBR-1 1951*
- *EBR-II (20 MWe) 1963 → 1994*
- *FFTF (400 MWth) 1980 → 2000*
- *Clinch River Project cancelled in 1983*

Europe

- *Rapsodie (20 MWth) 1967 → 1983*
- *DFR (14 MWe) 1962 → 1977*
- *KNK-II (17 MWe) 1978 → 1991*
- *Phénix (250 MWe) 1973 → 2009*
- *PFR (250 MWe) 1975 → 1994*
- *SNR300 (300 MWe) never put into service*
- *Superphenix (1200 MWe) 1986 → 1998*
- *EFR Project cancelled in 1998*

Japan

- *Joyo (140 MWth)*
- *Monju (280 MWe) 1995 →*

Russia & Kazakhstan

- *BOR-60 (60 MWth) 1969 →*
- *BN-350 (90 MWe) 1973 → 1999*
- *BN-600 (600 MWe) 1980 →*
- *BN-800 (800 MWe) 2014*

India

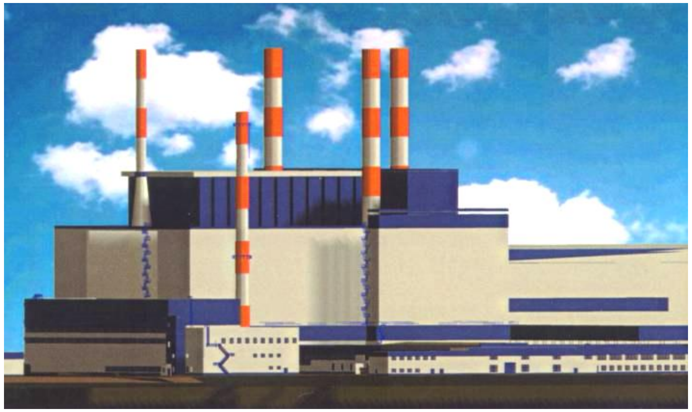
- *FBTR (40 MWth) 1985 →*
- *PFBR (500 MWe) 2013*

China

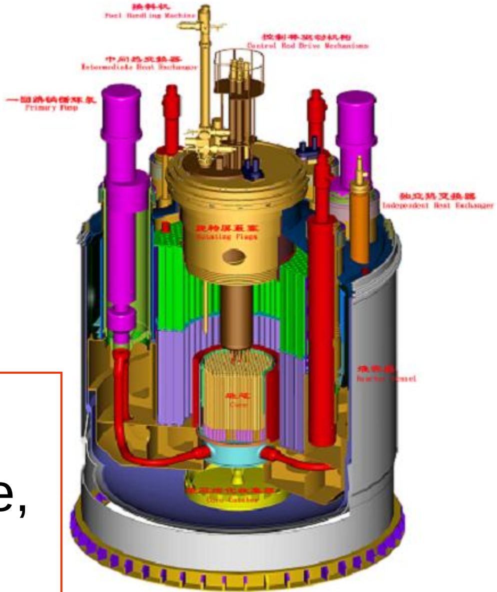
- *CEFR (25 MWe) 2010*

Sodium Fast Reactors in India, Russia & China

Breeding Pu ASAP for FNRs (vs Burning Pu/TRU)

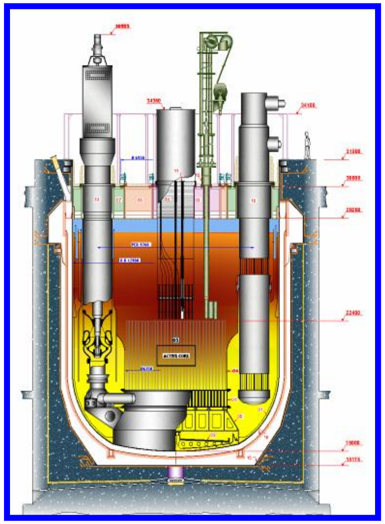


BN-800 (Russia)
800 MWe, 2014



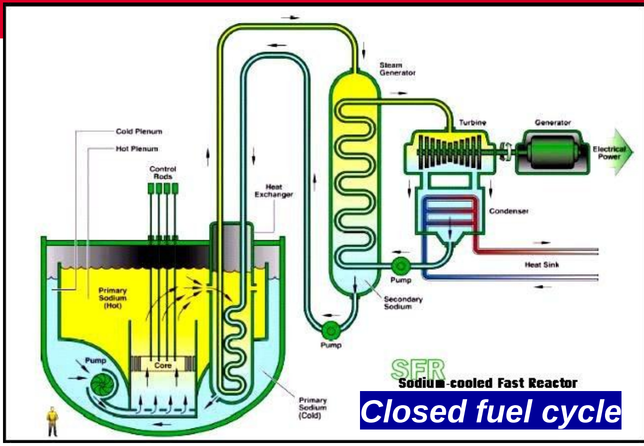
CEFR (China)
65 MWth, 25 MWe,
July 2011

PBFR (India)
500 MWe, 2013

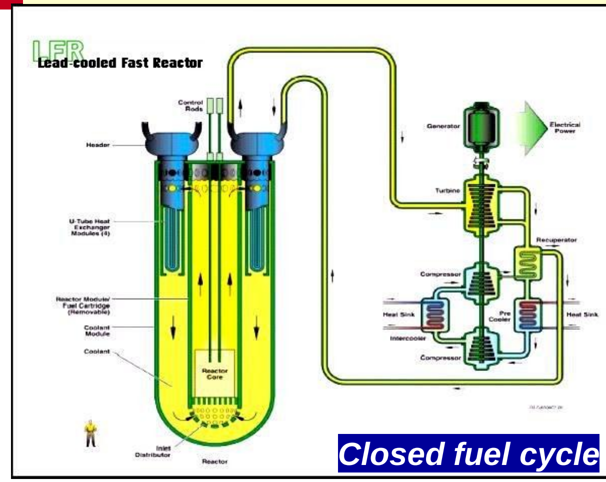


Generation IV International Forum: Six Systems for R&D

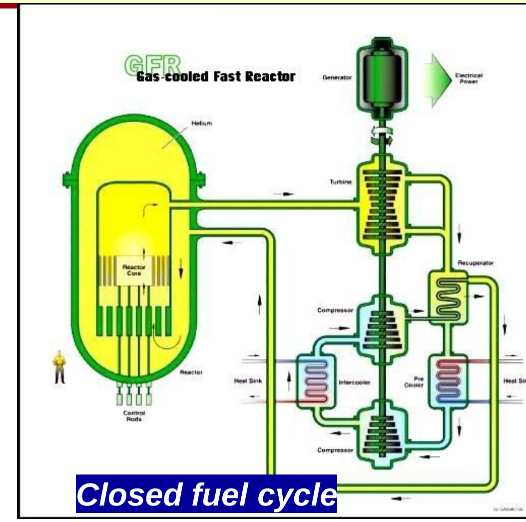
GIF Selection of six Nuclear Systems



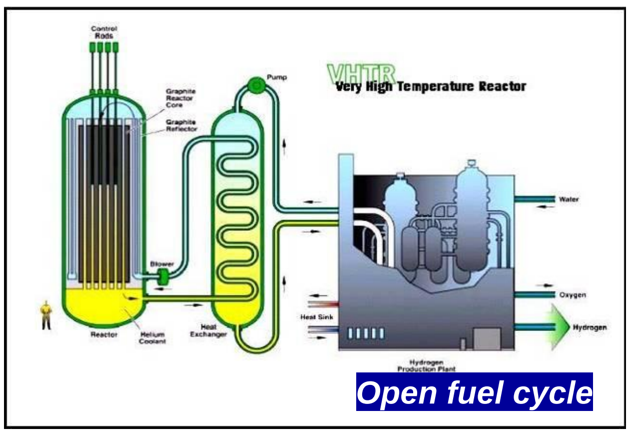
Sodium Fast Reactor



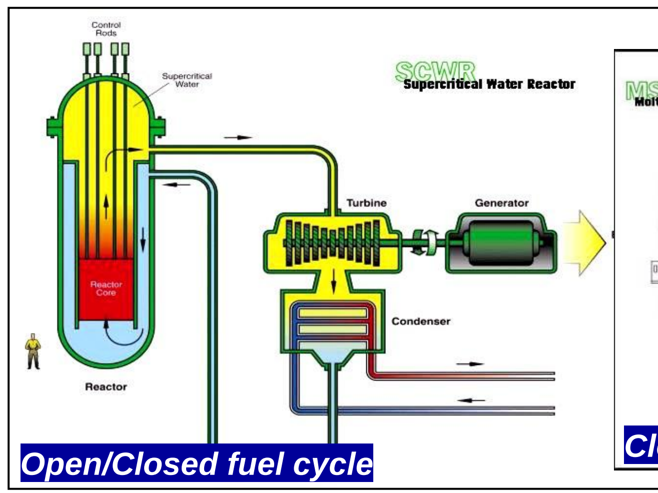
Lead Fast Reactor



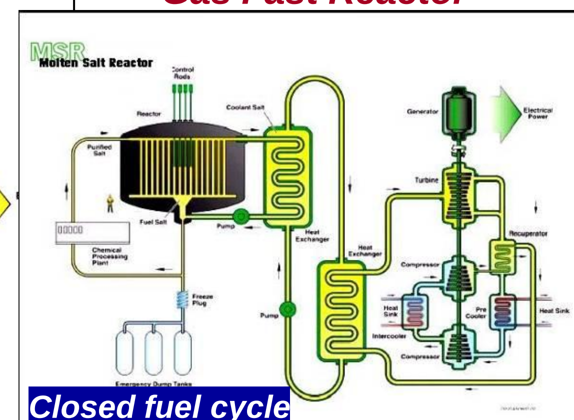
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



Molten Salt Reactor

The recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissile re-generation) and waste minimization *(minor actinide burning)*

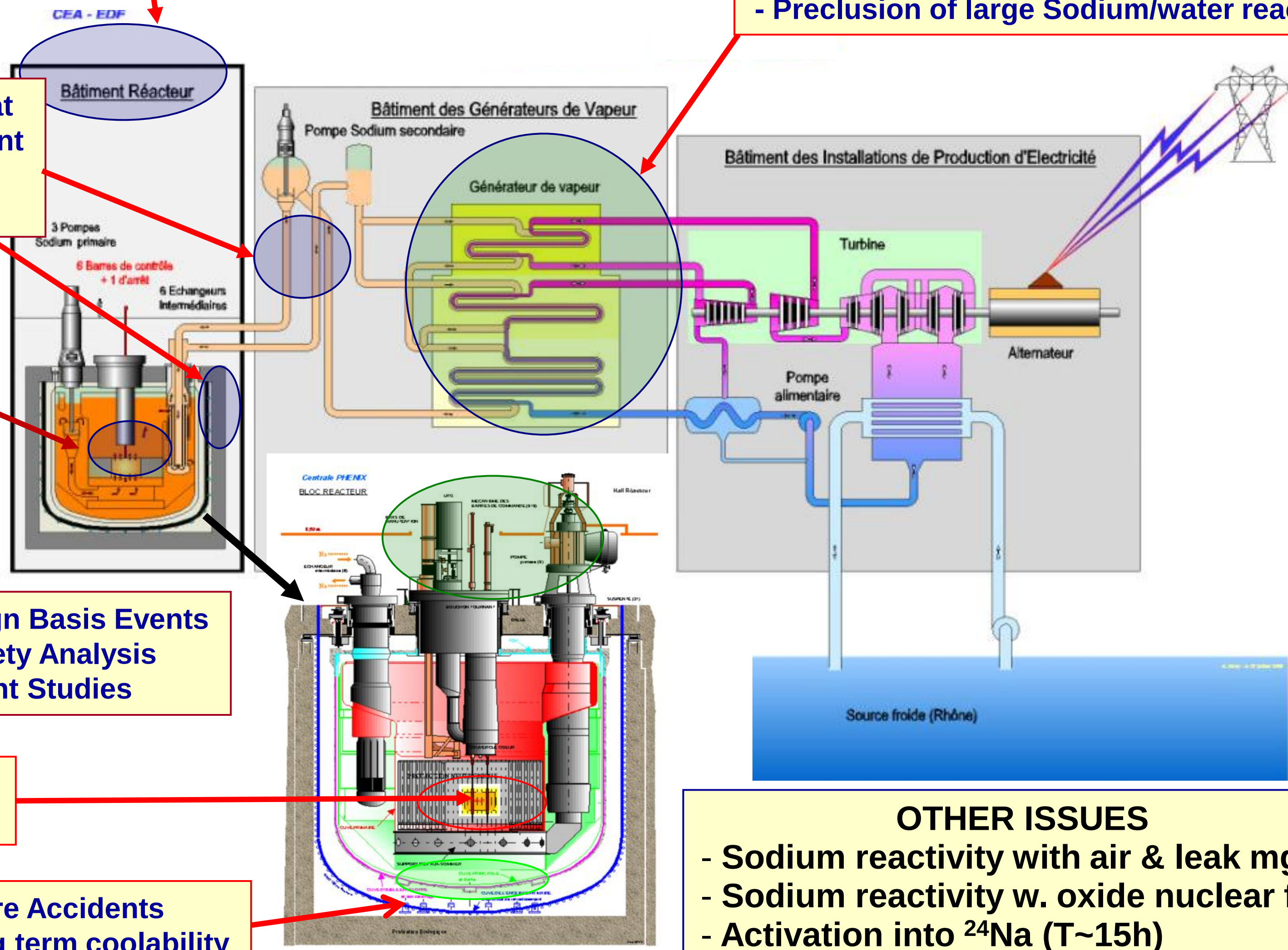
Issues Considered for Future Sodium Fast Reactors

- Better controlled containment of radioactive materials & Sodium Risks

- Improved decay heat removal with redundant active and passive systems

- Improved reactivity control

- Preclusion of large Sodium/water reaction



-Assessment of Design Basis Events
-Probabilistic Safety Analysis
- Severe Accident Studies

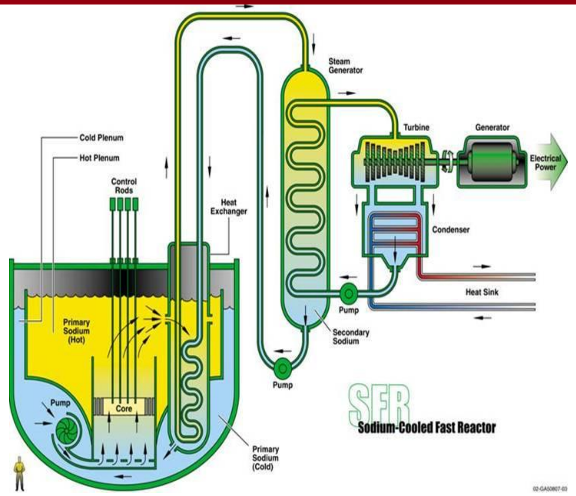
- Low void reactivity effect core design

-Control of Severe Accidents
- Core catcher & Long term coolability

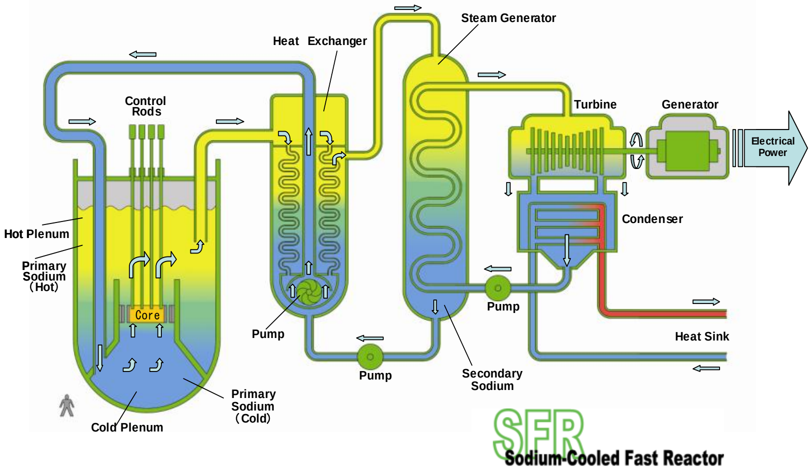
OTHER ISSUES
- **Sodium reactivity with air & leak mgt**
- **Sodium reactivity w. oxide nuclear fuel**
- **Activation into ^{24}Na (T~15h)**
- **In service inspection & repair**

Sodium Fast Reactor *(SFR)*

- **A new generation of Sodium Fast Reactor**
- **Towards enhanced safety features**
  + Better prevention/mgt of severe accidents
  + Preclusion/minimization of sodium risks
- **Reduced investment cost** *(design…)*
  Improved operability *(ISIR, modular component design, water/gas PCS…)*
- **Flexible recycling of Transuranics (TRU)**



- **2009/15: Feasibility/Performance → 2020s: Demo SFR** ***(FR, RU, JP, CN…)***
- **Common Fast Reactor Design Criteria**



Time Line for SFR Prototype ASTRID & Associated Facilities

AREVA

EDF

Preliminary selection of design options

Decision to proceed

Decision to build

Start-up

ASTRID

2009 2010 2011 2012 2013 2014 2015 2016 2017

Pre-conceptual Design → **Conceptual Design** → **Detailed Design** → **Detailed Design & Construction**

Cycle

Feasibility Report on Minor Actinides Partitioning

Position Report on Minor Actinides Partitioning and Transmutation

Core Manufacturing Workshop (AFC)

Minor Actinides bearing Fuels Fabrication Facility

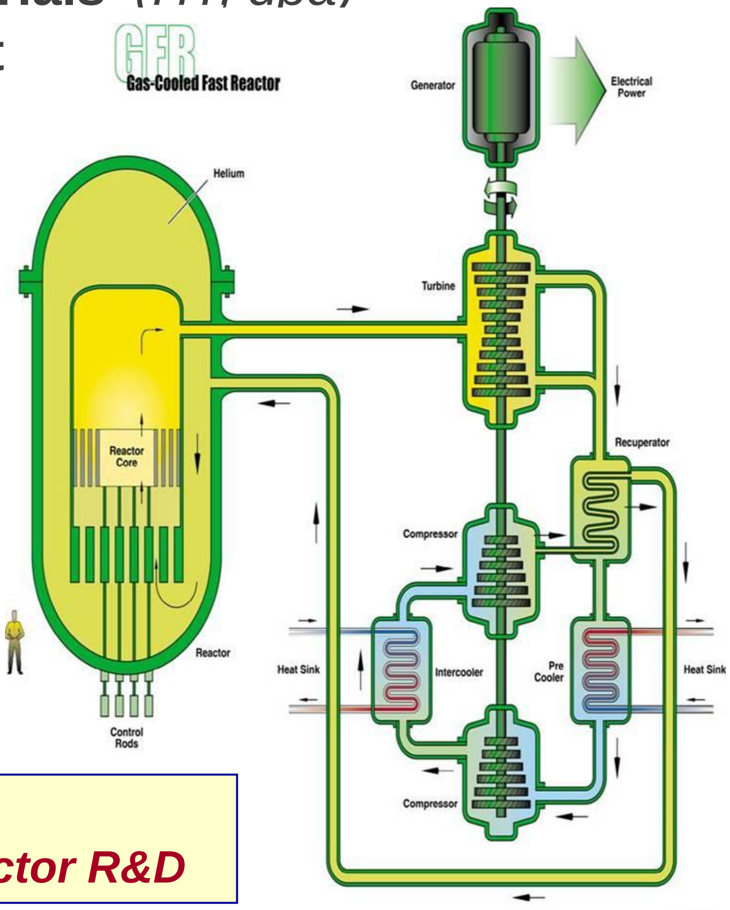
French Act of June 28, 2006 for a Sustainable Management of Nuclear Materials and Waste

Gas Fast Reactor *(GFR)*

- **A new concept of Gas-cooled Fast Reactor:**
  → a longer term option than the SFR and a sustainable VHTR
- **1200 MWe – T_{He} ~ 850 °C – Co-generation electricity + H_2**
- **Robust fuel** *(ceramics clad UPuC)* **& Materials** *(HT, dpa)*
- **Designed for safe cooling accidents mgt**
- **Flexible recycling of TRU fuel**

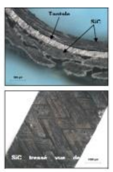
→ 2012: Feasibility → >2025: Allegro *(EU ?)*
2020: Performance → >2030: Demo GFR

GCFR
GoFastR
EU FP5-6-7



- ***2010 – Consortium HR, CZ, SK + PL (2012)***
- ***2012 – Centres of Excellence for Gas-cooled Reactor R&D***

GFR – Gas Fast Reactor & Experimental Prototype



SiC clad Fuel (CEA)

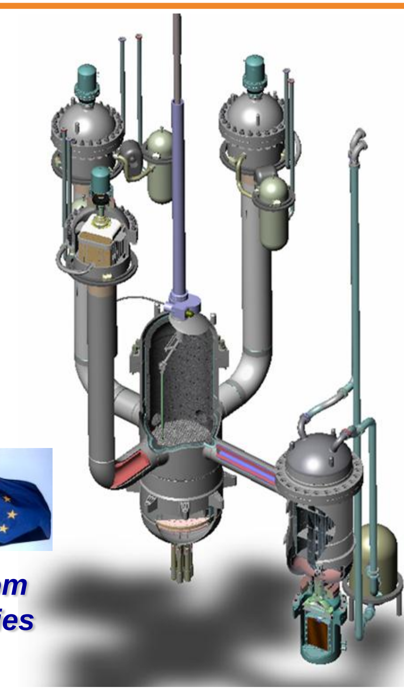
GFR 2400 MWt reference concept

- *2007 – First concept & pre-feasibility report*
- *2012 – Upgraded concept & Feasibility report*

Robust decay heat removal strategy (passive after 24hrs)

- *GCFR EU-FP6 Project*
- *GoFastR EU-FP7 Project*
- *Alliances EU-Horizon 2020*
- *2010 – Consortium HR, CZ, SK + PL (2012)*
- *2012 – Centres of Excellence*

Euratom countries

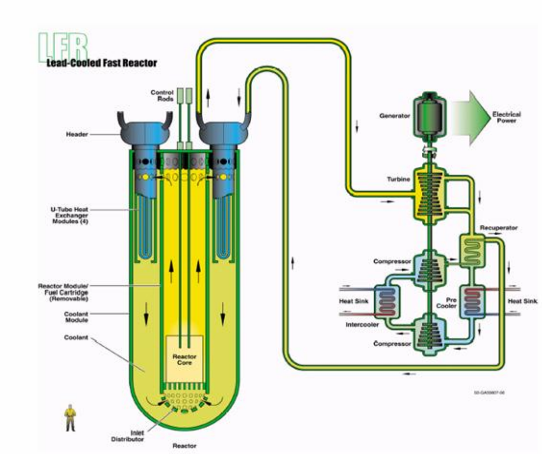


Allegro (50 MWt)

Lead Fast Reactor (LFR)

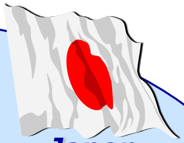
- **An alternative Liquid Metal cooled Fast Reactor:**
  → *thermal management of lead*
  → *in service inspection and repair*
- **~ 600 MWe – T_{Pb} ~ 480 °C**
- **Weight of primary system** *(seismic behaviour, sloshing…)*
- **Prevention of corrosion of 1^{ry} system structures**
- **Flexible recycle of TRU fuel**

- **2015: Feasibility → 2020+: Techno Demo** *(RU, EU ?)*
- **2020: Performance → 2030+: LFR Prototype**



ELSY
ALFRED
in EU FP6-7

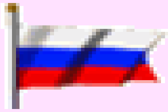
Euratom countries



Japan

LFR Steering Committee

✓ ***Memorandum of Understanding in 2012***



Russia

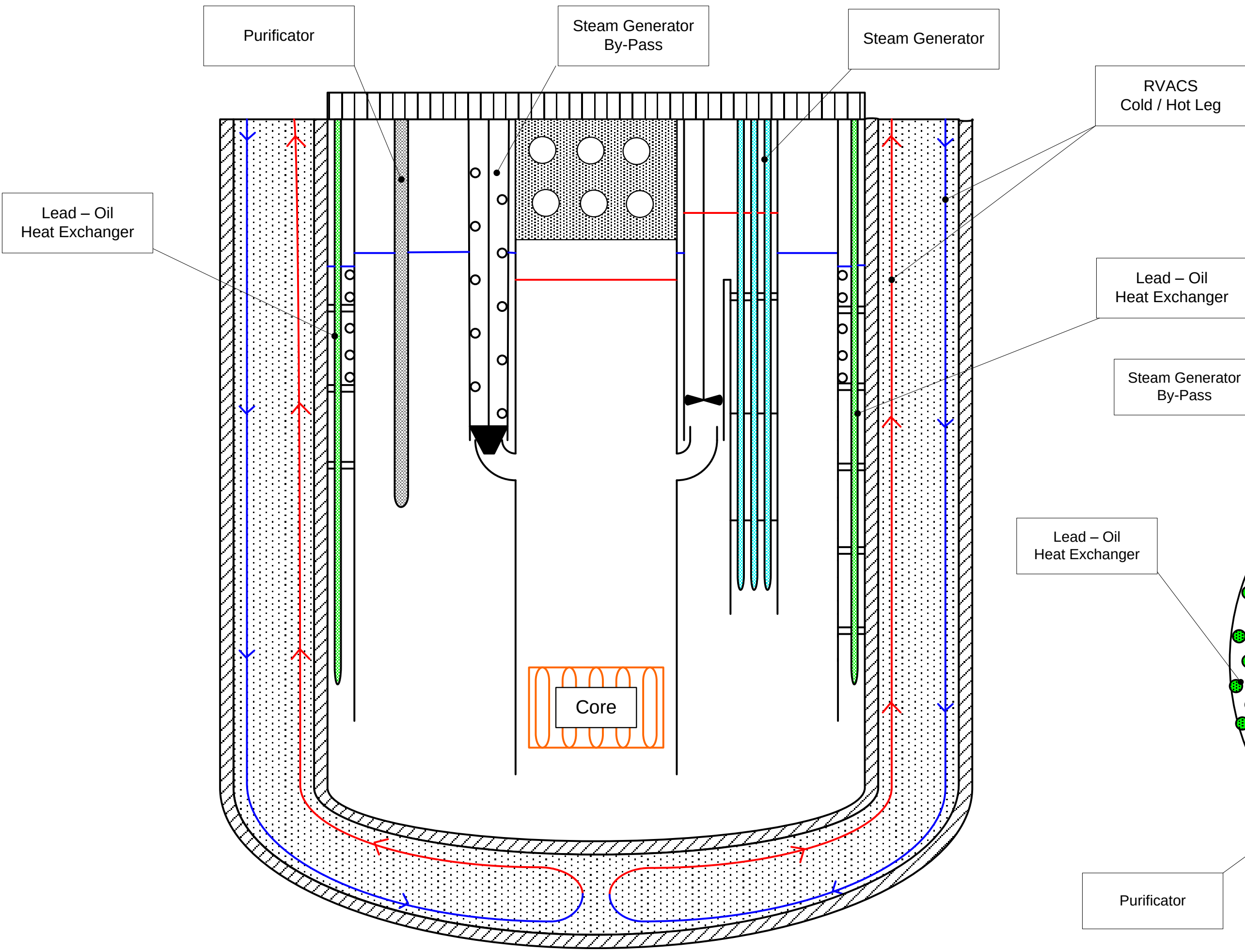
SVBR-100 *(PbBi)*
BREST-300 *(Pb)*

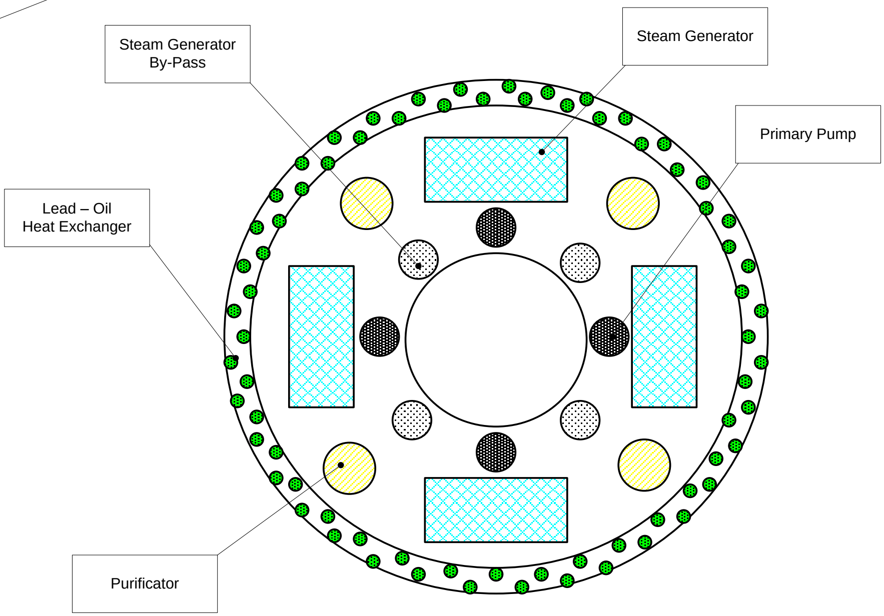
Layout of ALFRED Prototype Reactor

ALFRED – Advanced Lead Fast Reactor
European Demonstrator *(MOX fuelled, 300 MWth)*

Euratom countries

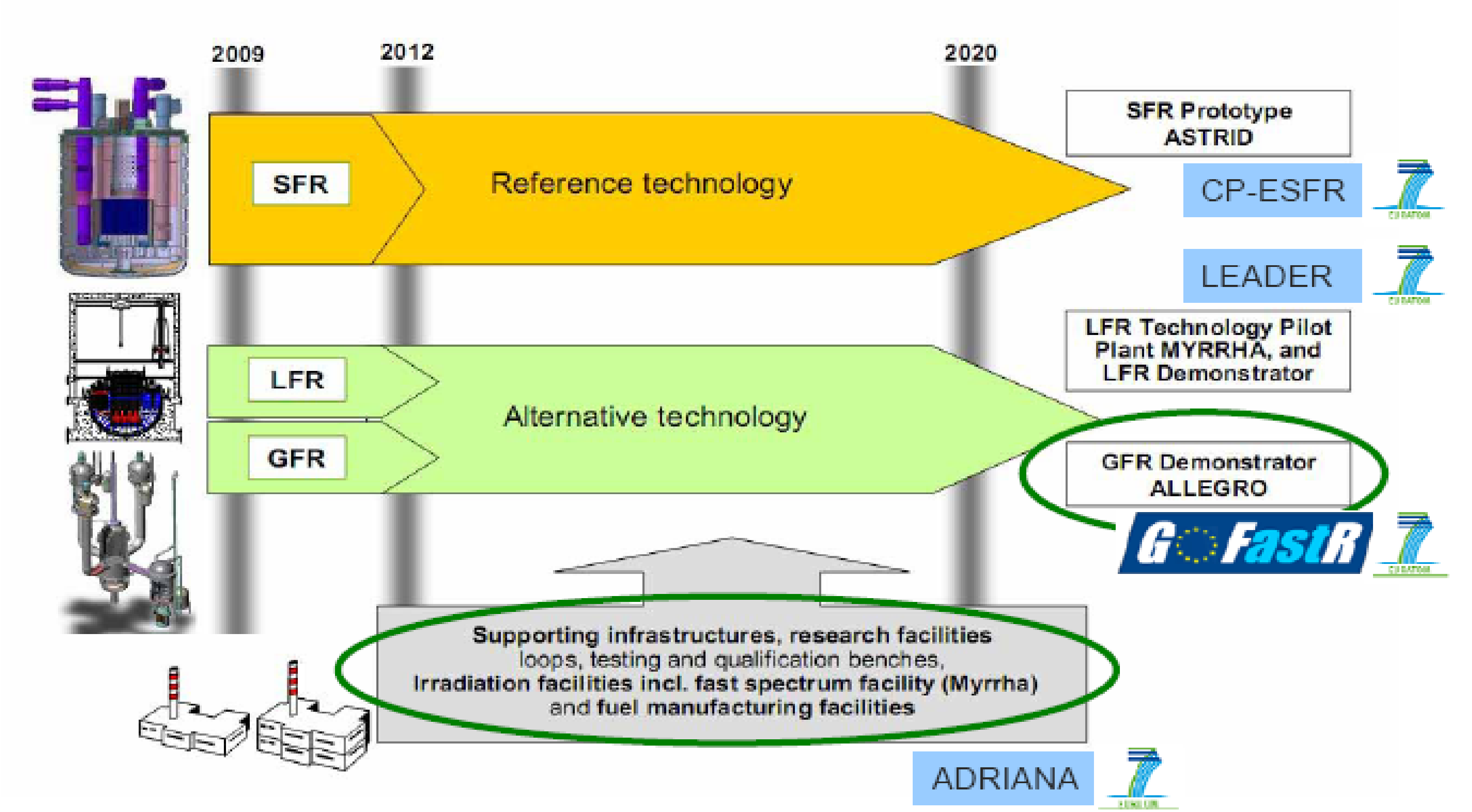
Operating temperature [400 – 480°C] to limit corrosion of advanced ferritic & austenitic steels





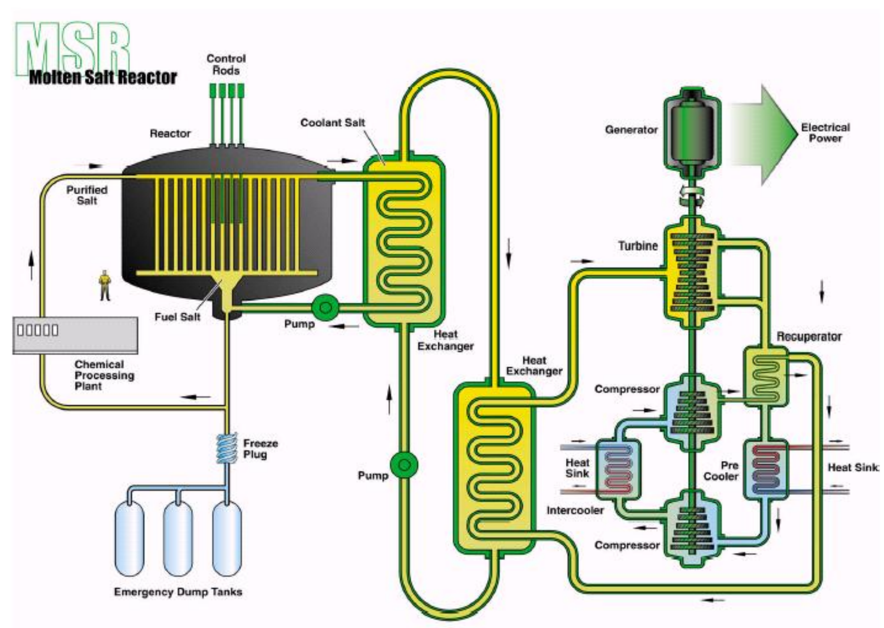
European Sustainable Nuclear Industrial Initiative on Gen. IV FNR Technologies

- **The Road Map**



Molten Salt Reactor *(MSR)*

- Potential for breeding with the U-Th fuel cycle ?
- 1700 MWth - 800 °C
- Specific safety issues and bounding events TBD
- Corrosion of structural materials
- Treatment of used salt
- In service inspection & Repair



✓ ***Memorandum of Understanding in 2010***

Candidate Coolants & Fast Reactor Types

Visions of Fast Neutron Reactors

- Historically the first means to produce weapon grade nuclear materials. Designed with the best available coolant technology *(Hg, NaK, Na)*
- A vision of sustainable nuclear power when fitted with a closed fuel cycle. An institutional priority for Uranium-poor nuclear countries: effective utilization of ^{238}U as Pu & mitigation of long lived high level waste burden
- A vision of TRU burner for HLW minimization in Uranium rich countries

Country-dependent goals

- **Breeding:** maximum for China, India (+ Russia ?)
  breakeven for France & other historical nuclear countries
- **Doubling time:** minimum for China, India (+ Russia ?)
  → High power density → Efficient cooling required
- **Fuel recycling:** recycle of UPu only
  + partial or integral recycle of Minor Actinides

→ Towards varied types of Fast Neutron Reactors & Closed fuel cycles?

Evolving Context for Fast Reactor Development

Towards harmonized safety & security criteria / standards

- Multinational Design Evaluation Program (MDEP) *(Safety, Codification…)*
- Gen-IV Forum initiative on « *Common Design/Safety criteria* »
- Non-proliferation / Safeguards + Physical Protection

→ *Demonstration of best available technologies / practices on prototype and experimental reactors*

- Conduct R&D today on Gen-IV Fast Neutron Nuclear Systems
  - *Build upon past prototypes to advance Sodium Fast Reactor technology and performances*
  - *Take benefit from international collaboration to advance alternative types of Fast Neutron Reactors (GFR, LFR…) in parallel*
- Stakes in international collaboration *(Generation-IV International Forum, IAEA-INPRO, EU-SNE-TP…)*
  - *To share cost of R&D and large demonstrations (safety, security, recycling)*
  - *To progress towards harmonized international standards*

Need for Science-driven Innovations & Technology Breakthroughs

Gen-IV Goals for Fast Neutron Reactors

- **Enhanced safety goals derived from strengthened requirements for Gen-III LWRs and lessons from Fukushima accident**
  + Need for robust safety demonstration *(margin, cliff-edge effects…)*
  - *Better prevention, control and mitigation of severe accidents*
    → *Improved reactivity control: low* ***coolant*** *void reactivity effect core design…*
    → *Risk preclusion /minimisation of large chemical accident (reactions between* ***coolant****/ turbine working fluid,* ***coolant****/air/water…)*
  - *Improved decay heat removal with redundent active & passive* ***cooling*** *systems*
- **Improved economic competitiveness & Operability** */ other power plants*
  - *Improved in-service inspection & repair technologies (instrumentation...)*
  - *Minimisation of* ***coolant*** *leaks & reaction with other plant working fluids*
  - *Improved compatibility of nuclear fuel with* ***coolant*** *& cladding failure detection*
  - *Modular design of* ***cooling*** *systems & components*
- **Improved security**
  - *Enhanced physical protection*
  - *Enhanced safeguards & intrinsic non-proliferation features in nuclear fuel cycle*