SFEN – Groupe Régional Rhône-Ain-Loire
Réunion Débats (21 mars 2017, Lyon)

DE LA RECHERCHE À L'INDUSTRIE

LES SYSTÈMES NUCLÉAIRES DU FORUM INTERNATIONAL GENERATION-IV

Frank Carré

franck.carre@cea.fr

CEA, Direction de l'énergie nucléaire

www.cea.fr

Plan de l'exposé

- Bref historique du Forum International Generation-IV
- Actualité des six systèmes Gen-IV et priorités de R&D
- Interactions avec l'AEN, l'AIEA, EU/SNE-TP…
- Place des systèmes Gen-IV dans le nucléaire du futur
- Perspectives

New Requirements to support a Sustainable Development

Steady Progress:
- Economic competitiveness
- Safety and reliability

Nuclear Power for centuries
- Resource saving
- HL Radwaste minimisation
- Non-proliferation

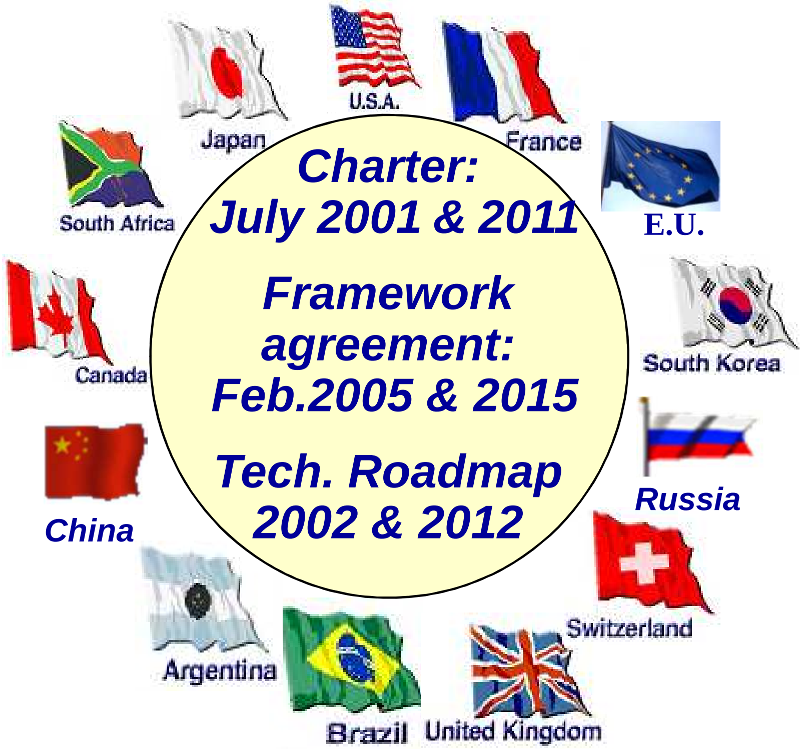
New applications

Hydrogen, drinkable water, heat

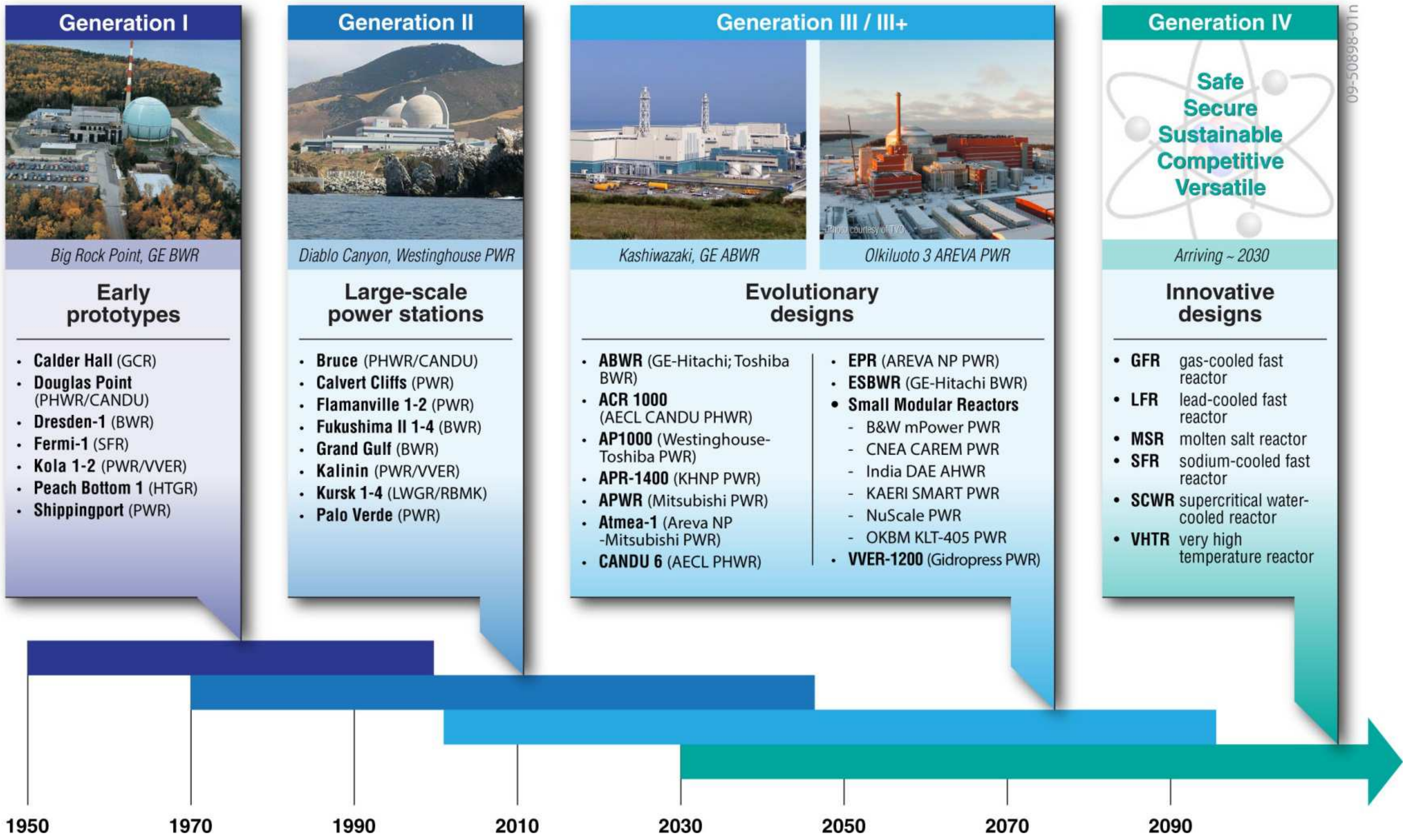
Industrial deployment ~2040

Multilateral cooperation with 3 levels of agreements:

✓ *Intergovernmental*
✓ *Systems (x 6)*
✓ *R&D Projects (3 à 6 / System)*

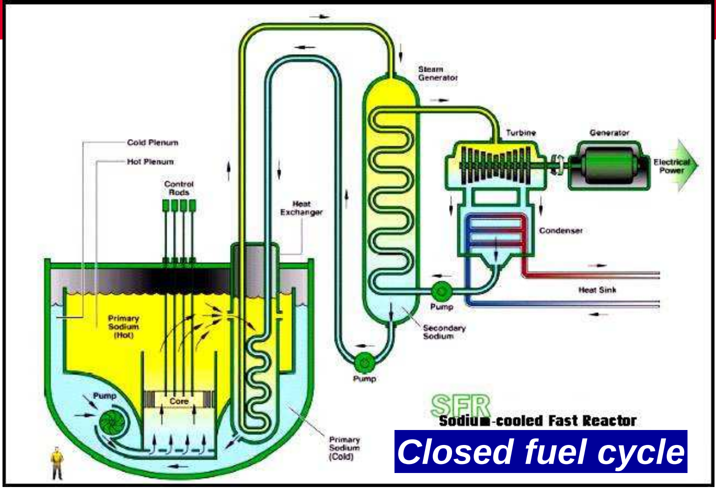


GENERATION IV INTERNATIONAL FORUM

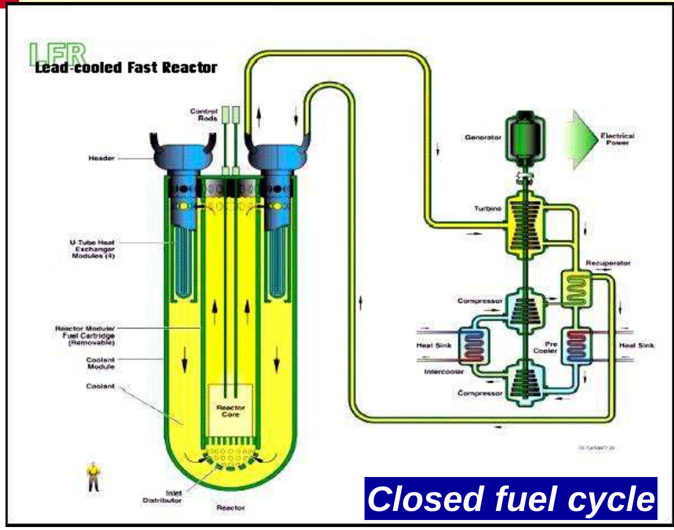


GEN-IV INTERNATIONAL FORUM: SIX SYSTEMS FOR R&D

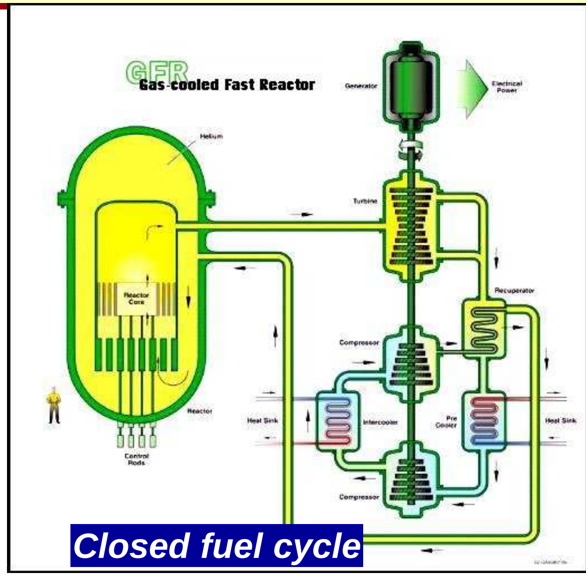
GIF Selection of six Nuclear Systems



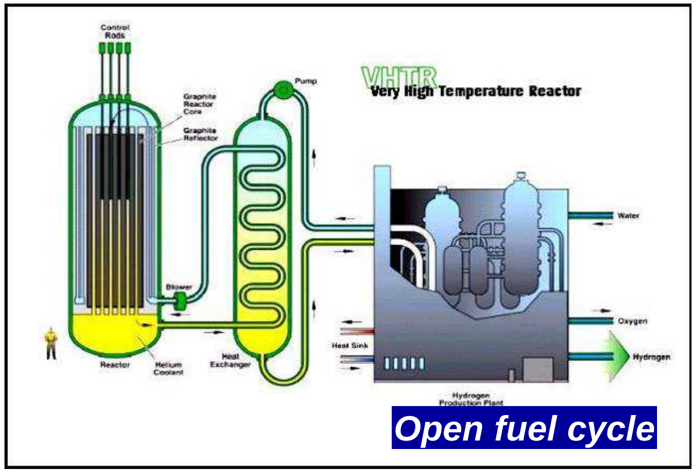
Sodium Fast Reactor



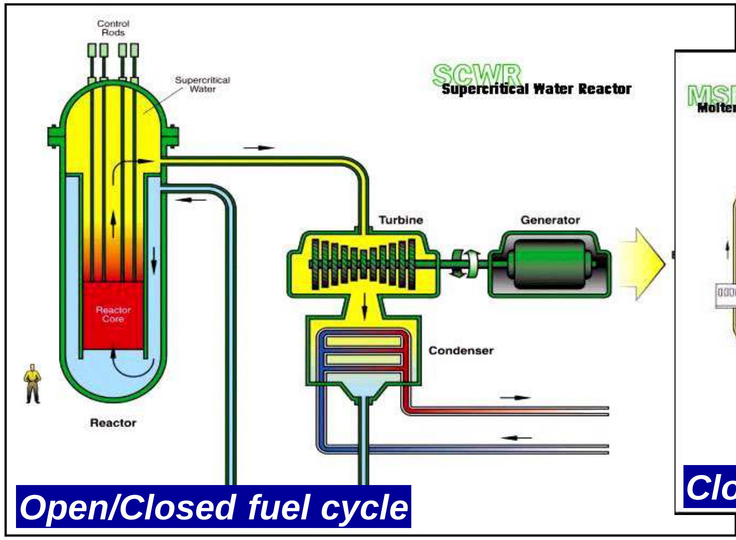
Lead Fast Reactor



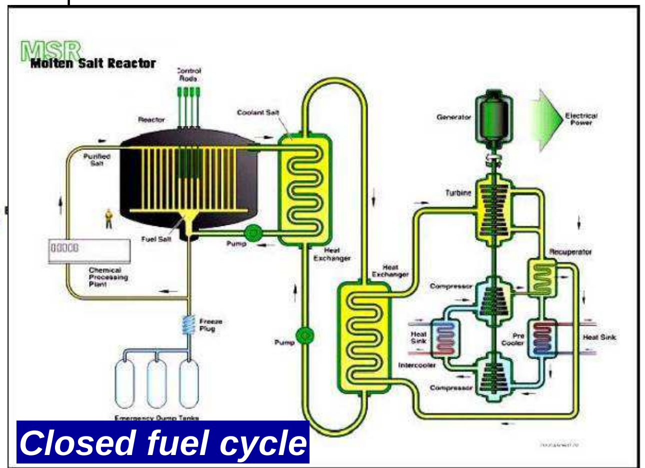
Gas Fast Reactor



Very High Temperature Reactor



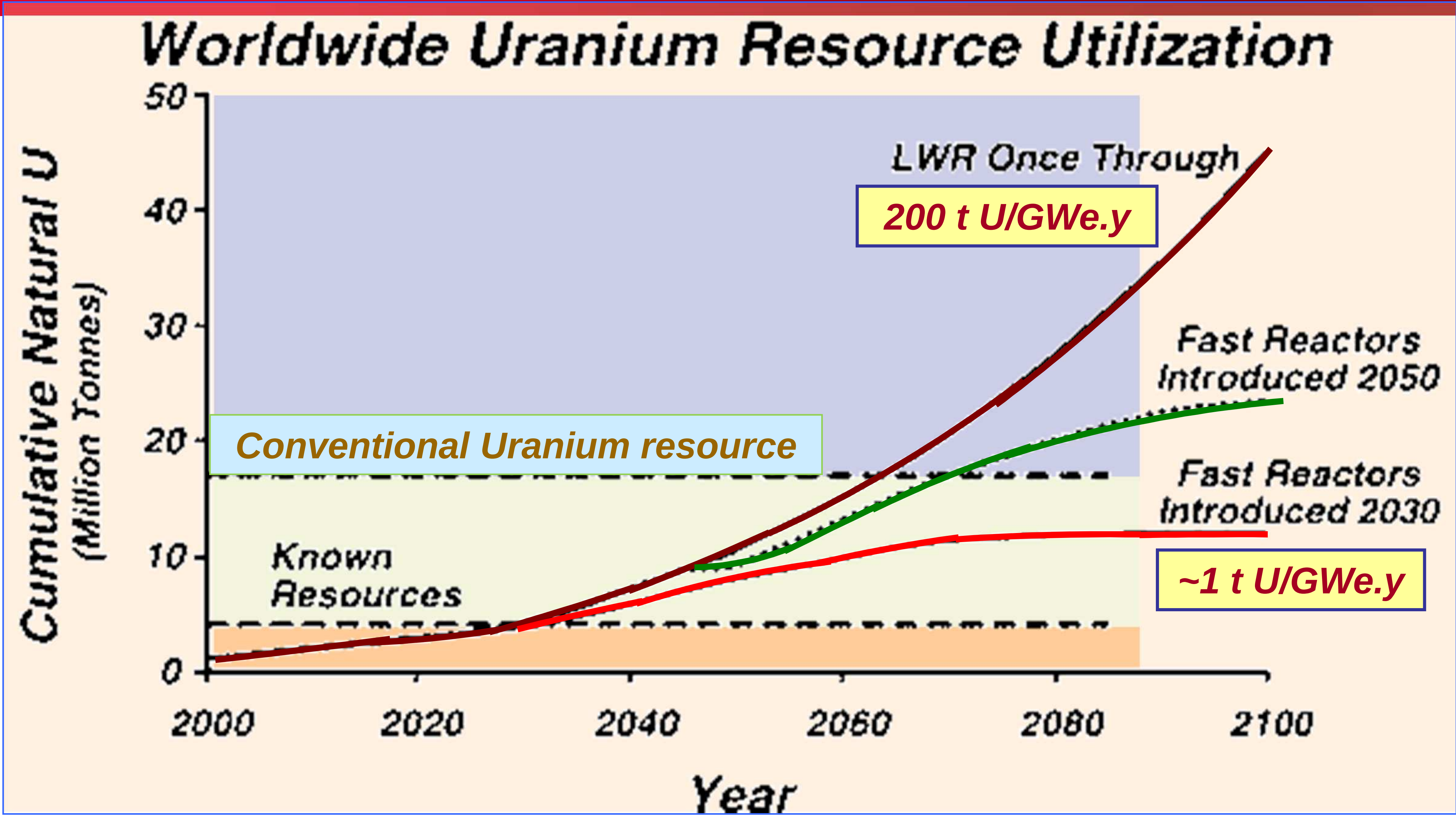
Super Critical Water Reactor



Molten Salt Reactor

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

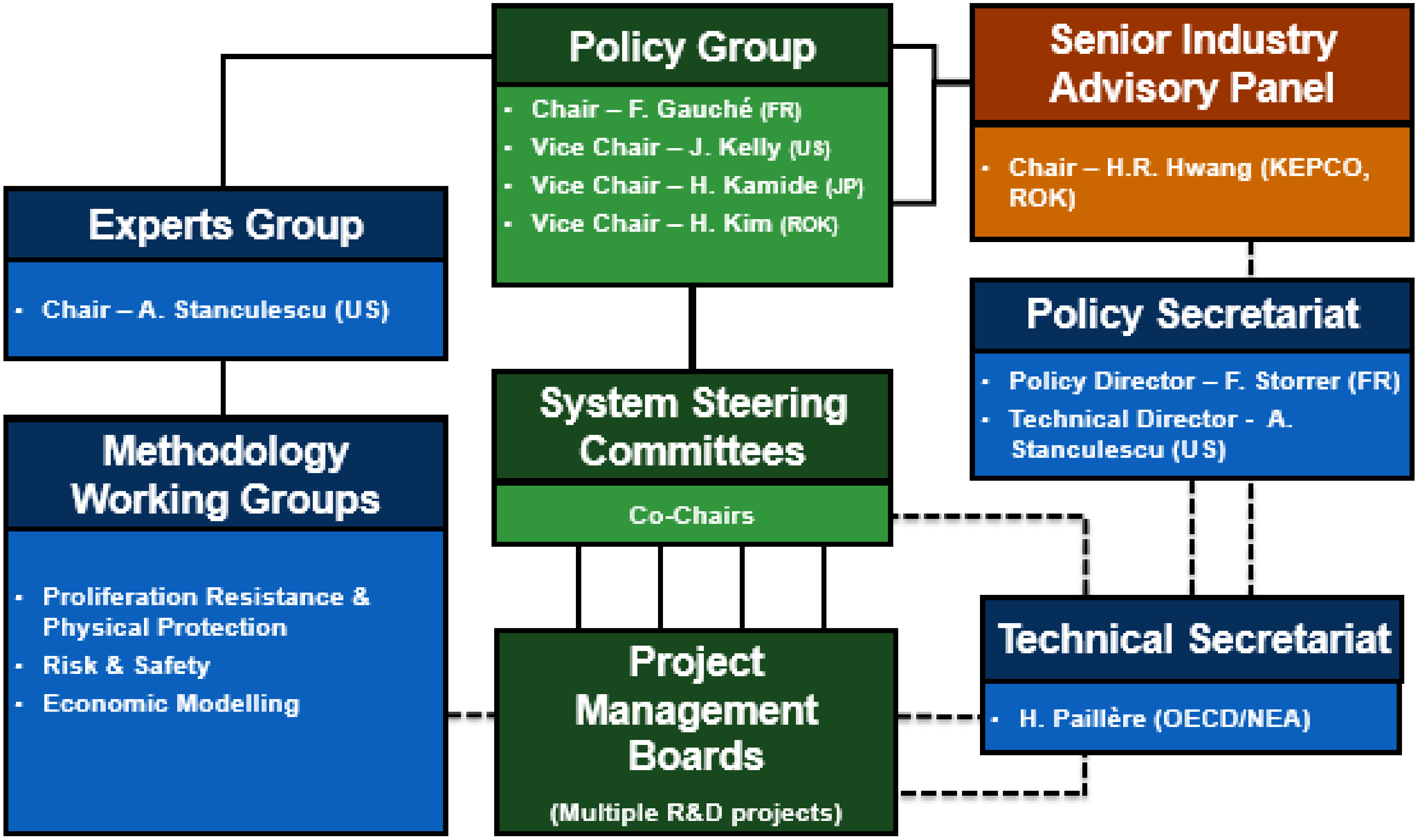
DURABILITY OF URANIUM RESOURCE



Source: “A Technology Roadmap for Generation IV Nuclear Energy Systems”, December 2002

GIF STRUCTURE AND GOVERNANCE

Current PG Chair's mandate: 2015 - 2018



Task Force: E&T, SDC/SDG for SFR, Sustainability

MEMBERSHIP AND SYSTEM DEVELOPMENT (2017)

	Canada	China	France	Japan	Korea	Russia	South Africa	Swiss	USA	EU
SFR		●	●	●	●	●			●	●
VHTR		●	●	●	●			●	●	●
LFR*				●		●				●
SCWR	●	●		●		●				●
GFR			●	●				●		●
MSR*			●			●				●

Cooperative R&D, except for LFR & MSR is carried under System Arrangements Cooperative R&D for LFR and MSR is conducted under a Memorandum of Understanding

Argentina Brazil UK **are non-active members**

Australia **Australia signed the Charter on 22 June 2016**

TECHNOLOGY ROADMAP UPDATE (2014) & REVIEWS

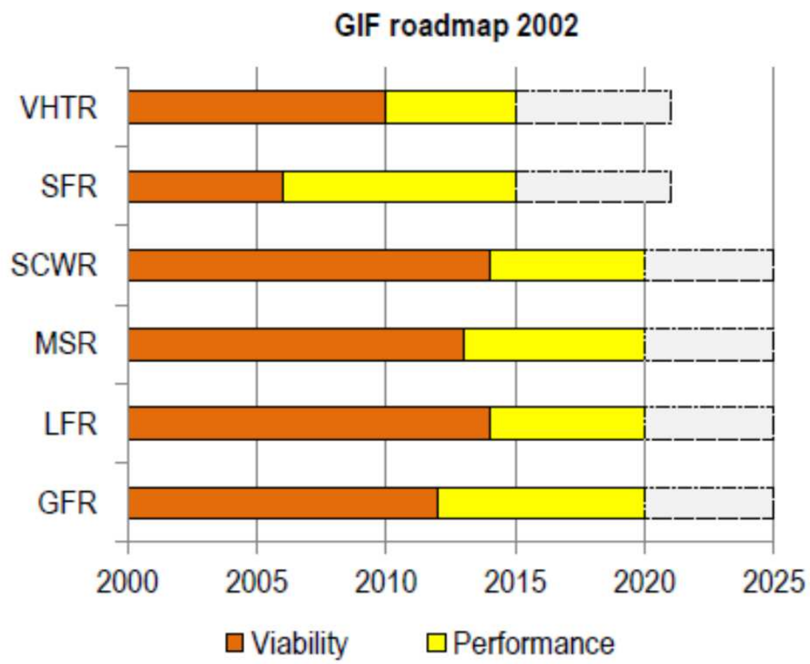
Technology Roadmaps: 2002 & 2014 update

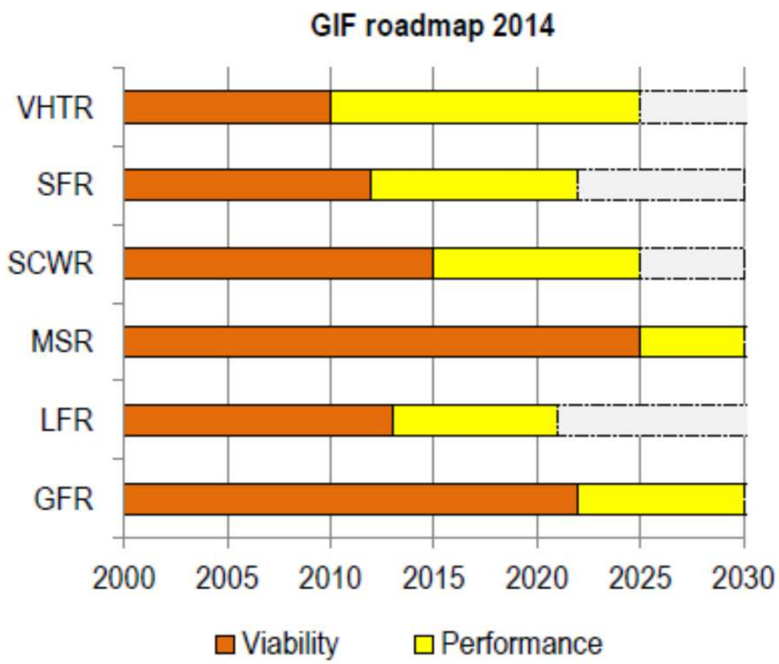
- *R&D timeline: Viability & Performance phases*
- *Path from current R&D status to Gen-IV systems Technology Demos*

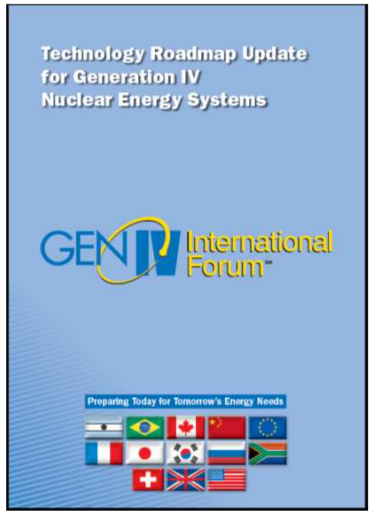
www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf

IRSN Review of Gen-IV Nuclear Energy Systems (2012)

RGN (Mars-Avril 2015): Les réacteurs nucléaires du futur : Gen-IV & SMR

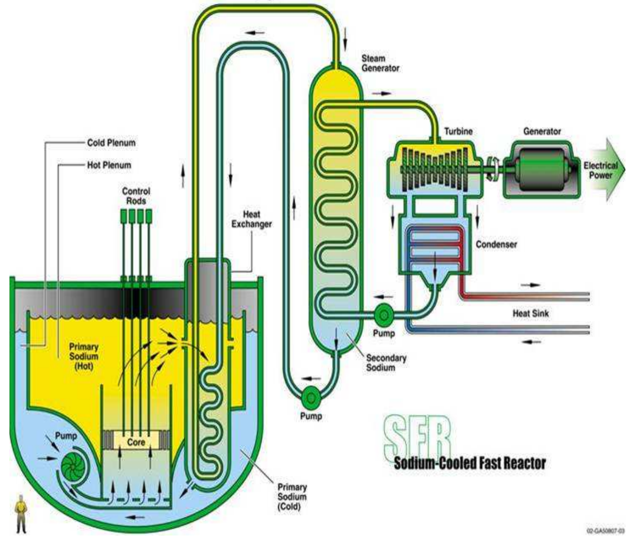




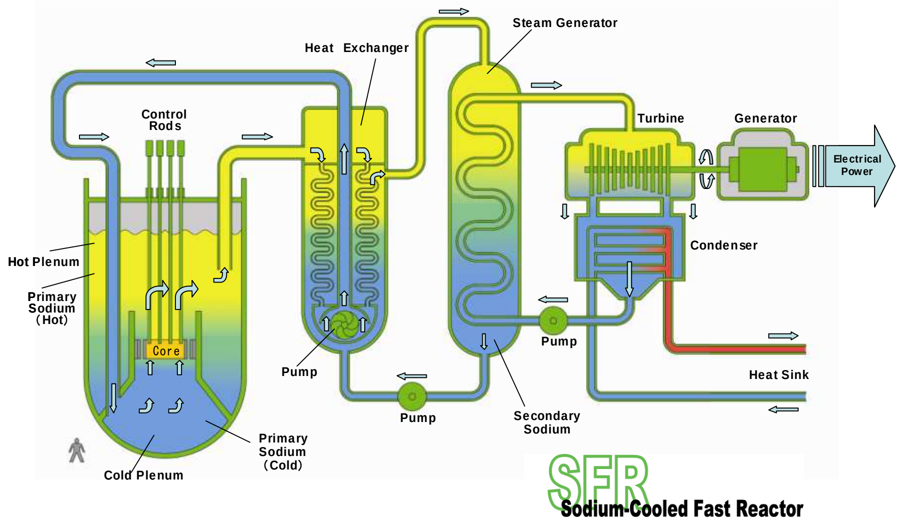


SODIUM FAST REACTOR *(SFR)*

- **A new generation of Sodium Fast Reactor**
  - *Component Design & Balance of Plant for **enhanced economics***
  - ***Improved operability** (ISI&R, modular design, water/gas PCS)*
- **Towards enhanced safety & reliable operation**
  - *Better prevention/**mgt of Severe accidents***
  - *Minimization/preclusion of **Sodium risks***
- **Flexible recycling of Transuranics (TRU)**
  - ***Advanced Fuel** + **Global Actinide Cycle** Int. Demo (GACID)*



- **2012/22: Feasibility/Performance → 2020s: Demo SFR *(FR, RU, JP, CN…)***
- **Common Fast Reactor Design Criteria**



SODIUM COOLED FAST REACTOR (SFR)

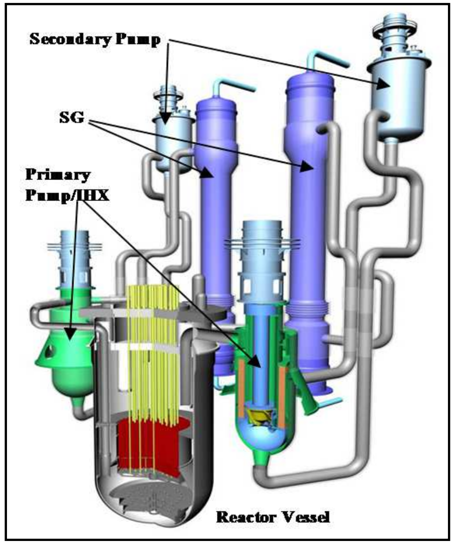
China, Japan, Russia, France, Korea *(+ India outside GIF)*

Loop, Pool & SMR baseline concepts

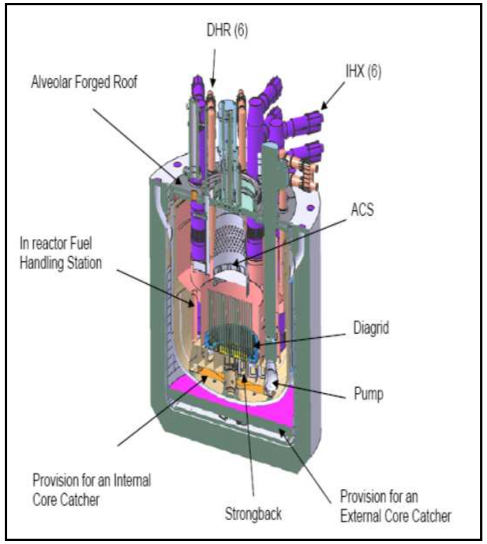
- *Safety Design Criteria*
- *Safety & Operation*
  - *Core inherent safety, Decay Heat Removal & Ultimate heat sink, ISI&R*
  - *Prevention/Mitigation of Severe Accidents with large energy releases + Sodium fires*
- *Advanced Fuel + Global Actinide Cycle Int. Demonstration*
- *Component Design & Balance of Plant*
- *System Integration & Assessment*

Loop

JSFR

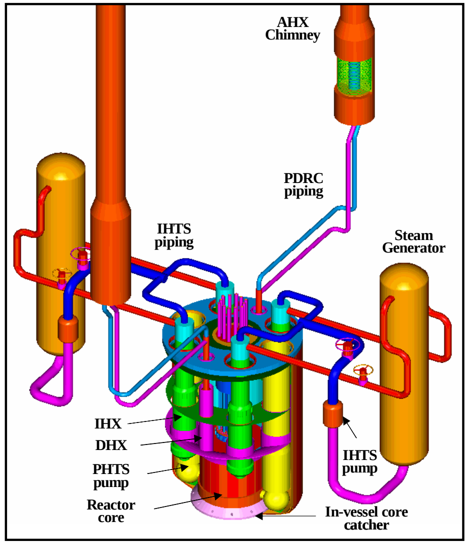


ESFR



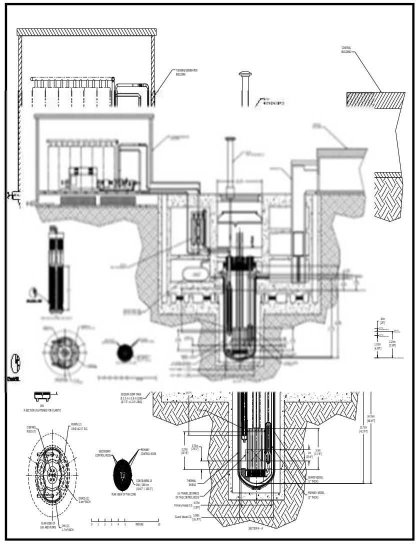
Pool

KALIMER



Small Modular

SMR



WORLD EXPERIENCE IN SODIUM FAST NEUTRON REACTORS

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

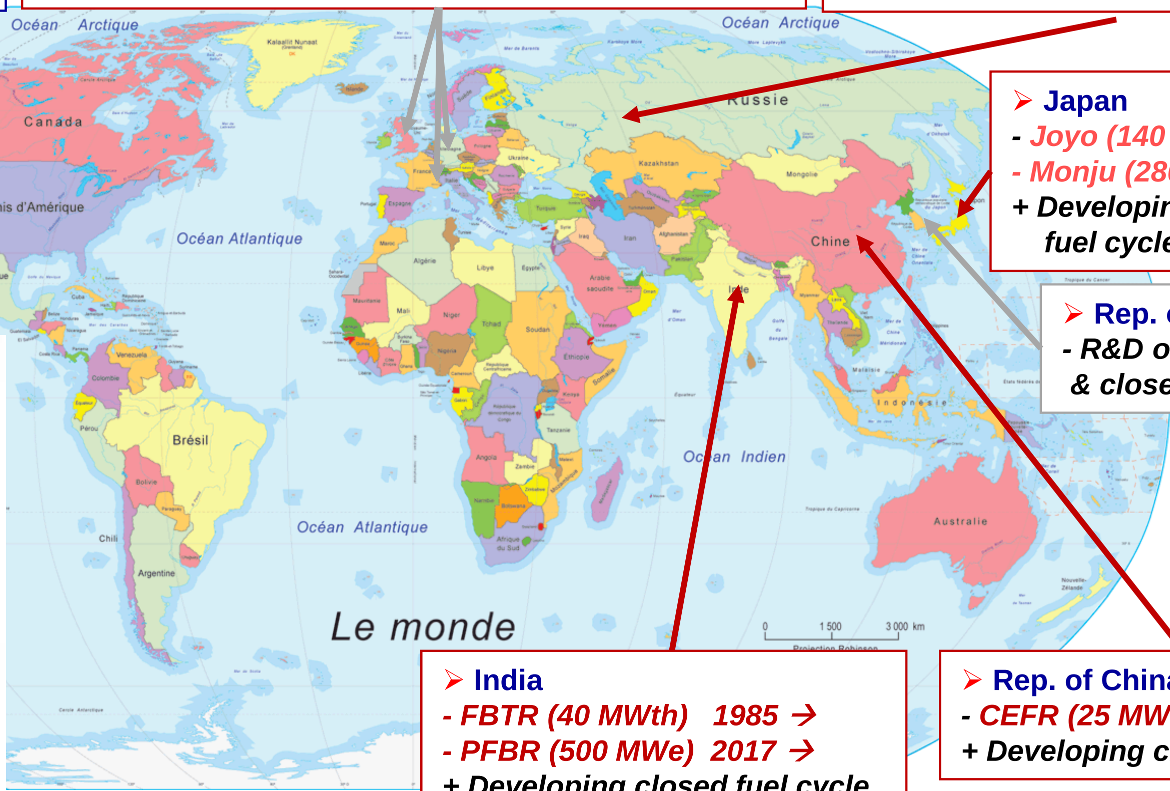
+ R&D on fuel cycle
+ Strategy under development

➢Europe *(France, Germany & UK)*
- *Rapsodie (20 MWth) 1967 → 1983*
- *DDFR (60 MWth), KNK II (17 MWe) 1978 → 1991*
- *Phenix (250 MWth) 1973 → 2009*
- *PFR (250 MWe) 1975 → 1994, SNR300*
- *Superphenix (1200 MWe) 1986 → 1998*

+ Industrial nuclear fuel cycle in France & the UK
+ R&D on closed nuclear fuel cycle + ASTRID Project

➢ Russian Federation
- *BOR-60 (60 MWth)*
- *BN350 (90 MWth) 1973 → 1999*
- *BN600 (600 MWth) 1980 →*
- *BN800 (800 MWth) 2015 →*
- *BN1200 (1200 MWth) 2020s*

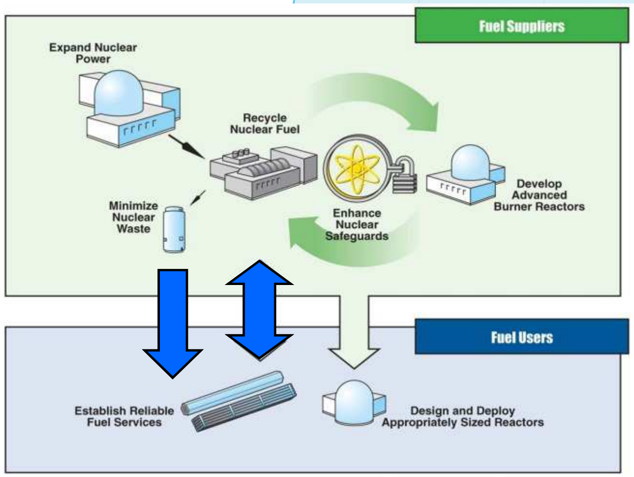
+ Developing closed nuclear fuel cycle



➢ Japan
- *Joyo (140 MWth)*
- *Monju (280 MWth) 1994 →*

+ Developing closed fuel cycle

➢ Rep. of Korea
- ***R&D on reactor & closed fuel cycle***



➢ India
- *FBTR (40 MWth) 1985 →*
- *PFBR (500 MWe) 2017 →*

+ Developing closed fuel cycle

➢ Rep. of China
- *CEFR (25 MWe) 2010 →*

+ Developing closed fuel cycle

GNEP: a strategy to enable expansion of nuclear power in the U.S. and around the world, promote nuclear nonproliferation goals, and help resolve nuclear waste disposal issues

SFR R&D: GLOBAL STANDARDS OF SAFETY DESIGN

- **Safety design requirements** (safety design criteria (SDC) / guidelines (SDG)) toward the safety enhancement of SFR in the world.
- FR development countries intend to reflect them in their safety design.

➡ De facto global standards

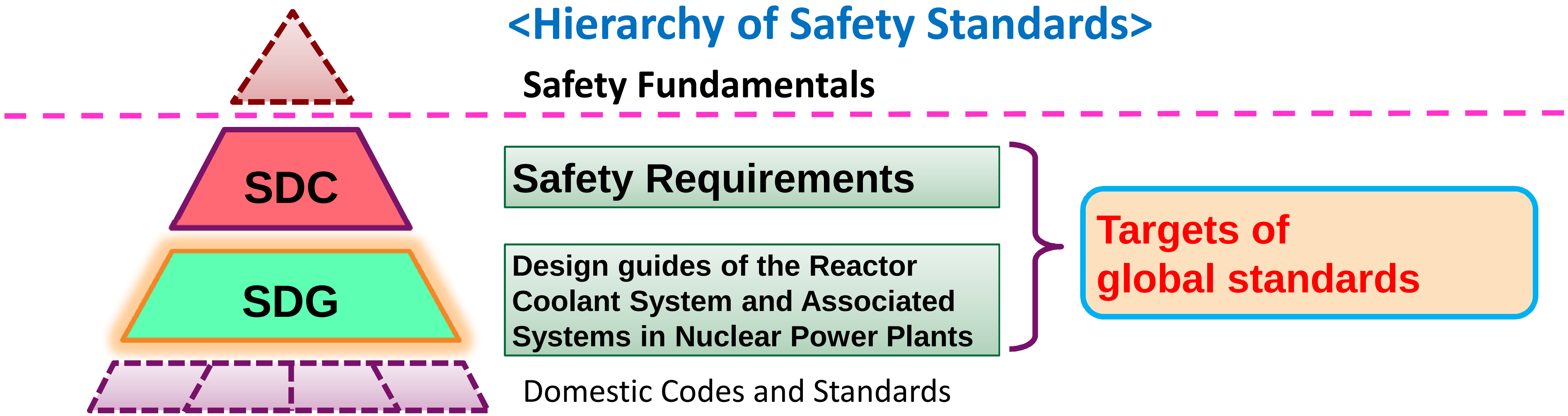
◆ Positioning and purpose of SDC / SDG

- Global standardization of the safety design concepts toward the commercialization
- Safety improvement of FRs in the world

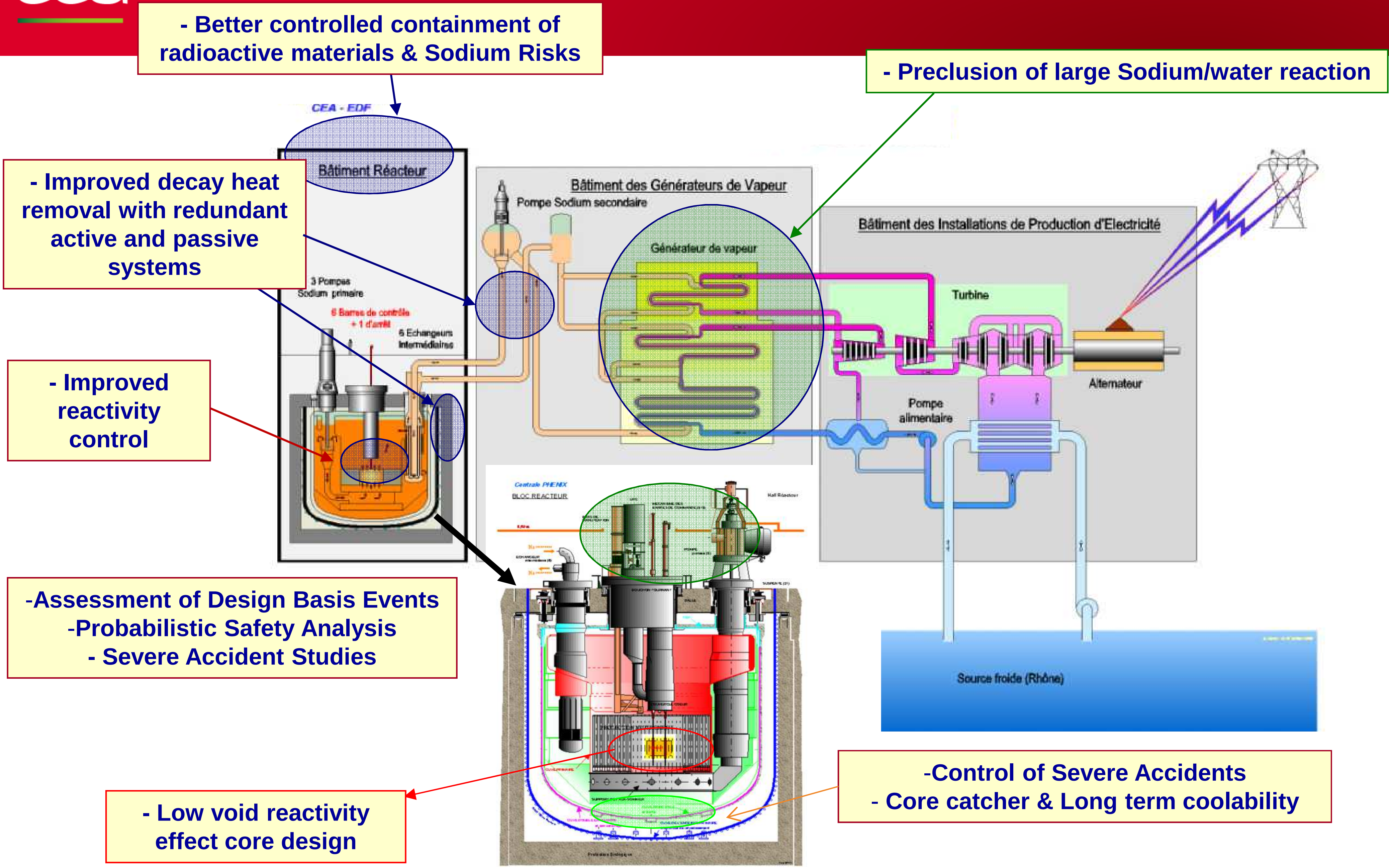
◆ Main results: SDC report (approved by GIF in May 2013)

- Review is in progress among regulatory bodies/technical support organizations of FR development countries and by international organizations (IAEA, OECD/NEA/CNRA, etc.)
- Russia, China, India etc. intend to reflect in the safety design

<Hierarchy of Safety Standards>



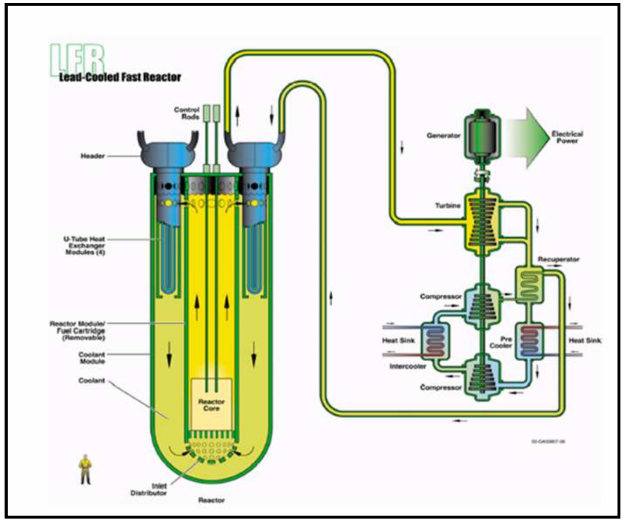
IMPROVED SAFETY OBJECTIVES FOR ASTRID



LEAD FAST REACTOR *(LFR)*

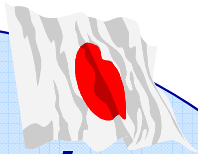
- **An alternative Liquid Metal cooled Fast Reactor (~600 MWe, T_{Pb}~480°C)**
  - *Thermal management of lead (Tm ~327°C) + ISI&R*
- **Weight of primary system** *(seismic behaviour, sloshing…)*
- **Prevention of corrosion of 1[ry] system structures**
- **Flexible recycle of TRU fuel**

- **2015: Feasibility → 2020+: Techno Demo** *(**RU**, EU ?)*
- **2022+: Performance → 2030+: LFR Prototype**

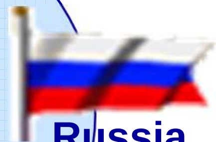


ELSY
ALFRED
in EU FP6-7

Euratom countries



Japan



Russia

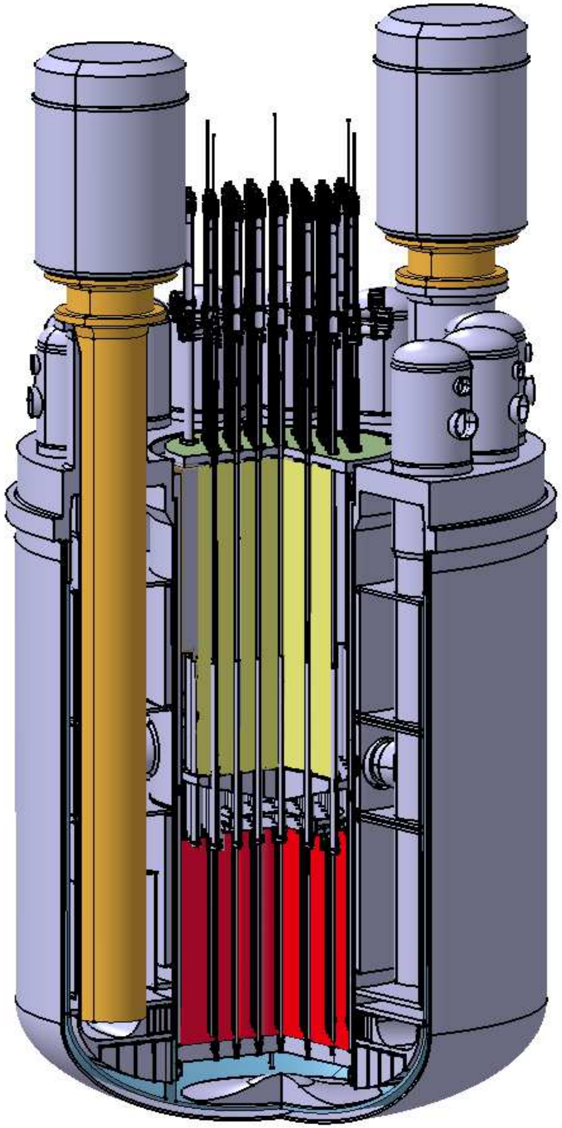
LFR Steering Committee

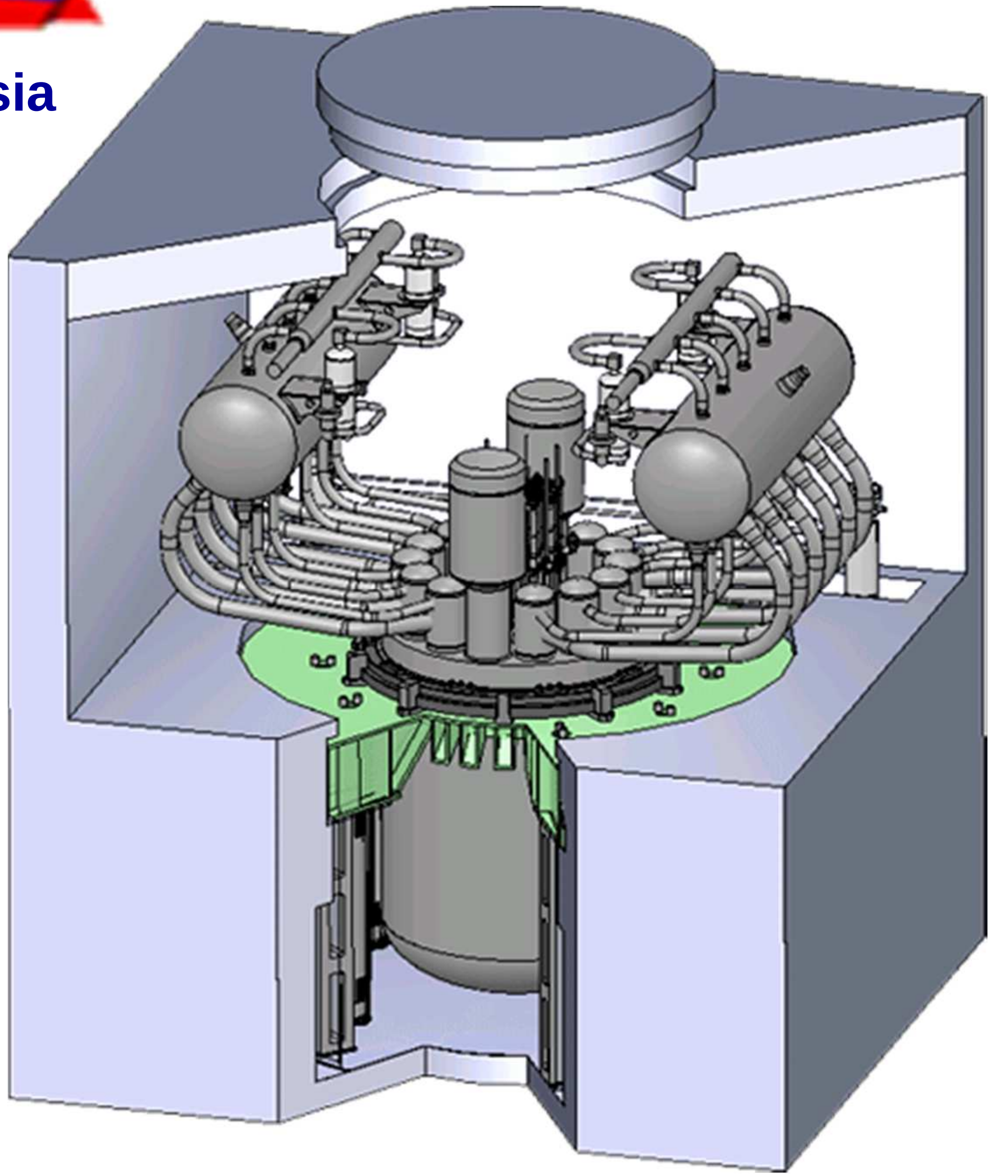
SVBR-100 *(PbBi)*
BREST-300 *(Pb)*

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

SVBR-100 PB-BI REACTOR SYSTEM *(2020s ?)*

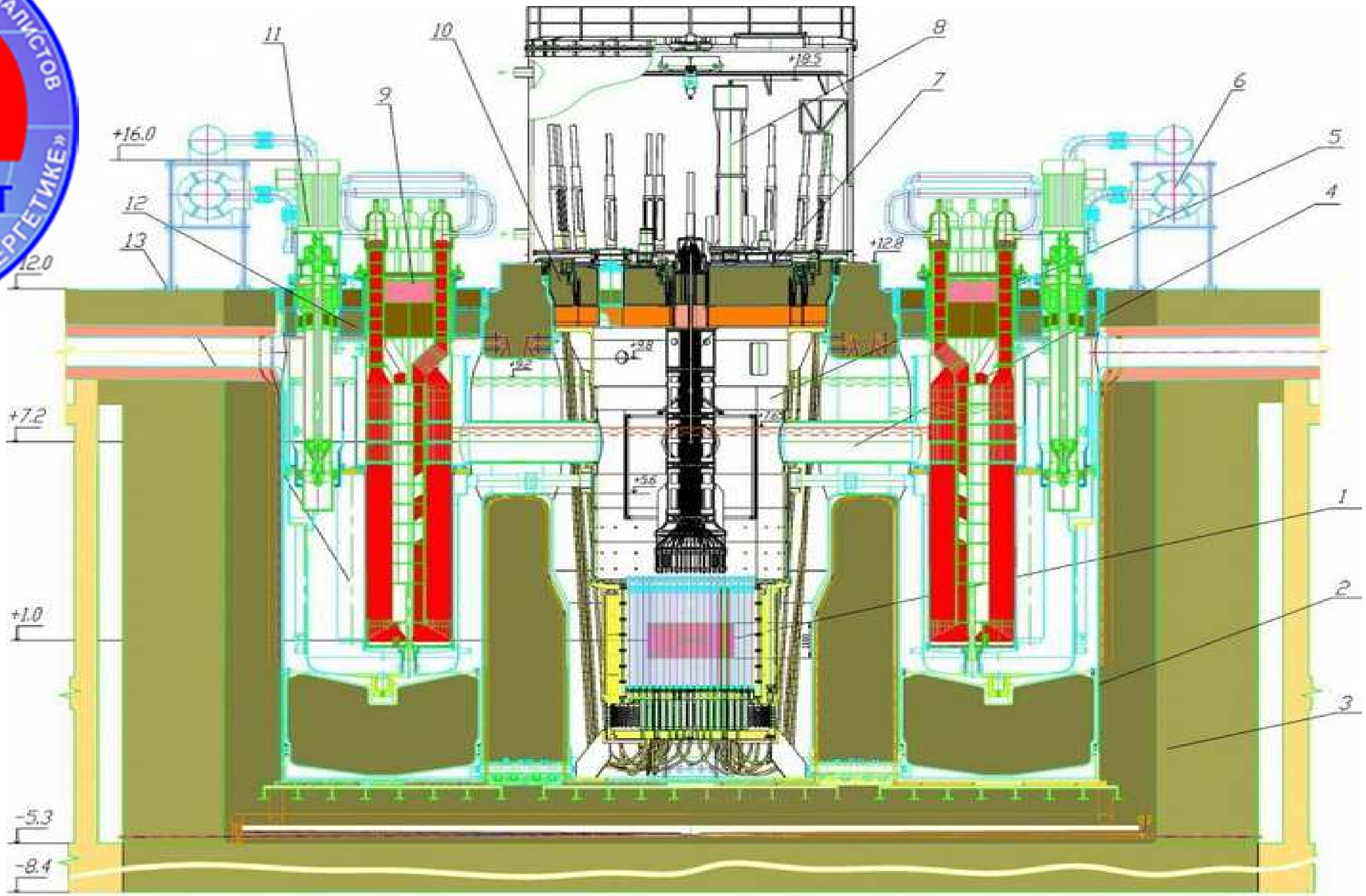
Russia





BREST-300: LEAD-COOLED FAST REACTOR *(2020+)*

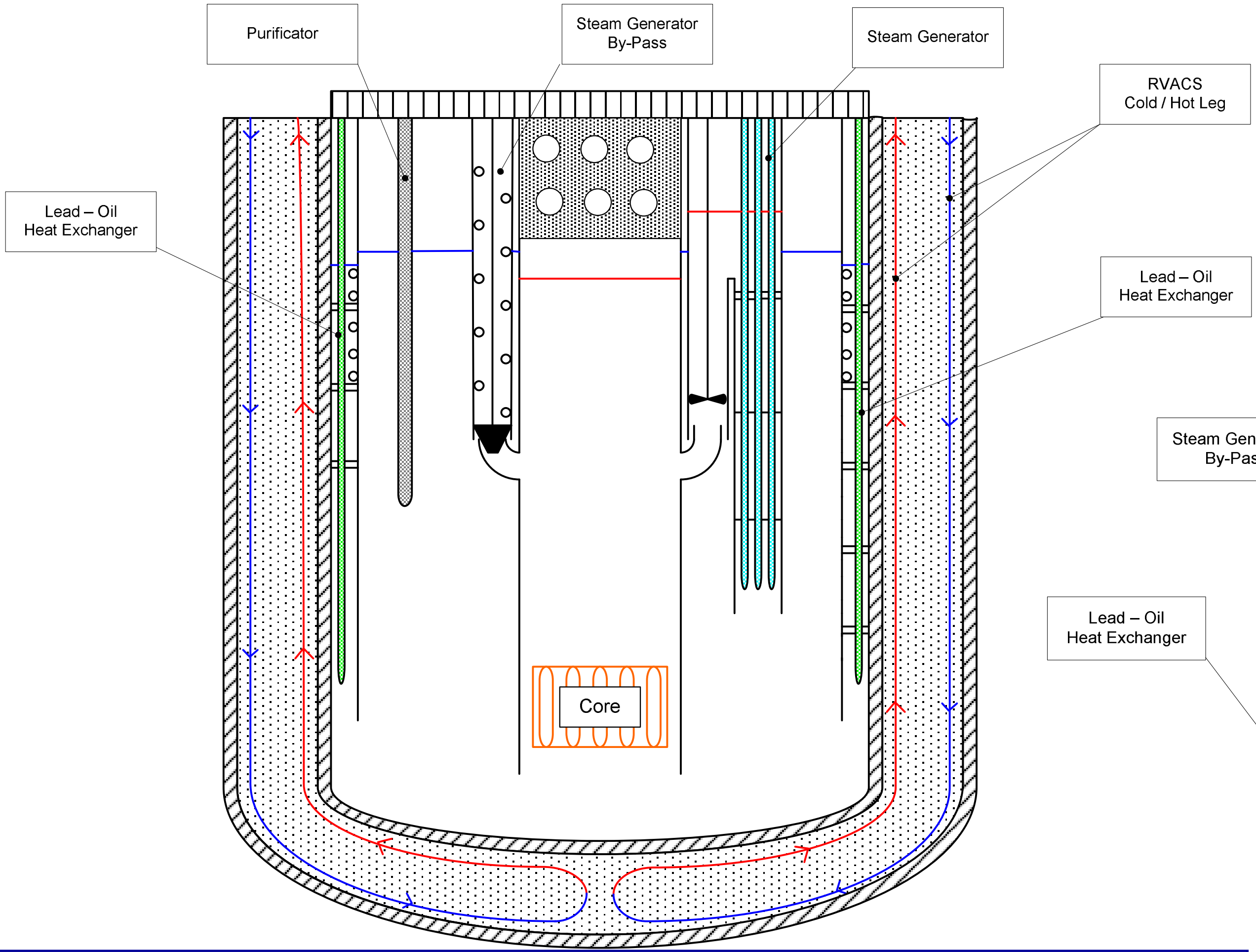
НИКИЭТ 2017



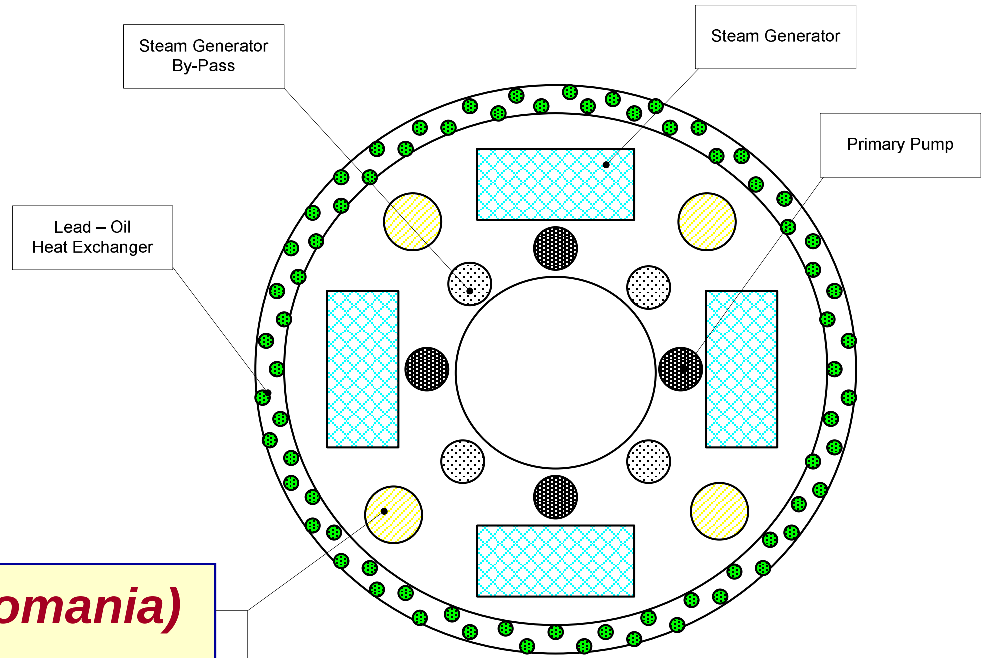
1. Зона активная
2. Блок корпусов
3. Шахта реактора
4. Трубопровод коллектора
5. Корзина активной зоны
6. Система расхолаживания
7. Колонна измерительная
8. Машина внутриреакторная перегрузочная
9. Парогенератор
10. Перекрытие верхнее
11. Главный циркуляционный насос
12. Блок парогенератора-ГЦН
13. Фильтр

Layout of ALFRED Prototype Reactor

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



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



- ***2013 – Consortium ENEA, Ansaldo, ICN (Romania) for a demonstration plant 120 MWe***

GAS FAST REACTOR *(GFR)*

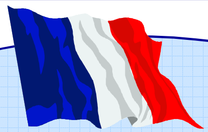
- **A new concept of Gas-cooled Fast Reactor:**

→ ***a longer term option than the SFR and a sustainable V/HTR***

- **1200 MWe – T_{He} ~ 850 °C – Co-generation electricity + H_2**
  - *Conceptual design & Safety*
    - *- Designed for a **safe management of LOCA***
  - *Fuel & Core Materials*
    - *- **Robust fuel** (ceramics clad UPuC) **& Materials***

→ 2022: Feasibility → >2030: Performance
→>2030: Allegro: GFR technology *(EU ?)*

GCFR
GoFastR
EU FP5-6-7



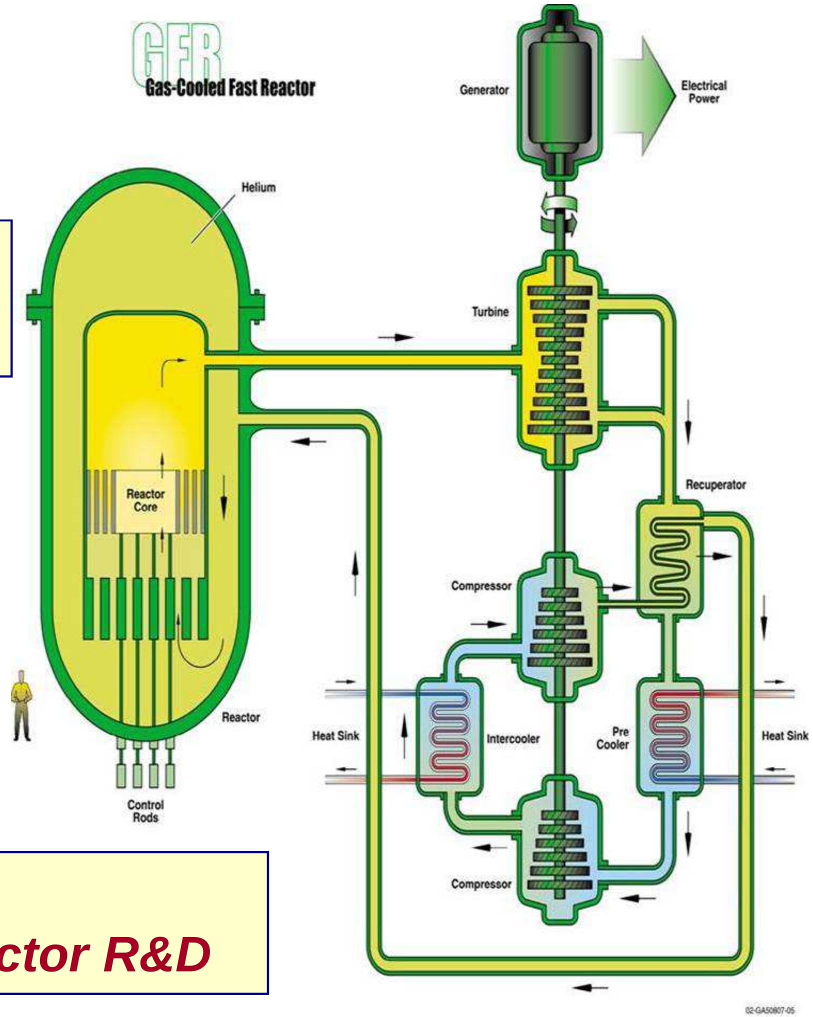
France

Japan

Euratom countries

GFR Steering Committee

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



GFR – GAS FAST REACTOR & EXPERIMENTAL PROTOTYPE

Robust decay heat removal strategy (passive after 24hrs)

- ***GCFR EU-FP6 Project***
- ***GoFastR EU-FP7 Project***
- ***Alliances EU-Horizon 2020***

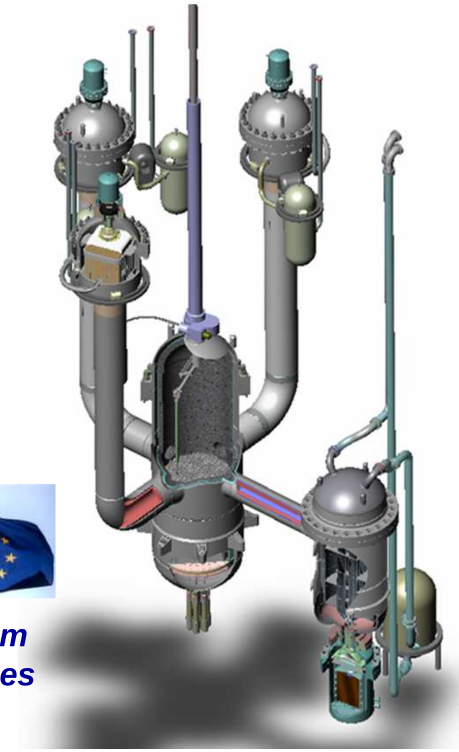
- ***2010 – Consortium HR, CZ, SK + PL (2012)***
- ***2012 – Centres of Excellence***

SiC clad Fuel (CEA)

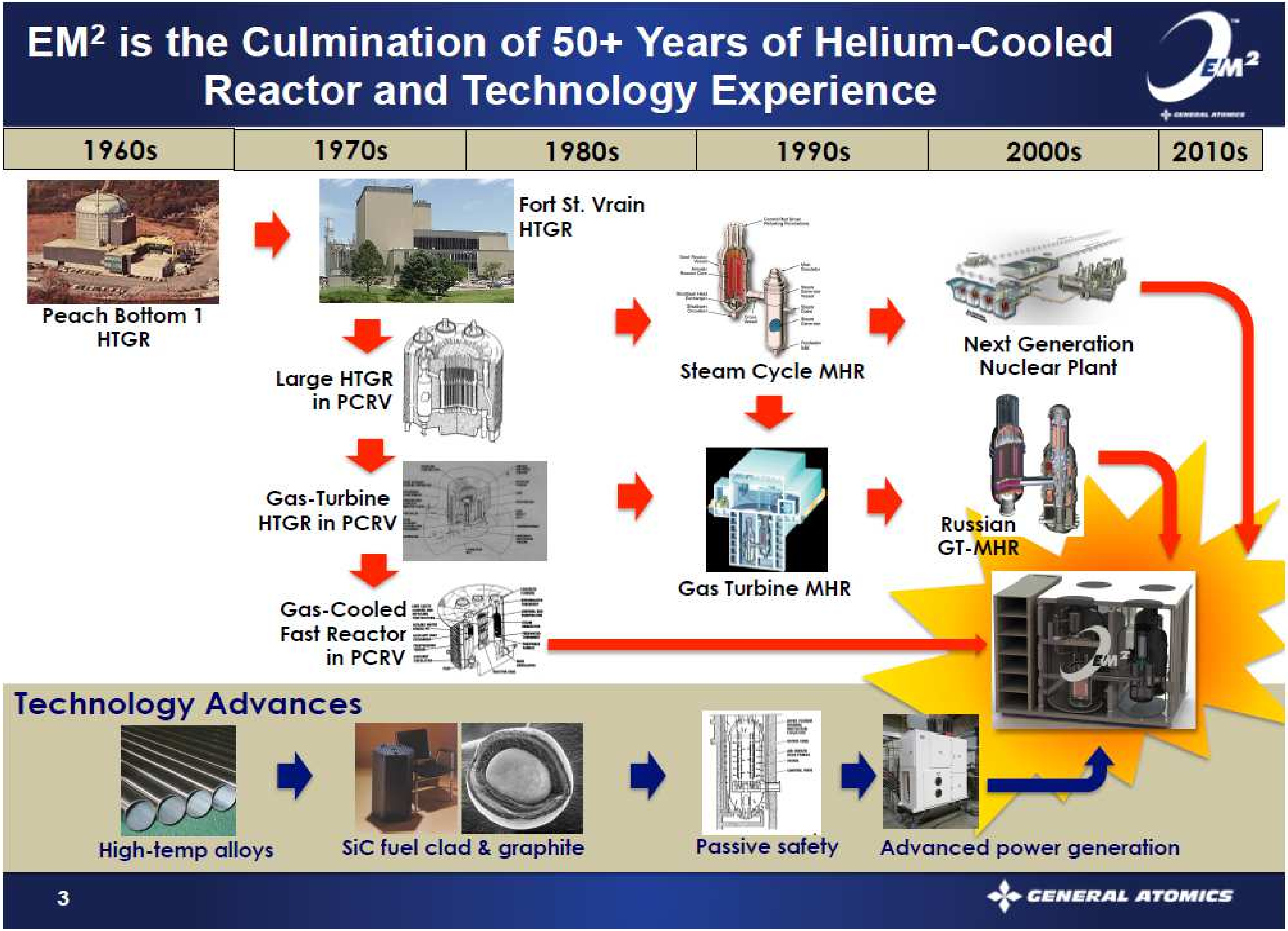
GFR 2400 MWt reference concept

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

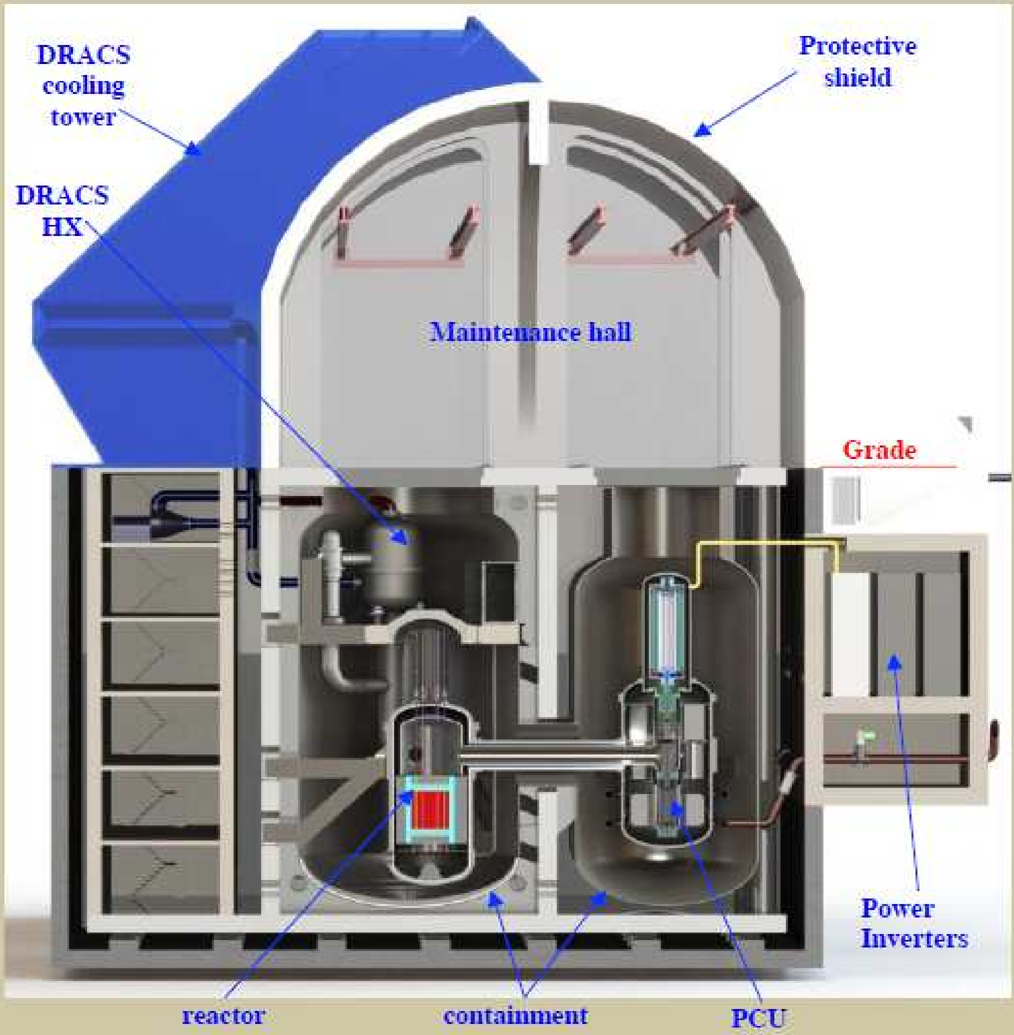
Euratom countries



Allegro (75 MWt)


EM2 is the Culmination of 50+ Years of Helium-Cooled Reactor and Technology Experience
1960s
1970s
1980s
1990s
2000s
2010s
Peach Bottom 1 HTGR
Fort St. Vrain HTGR
Large HTGR in PCRV
Gas-Turbine HTGR in PCRV
Gas-Cooled Fast Reactor in PCRV
Steam Cycle MHR
Gas Turbine MHR
Next Generation Nuclear Plant
Russian GT-MHR
Technology Advances
High-temp alloys
SiC fuel clad & graphite
Passive safety
Advanced power generation
3
GENERAL ATOMICS

EM² Modules Are Based on a, Helium-Cooled, "Convert and Burn" Fast Reactor System

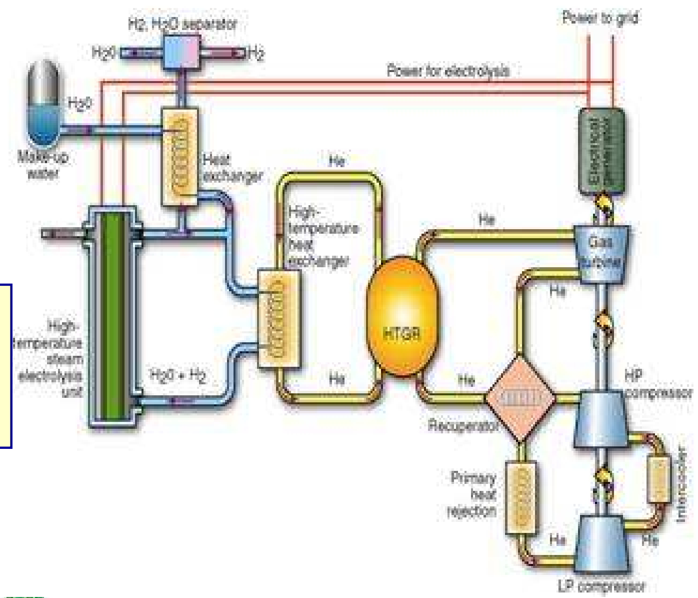


Specifications:

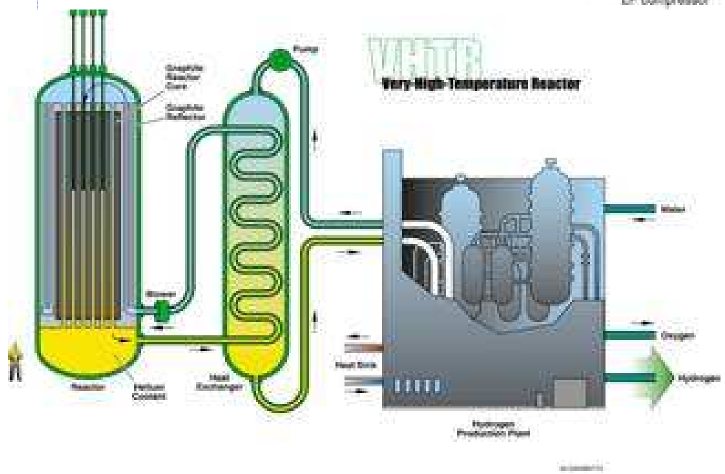
- 265/240 MWe per module for water/dry cooling
- 500 MW_t reactor power
- 850°C core outlet temperature
- Combined Brayton/R-245fa Rankine cycle
- 60 year plant life; 30 year core life
- 60 year dry fuel storage
- 14 % average fuel burnup:
- Reduced waste (< 25% waste mass of PWR)
- Seismically isolated primary system
- Multi-fuel capable

VERY / HIGH TEMPERATURE REACTOR *(V/HTR)*

- **A nuclear system dedicated to the production of HT process heat for the industry and hydrogen (600 MWth - T_{He} >750°C → 900 °C)**
  - ***Block or pebble core*** *concept with epithermal neutrons*
  - *Passive safety features*
- **Key R&D challenges**
  - ***Fuel particle*** *& Fuel Cycle*
  - ***Heat resisting materials***
  - ***Hydrogen production****: I-S cycle, HT Electrolysis…*



→ 2010: Feasibility – 2025: Performance
2018: HTR-PM / ~ 2020+: NGNP & Other Projects

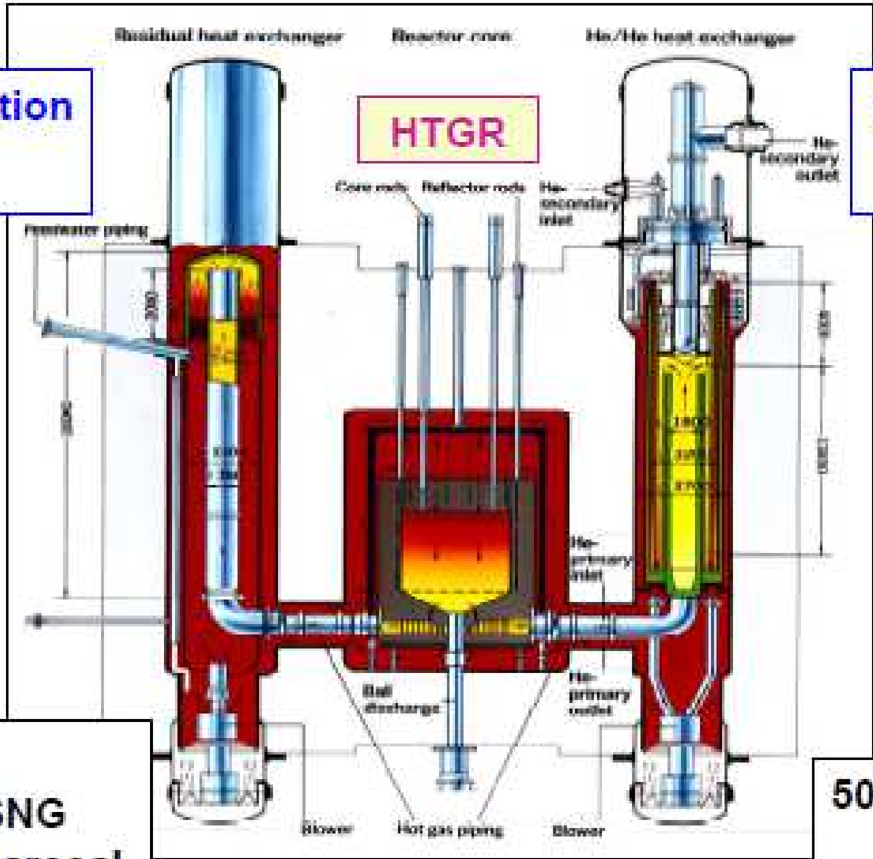


PNP PROJECT 500 MWTH (~1985, FZ-JÜLICH)

JÜLICH

Prototype Plant PNP-500

Hydro gasification of lignite



Steam gasification of hard coal

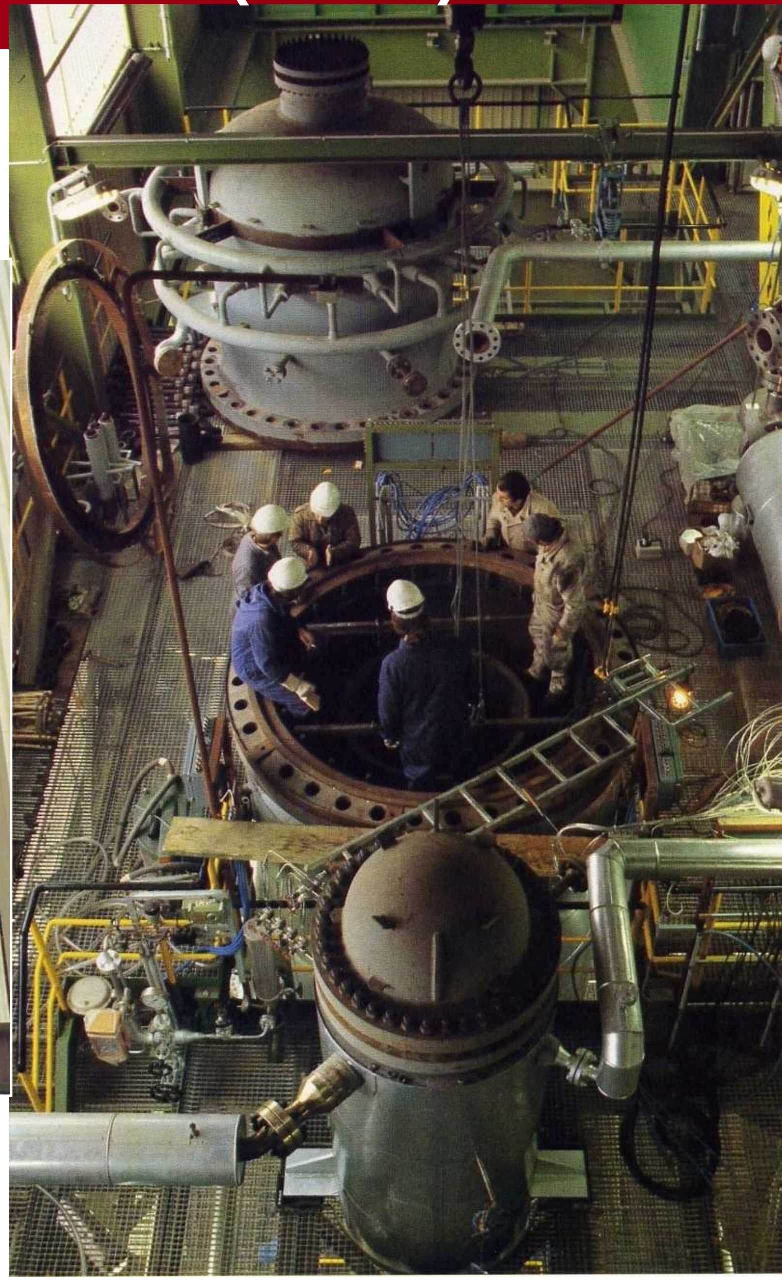
166 t/h coal
→ 26,500 m³ SNG
+ 18.4 t/h charcoal

50 t/h coal
→ 41,000 m³ SNG

OECD-IAEA Workshop 2013 Nuclear Industrial Process Heat Applications Karl Verfondern, FZJ-IEK-6 Folie 17

H_2 PRODUCTION BY STEAM METHANE REFORMING WITH NUCLEAR HEAT (1980S)

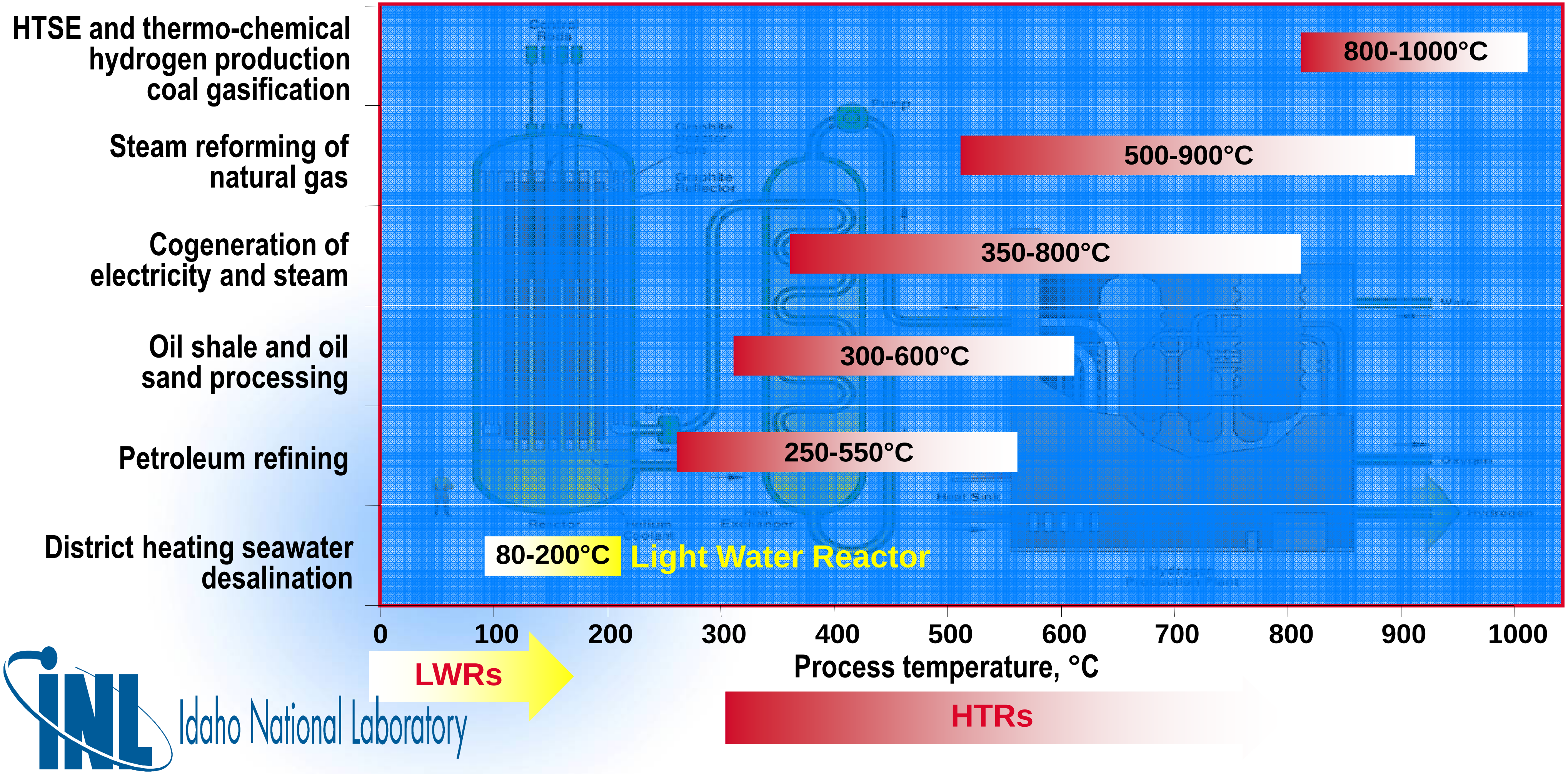
PNP Project
500 MW



EVA-II reformer tube bundle at the Research Center Jülich (FzJ)

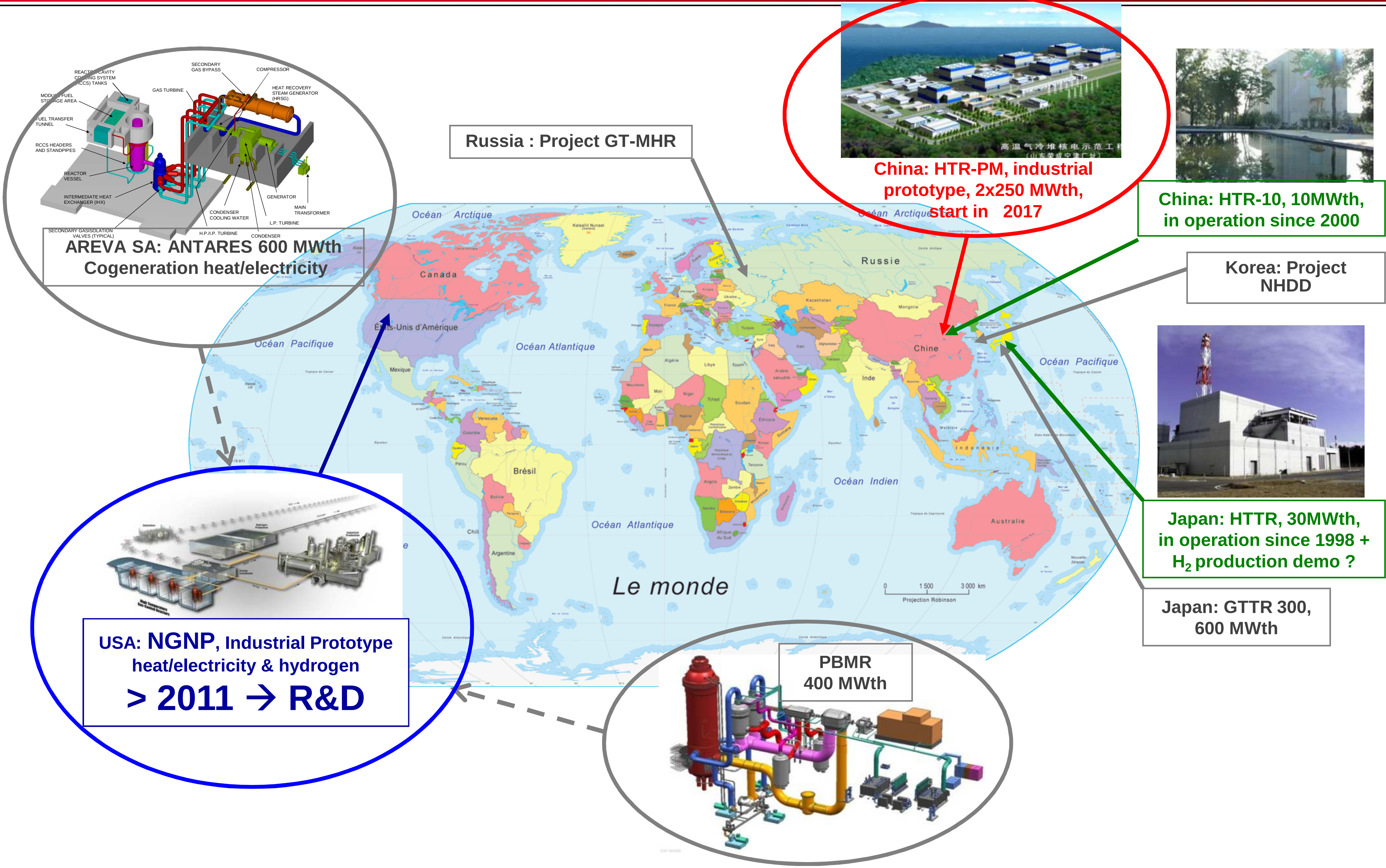
POTENTIAL OF HIGH TEMPERATURE REACTORS

Efficiency Gains could be Possible in the Future with High Temperature Reactors



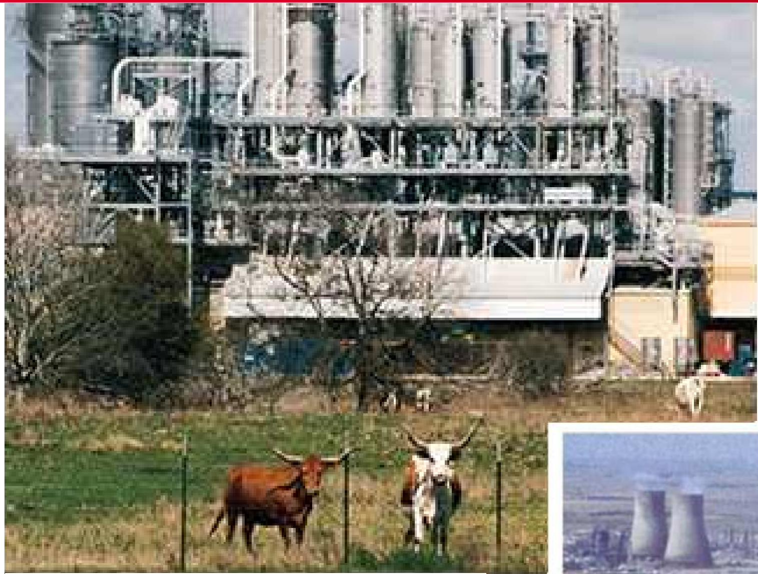
There is a role for existing LWRs, advanced LWRs, and small reactors…

HIGH TEMPERATURE REACTORS IN THE WORLD



POTENTIAL NUMBER OF HTGRS IN THE USA

U.S. DEPARTMENT OF ENERGY
Nuclear Energy



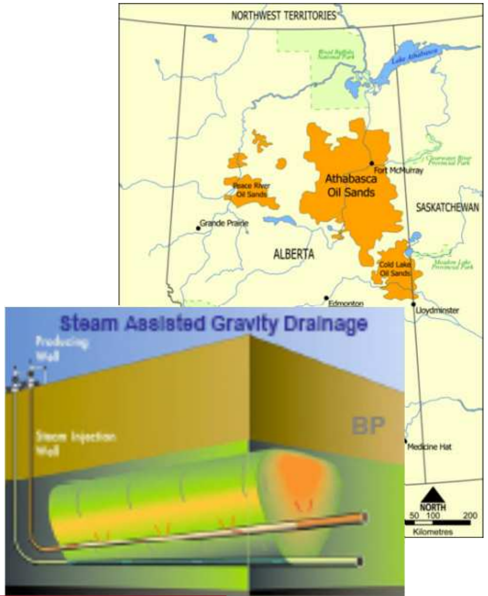
Petrochemical (150)

Petroleum Refining (50-100)

Sasol Secunda Plant

Coal-to-Liquids (100s)

Fertilizers/Ammonia (100+)



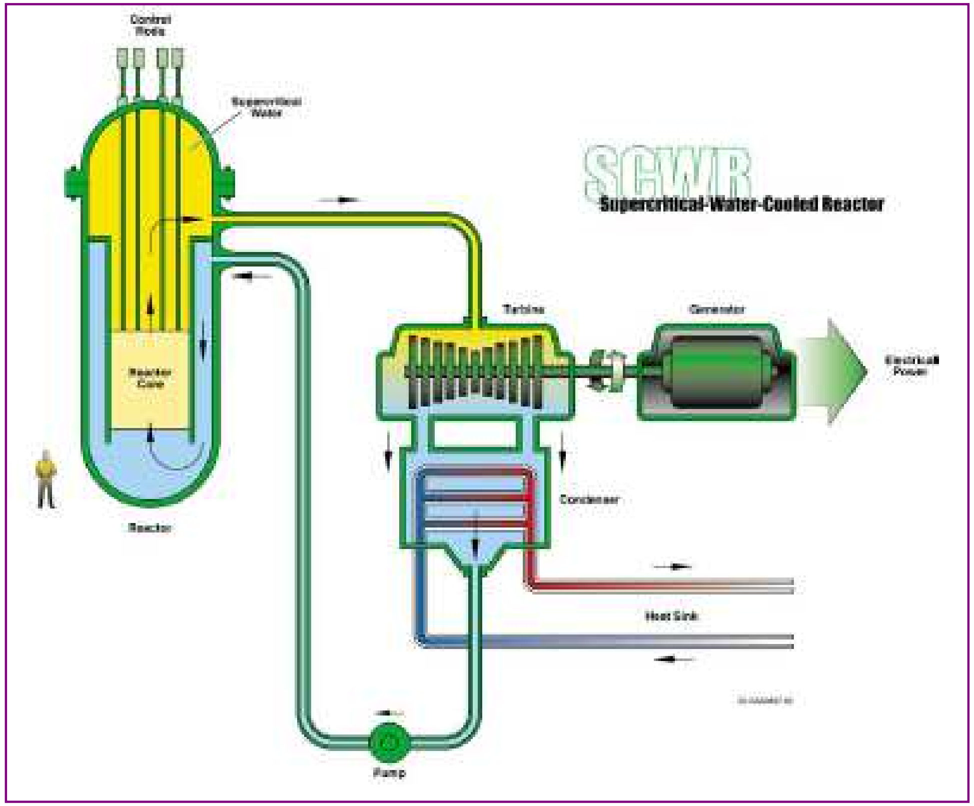
Oil Sands/Shale (200+)

1 Million Metric Tons CO_2/year avoided for every HTGR (500 MWth) used in lieu of Natural Gas

SUPERCRITICAL WATER REACTOR *(SCWR)*

- **Builds on LWR technology** *(> 22.1 MPa, 374 °C)*
- **Economic competitiveness** *(η > 44 % @ 550 °C - 25 MPa, compact)*
- **Thermal neutrons and open fuel cycle**
- **Key R&D challenges**
  - ***Thermal Hydraulics** & Safety (**stability of operation**)*
  - *Materials & Chemistry (**corrosion**)*
  - *System Integration and Assessment*

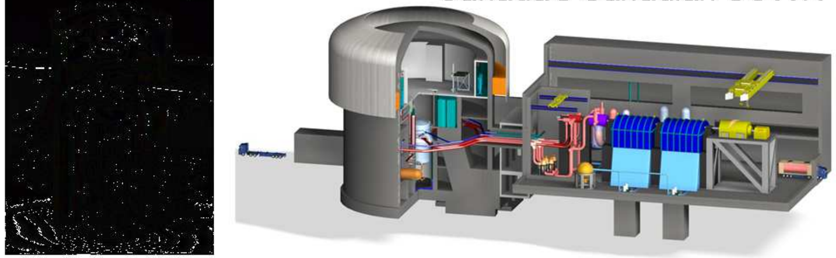
→ 2015: Feasibility – 2025: Performance



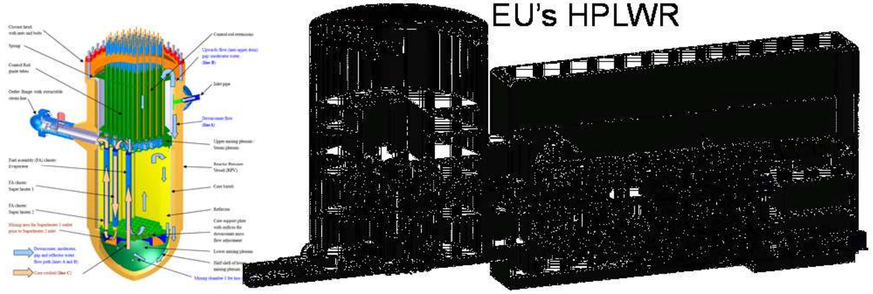
SCWR Concept Development

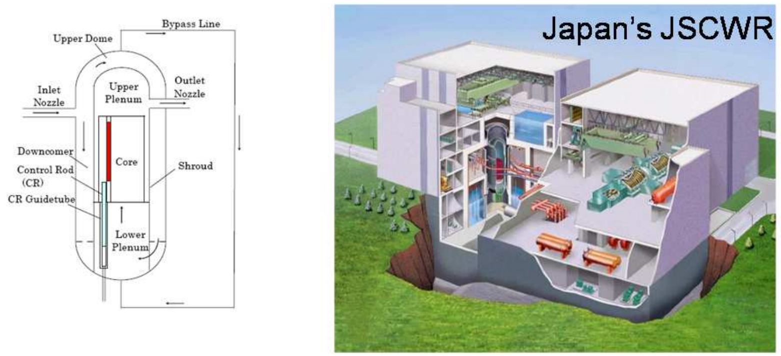
- ***Three SCWR concepts developed***

Canada's Canadian SCWR

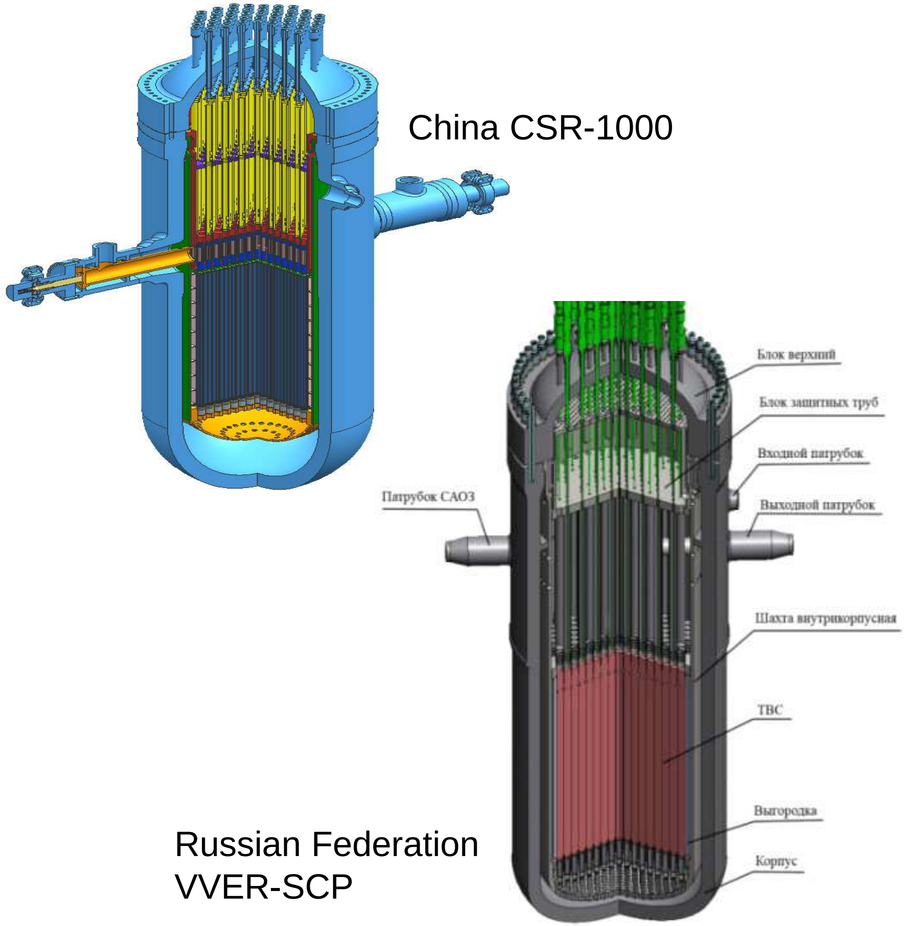


EU's HPLWR





- ***Two SCWR concepts under development***



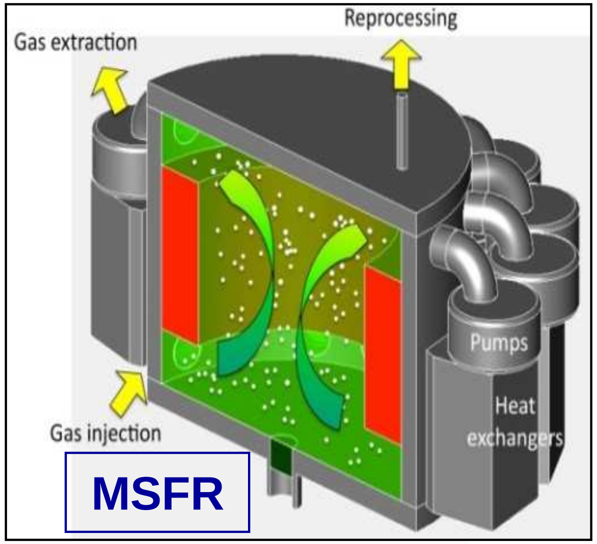
China CSR-1000

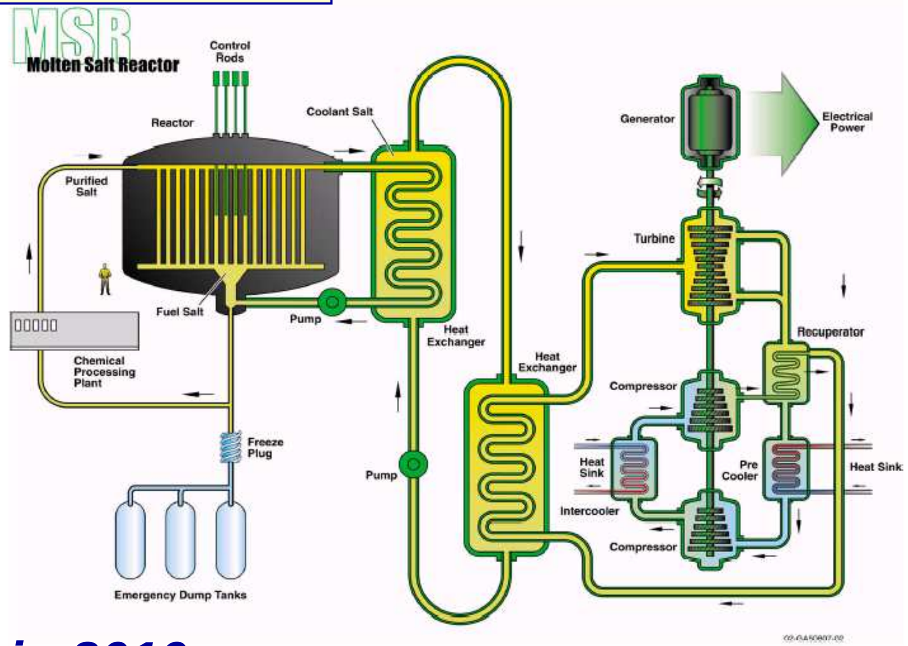
Russian Federation
VVER-SCP

MOLTEN SALT REACTOR *(MSR)*

- **1700 MW_{th} – Liquid fuel (550-750°C) & Epithermal**
- **Breeding with U-Th cycle / Burning actinides**
- **Key R&D challenges**
  - *Safety analysis methodology*
  - *Corrosion of structural materials*
  - *Management/control of salt + Treatment of used salt*
  - *Heat exchanger & other component technology*

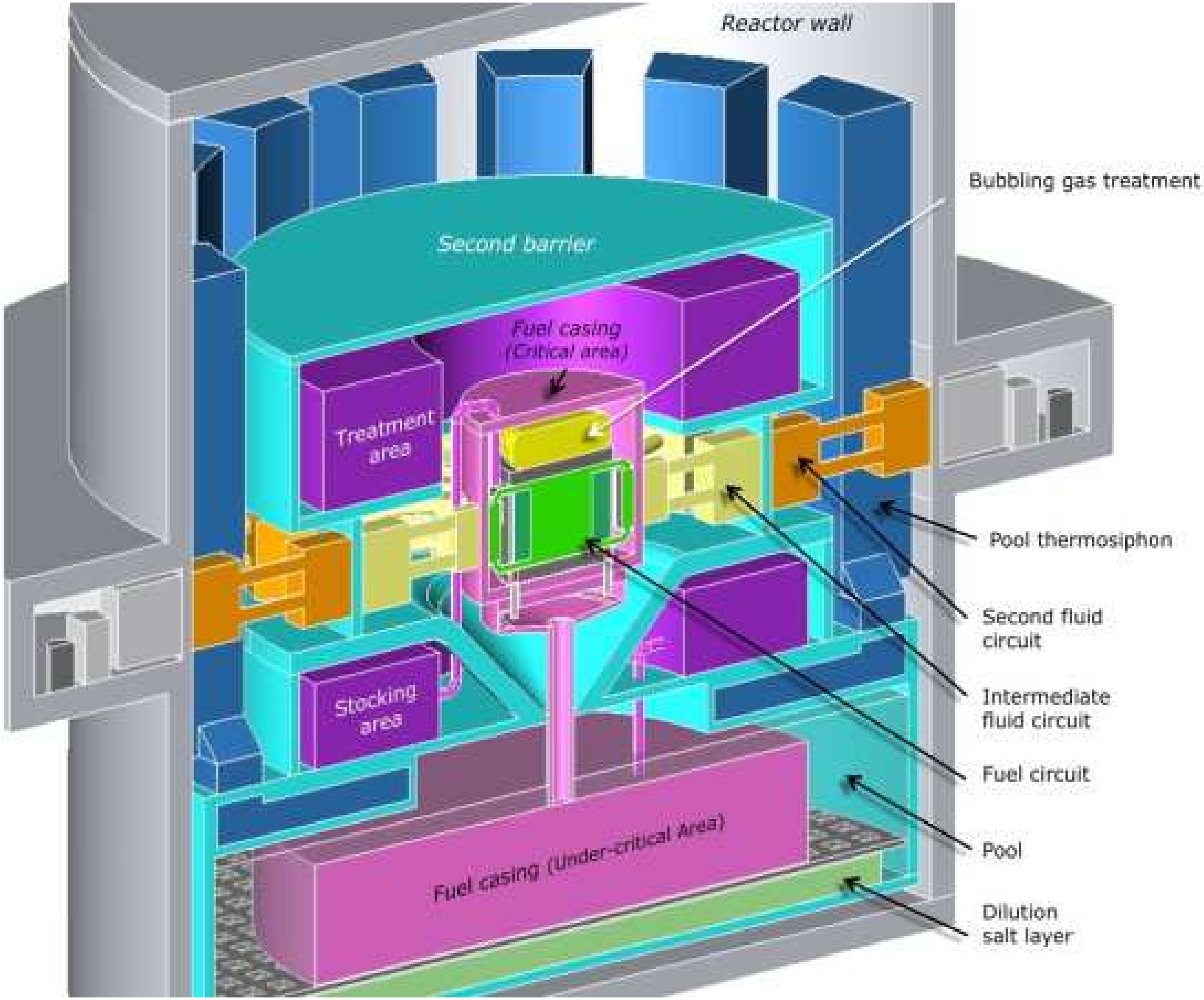
→ 2025: Feasibility *(MSFR, MOSART…)*





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

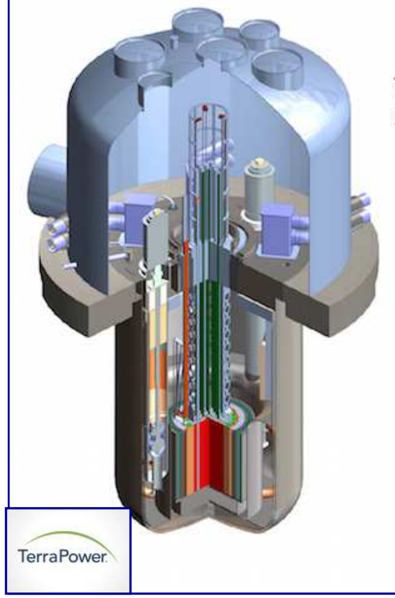
MOLTEN SALT FAST REACTOR *(MSFR)*



GAME CHANGERS FOR SUSTAINABLE NUCLEAR GROWTH?

***TWR:* A reactor for initiating the deployment of FNRs in a NTP member country without fuel cycle industry?**

Traveling Wave Reactor



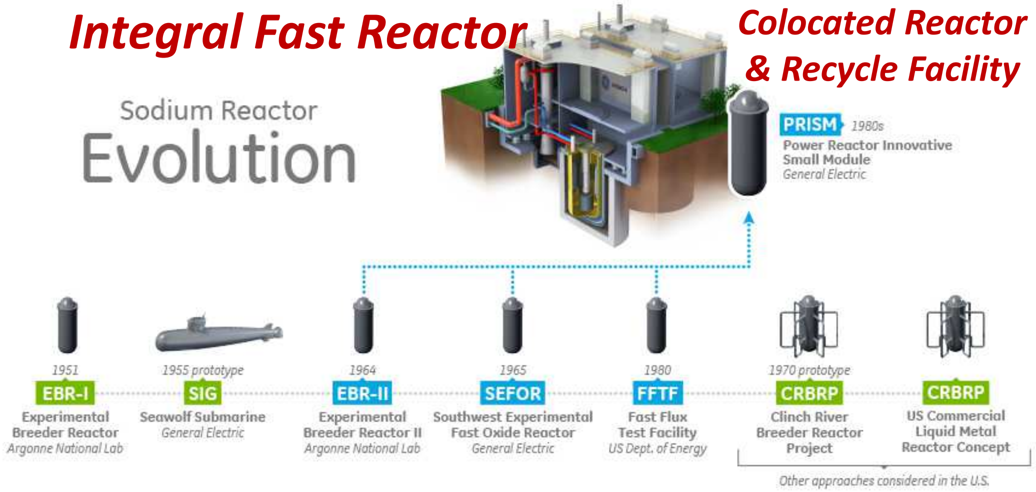
Turns depleted uranium into electricity, using a simple fuel cycle without requiring separations.

SIZE	600 MWe (Prototype Plant) 1150 MWe (Commercial Plant)
TEMPERATURE	510°C
PRESSURE	Low (Atmospheric)
PRIMARY FUEL	Depleted Uranium
COOLANT	Sodium
ENERGY CONVERSION	Steam (Rankine Cycle)
WASTE REPROCESSING	Not Required

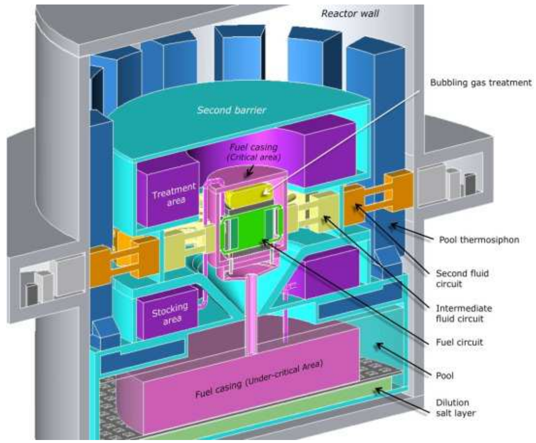
Transportable sealed & retrievable SMR with a long lifetime: An option for moderately reliable /stable newcomer nuclear countries?

Integral Fast Reactor

Colocated Reactor & Recycle Facility



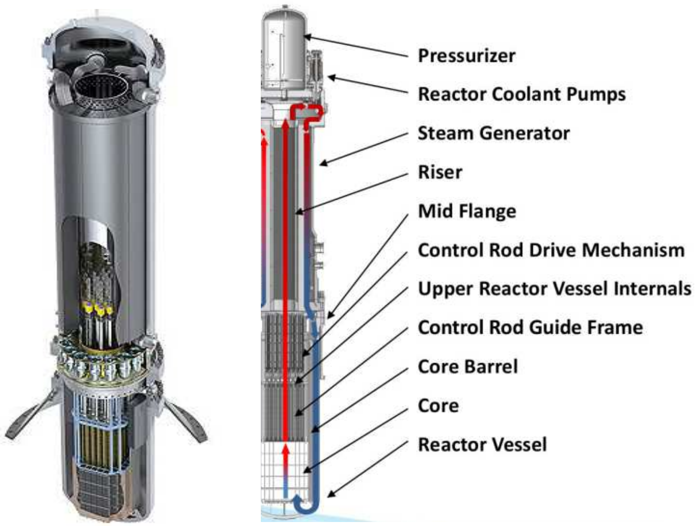
Nuclear systems with reactor & recycle facilities recycled: IFR? MSFR?... From fresh fuel to ultimate waste on the same site?



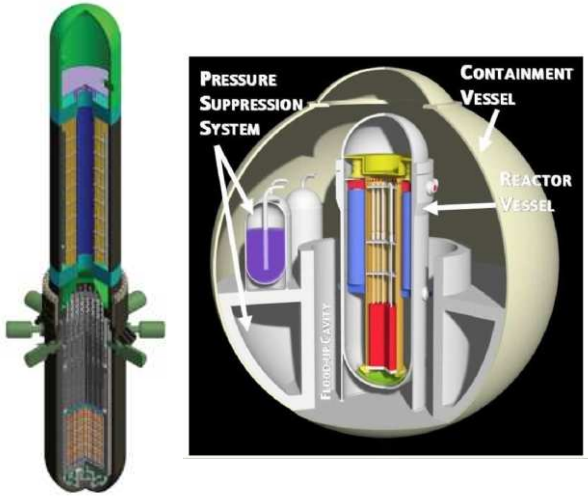
Molten Salt Fast Reactor

SMRS FROM THE USA, RUSSIA, JAPAN & ROK

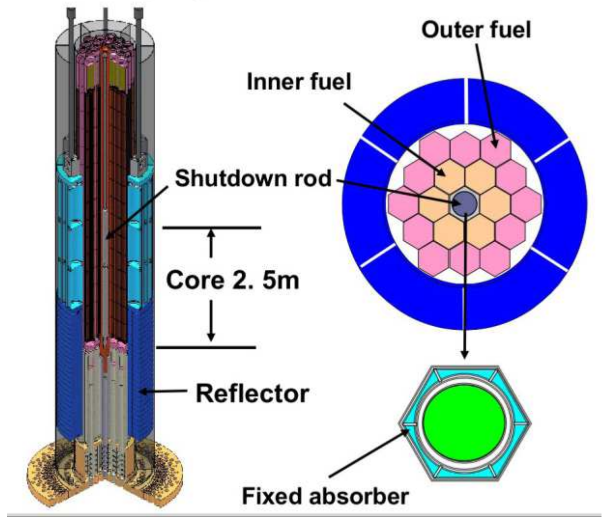
mPower 180 MWe
B&W + Bechtel



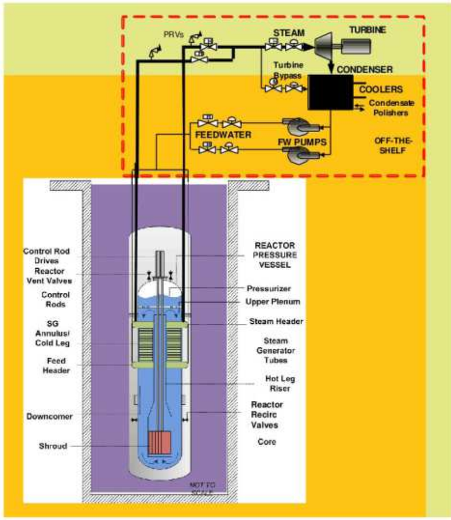
IRIS 300 MWe & SMR 200 MWe
Westinghouse



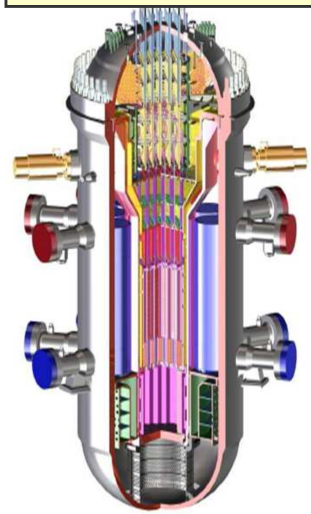
4S 10-50 MWe
Toshiba



Nuscale 45 MWe
Nuscale



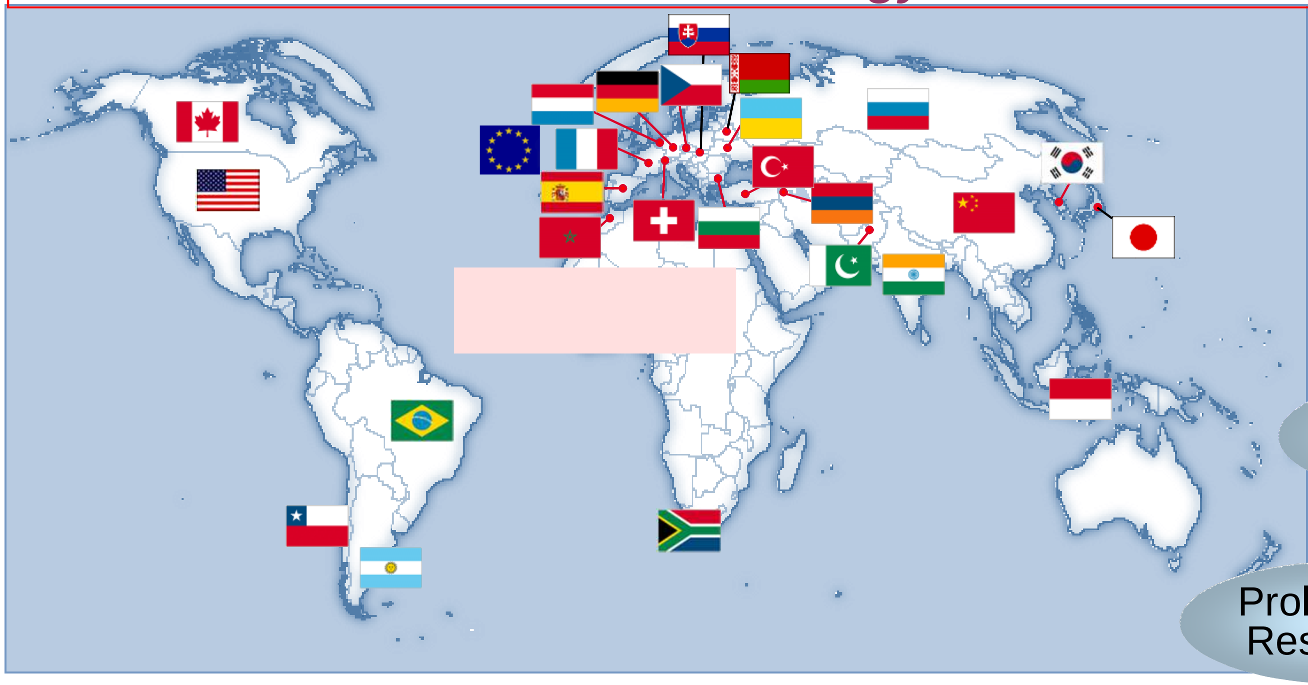
Smart 330 MWth
KAERI



АТЭС ММ 2x38 MWe
АСЭ РОСАТОМ

INPRO

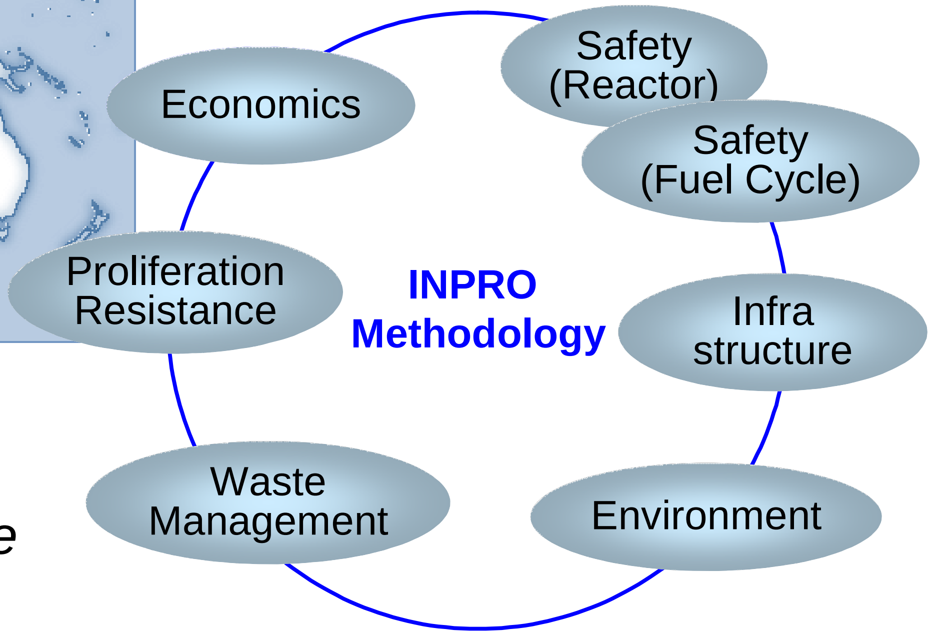
A unique forum for the development of nuclear energy in IAEA affiliated countries, strengthening the cooperation between Technology "Holders" & "Users"



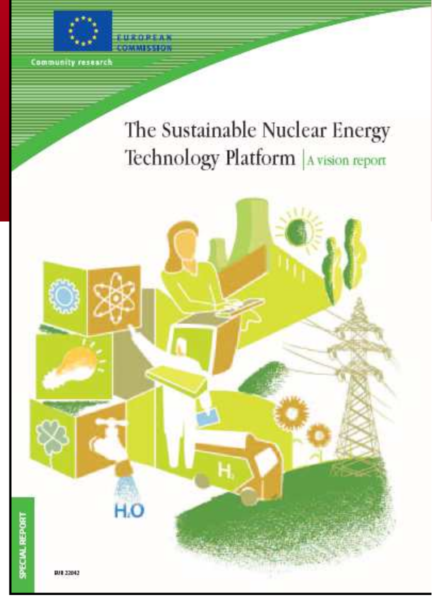
27 MEMBER STATES (status July 2007)

INPRO Methodology

A concrete achievement of INPRO phase 1, to be further assessed and improved during phase 2



EUROPEAN SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM *(SNE-TP)*



GEN II & III LWRs

New materials & fuels

Simulation & Experiments: reactor, safety, materials & fuels

R&D Infrastructures

Safety rules

GEN IV (V)HTR Process heat, electricity & H_2

GEN IV Fast Reactor &Closed Cycle

(SFR, LFR, GFR, ADS)

Energy Goals for Europe

- *Security of Supply*
- *Competitiveness*
- *-20% GHG by 2020*
- *Low carbon energy system by 2050*

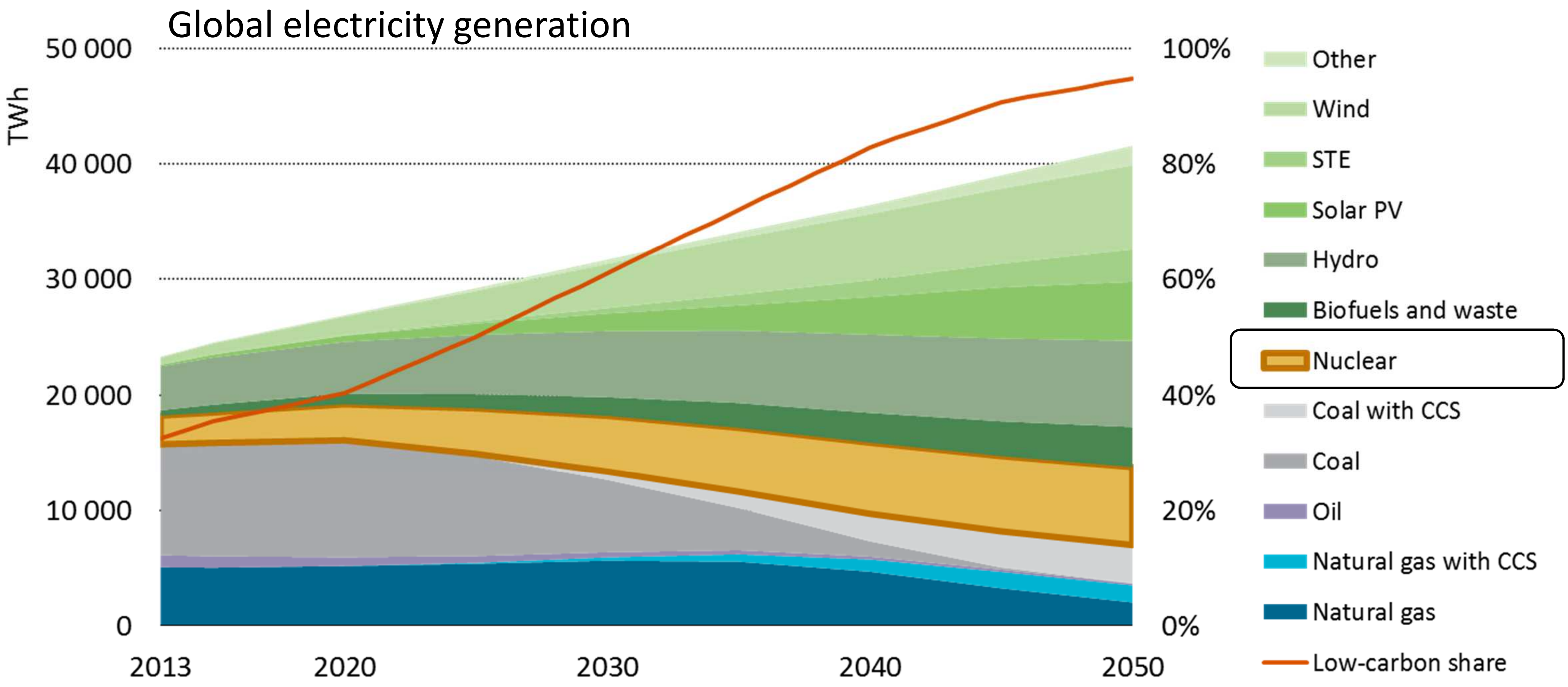
→ ***SET-Plan ('07)***

SNE-TP *(Oct. 2007)*

- ***R&D priority for industrial applications***
- ***Needs for large experimental facilities***
- ***Prototypes within the frame of "Public/Private Partnerships"***

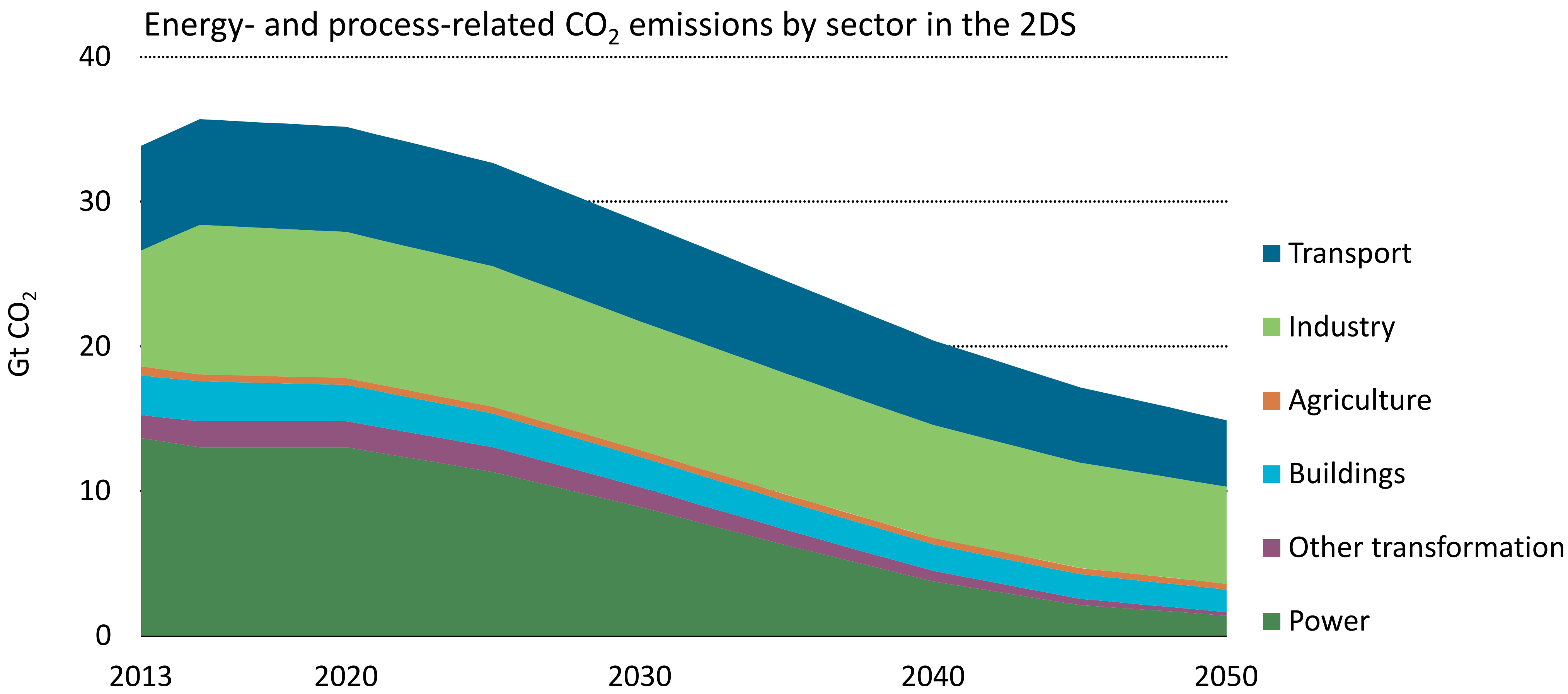
→ ***European Industrial initiative***

Power sector almost completely decarbonised in the 2DS



- Generation today:
  - Fossil fuels: 68%
  - Renewables: 22%
  - Nuclear: 11%
- Generation 2050:
  - Fossil fuels: 17%
  - Renewables: 67%
  - Nuclear: 16%

From 2 degrees to “well-below 2 degrees”



Industry and transport accounted for 45% of direct CO2 emissions in 2013, but they are responsible for 75% of the remaining emissions in the 2DS in 2050.

Le Forum International Generation-IV

- **Un cadre de coopération international sur la R&D de systèmes nucléaires visant des performances dépassant celles des REP/REB**
  - *Production nucléaire durable (SFR, LFR, GFR avec cycle du combustible fermé)*
  - *Production nucléaire élargie à la chaleur, l'hydrogène, HyC de synthèse…(V/HTR…)*
  - *Technologies en rupture (SCWR, MSR…)*

  → Partage des coûts de R&D, de démonstration, de recherche prénormative…
- **Un cadre de soutien des programmes nationaux et de partage d'infrastructures de R&D de classe mondiale**
- **Un cadre d'échange de vues et de prises de position sur les spécificités des réacteurs du futur et les besoins de R&D associés**
  - *Critères et orientations de sûreté + Besoins de R&D pour la certification*
  - *Evaluation des perspectives industrielles et besoins de R&D spécifiques*
  - *Analyse des perspectives de marché*
- **Un Forum en interaction avec l'AEN** *(Sec. tech, CNRA, GSAR...)*, **l'AIEA** *(Sûreté, INPRO, TWG…)* **et EU-SNE-TP** *(ESNII, NC2I…)*
- **Un facteur d'attaction pour la nouvelle génération de professionnels du nucléaire** *(Webinars…)*

En souvenir de Jacques Bouchard

http://www.gen-4.org/

Chairman
du Forum Gen-IV
2003-2006