

Generation IV Fast Reactors

Dr Richard Stainsby
AMEC
Richard.Stainsby@amec.com

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The Generation IV international research programme on advanced reactors

The case for fast reactors

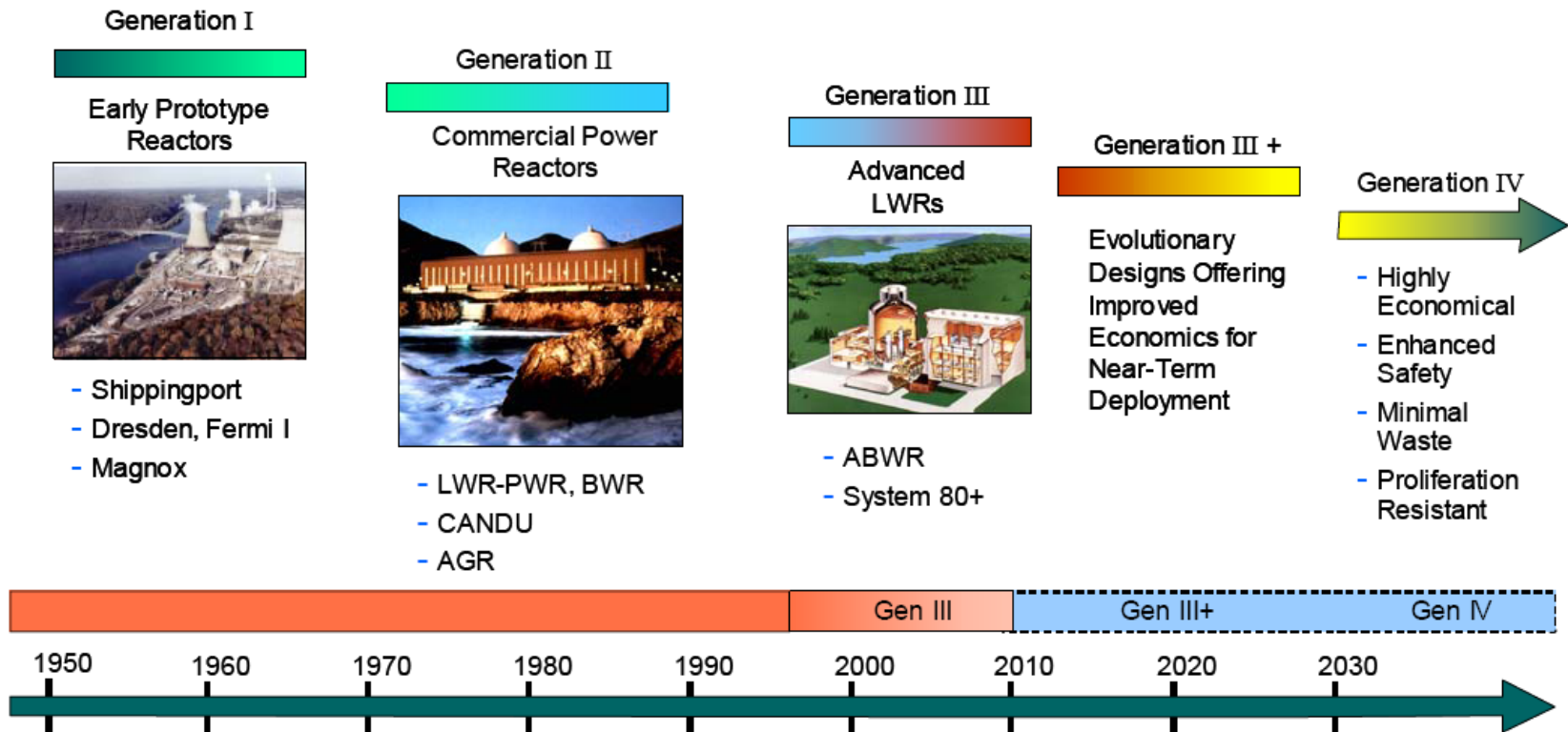
The technology:

- Sodium cooled (SFR)
- Lead cooled (LFR)
- Gas cooled (GFR)
- Molten Salt Fast Reactor (MSFR)

Conclusions

What is Generation IV

An international R&D programme to develop the most promising six systems for the next generation of nuclear power plants



Generation IV – Proposed systems

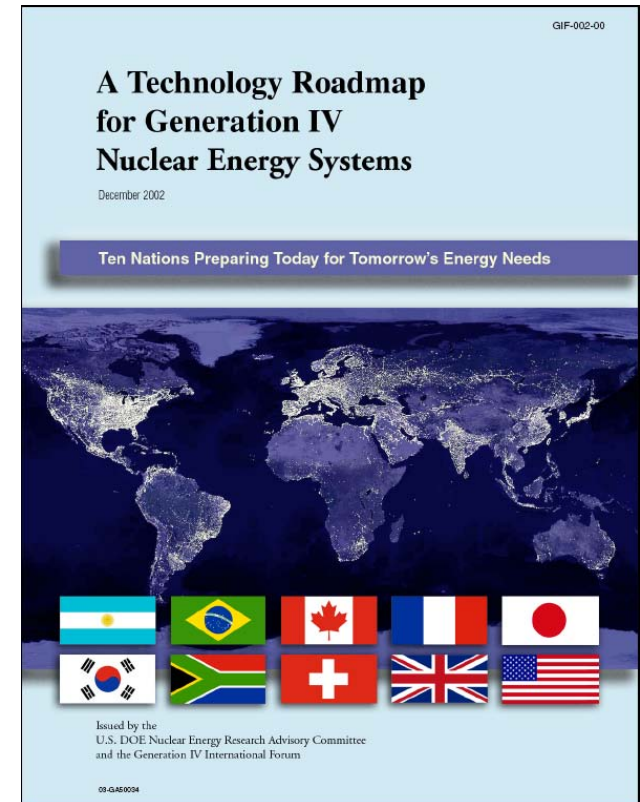
3 Fast Reactors

- Sodium Cooled Fast Reactor (SFR)
- Lead Cooled Fast Reactor (LFR)
- Gas Cooled Fast Reactor (GFR)

3 other systems (thermal, epithermal)

- Molten Salt Reactor (MSR) (Epithermal)
- Supercritical Water Reactor (SCWR) (Thermal or possibly fast)
- Very High Temperature Reactor (VHTR) (Thermal)

Concepts for fast reactor versions of the MSR and SCWR now exist



The Case for Fast Reactors



What is a fast reactor ?

A fast reactor makes use of fission induced by fast neutrons ($E > 0.1\text{MeV}$).

Characterised by having a compact core (no moderator) and a high power density ($\sim 400\text{MW}/\text{m}^3$ compared with $\sim 5\text{MW}/\text{m}^3$ for thermal reactors).

Why build fast reactors ?

Only 0.72% of natural uranium is fissile. For nuclear power to be sustainable it is essential we make better use of the natural resource.

- 0.72% uranium-235
- 0.0055% uranium-234
- 99.2745% uranium-238

Breeding of plutonium from uranium-238 in fast reactors allows considerably more of the natural uranium to be used.

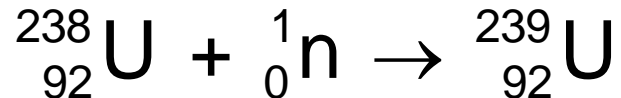
Both breeding and the utilisation of plutonium are more efficient in fast fission systems.

Long lived minor actinides that occur in nuclear waste (americium, neptunium and curium) can be burned.

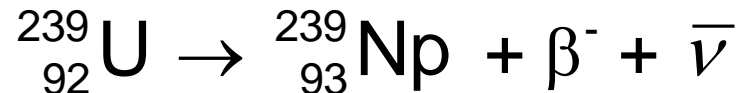
- Reduces radiotoxicity of wastes
- Significantly reduces waste storage times (to about 300 years instead of 300 000 years)

Plutonium Breeding Reaction

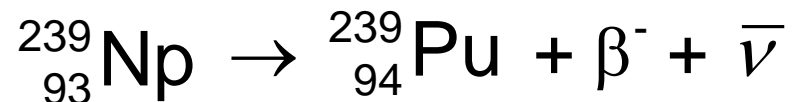
Starts with neutron capture in uranium-238



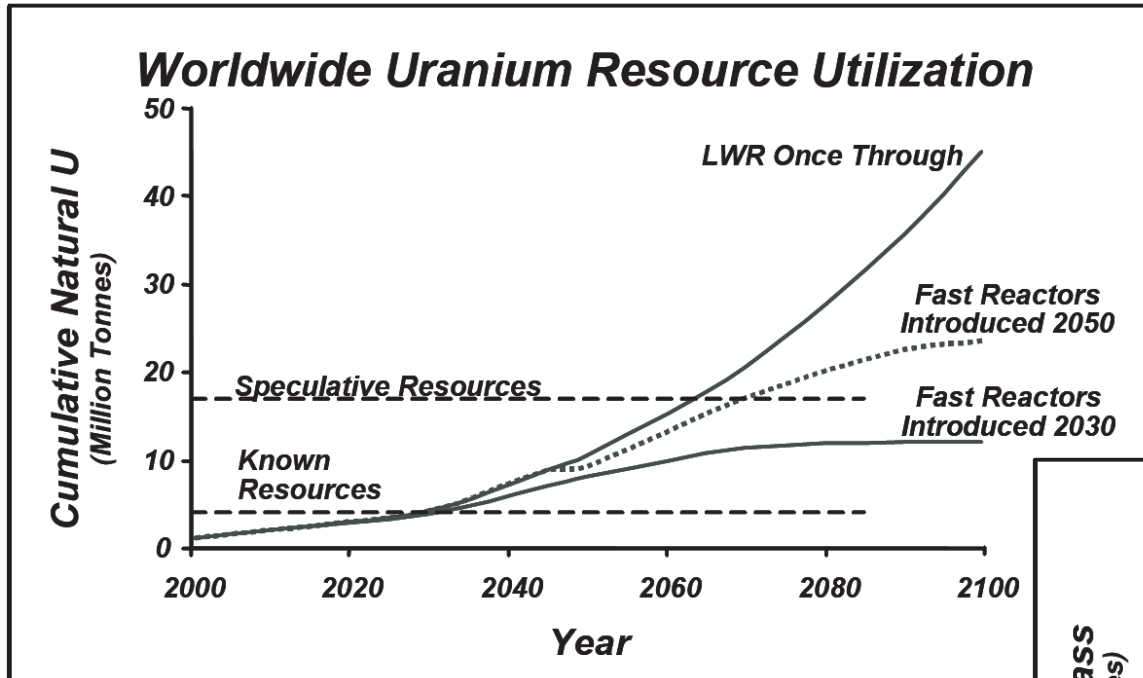
Uranium-239 has a half-life of 23 minutes and decays to neptunium-239 by beta decay



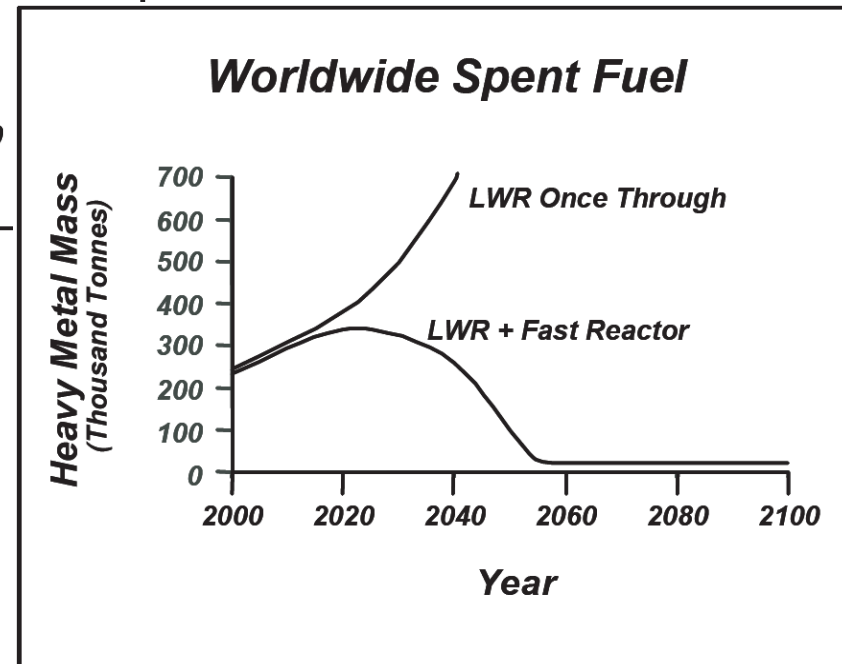
Neptunium-239 has a half life of 2.3 days and decays to plutonium 239 by a further beta decay



Forecast demand for natural uranium and reserves



Source:
**A technology Roadmap for Generation IV
 Nuclear Energy Systems, USDOE, 2002**



Plutonium breeding in thermal reactors

All reactors that contain uranium-238 will breed plutonium:

- Fast reactors are better at it than thermal reactors
- The measure of how good a reactor is at breeding is the “conversion ratio” (or exactly the same thing – the breeding ratio), C

C = number of fissile items created / number of fissile atoms consumed

For thermal reactors $C < 1$. For fast reactors $C \geq 1$ (but can be < 1 if we wish)

If we start with N fissile atoms, after irradiation in a reactor core we end up with $C N$ fissile atoms. After many recycles we get the total number of fissile atoms available to be:

$$N_T = N + CN + C^2N + C^3N + C^4N + \dots$$

For $C < 1$, $N_T = N / (1 - C)$, so for a LWR $C \sim 0.3 \rightarrow 0.5$, so $N_T = 1.4 N \rightarrow 2 N$

Conclusion – large-scale MOX recycle in LWRs allows nuclear fission power to be maintained for a short time after the exhaustion of natural uranium but precludes the future use of fast reactors

Plutonium breeding in fast reactors

Using fast reactors we increase the amount of fissile material available by a factor of 100 (not just by a factor of 1.4 \rightarrow 2 if we only recycle Pu as MOX in LWRs)

Because:

$$N_T = N + CN + C^2N + C^3N + C^4N + \dots \rightarrow \infty \quad \text{for } C \geq 1$$

In reality we are limited by the amount of uranium-238 that have ...

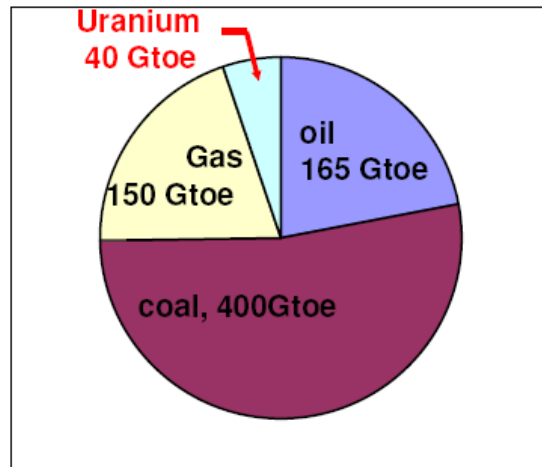
But we still have enough fuel to last about 4000 years !

Global energy reserves – no fast reactors

FOSSILE FUELS POTENTIAL RESERVES



Centre national de la recherche scientifique - Commissariat à l'énergie atomique



Uranium use
in thermal neutrons reactors

Identified conventional resources, Gtoe

(mémento sur l'énergie, CEA, 2010)

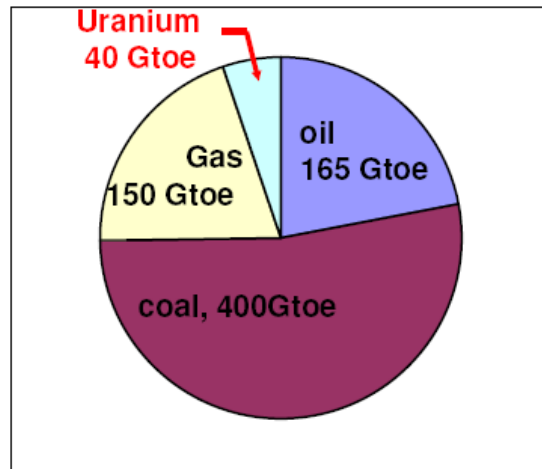
(Pétrole 165 Gt, charbon 826Gt, gaz 180 Tm³, uranium 3,3Mt)

Global energy reserves – no fast reactors

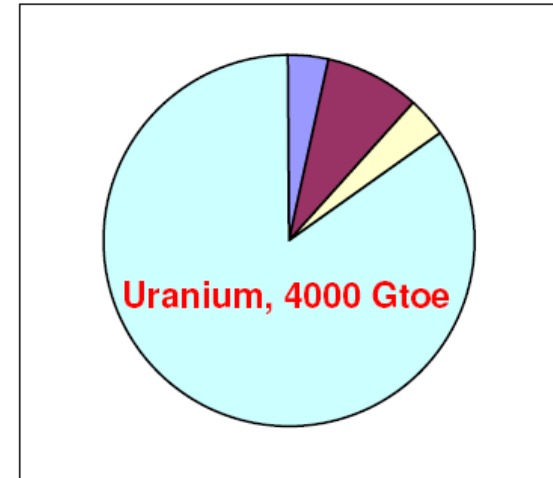
FOSSILE FUELS POTENTIAL RESERVES



centre atomique - centre d'analyse



Uranium use
in thermal neutrons reactors



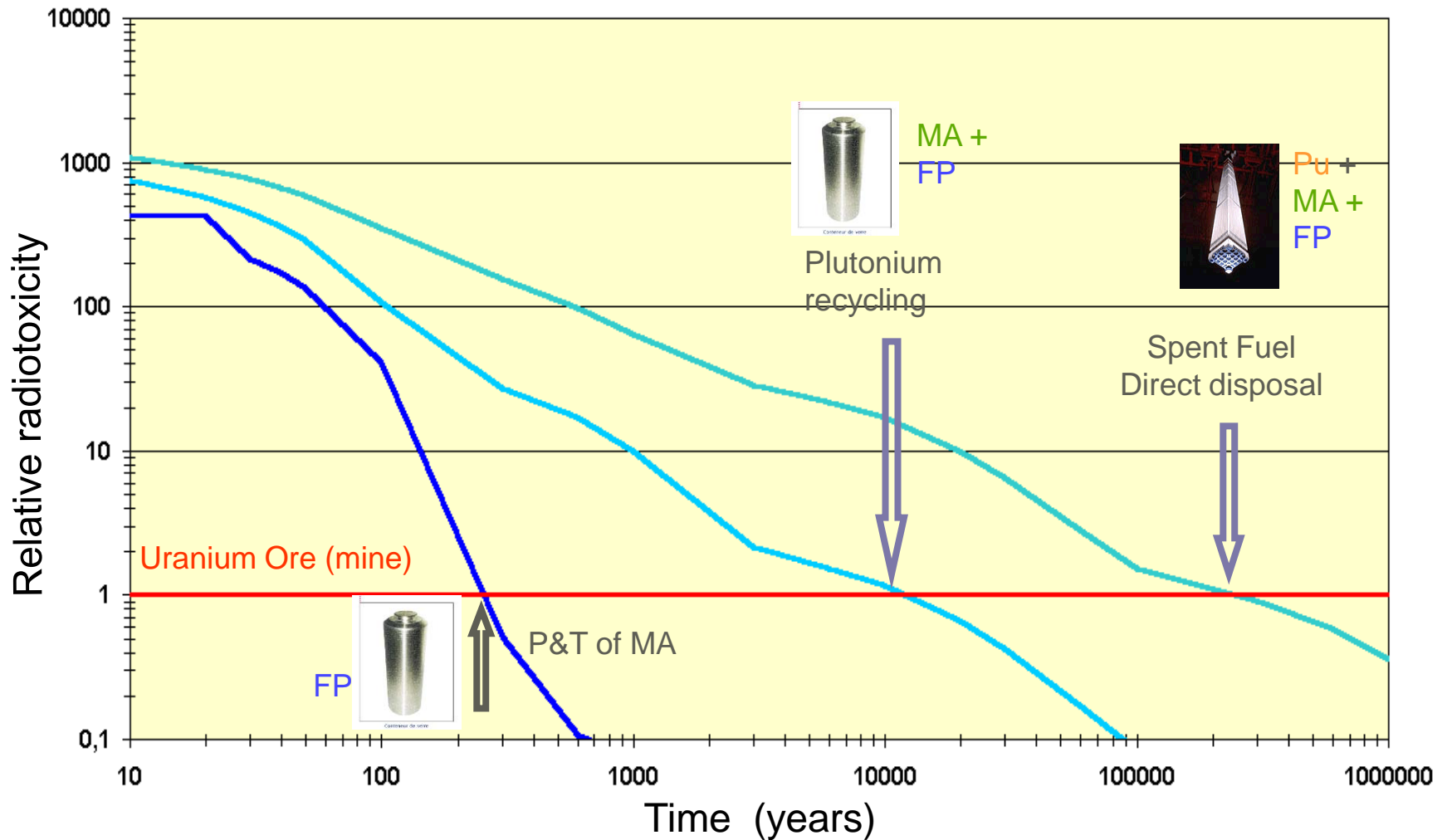
Uranium use
in fast neutrons reactors

Identified conventional resources, Gtoe

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(Pétrole 165 Gt, charbon 826Gt, gaz 180 Tm³, uranium 3,3Mt)

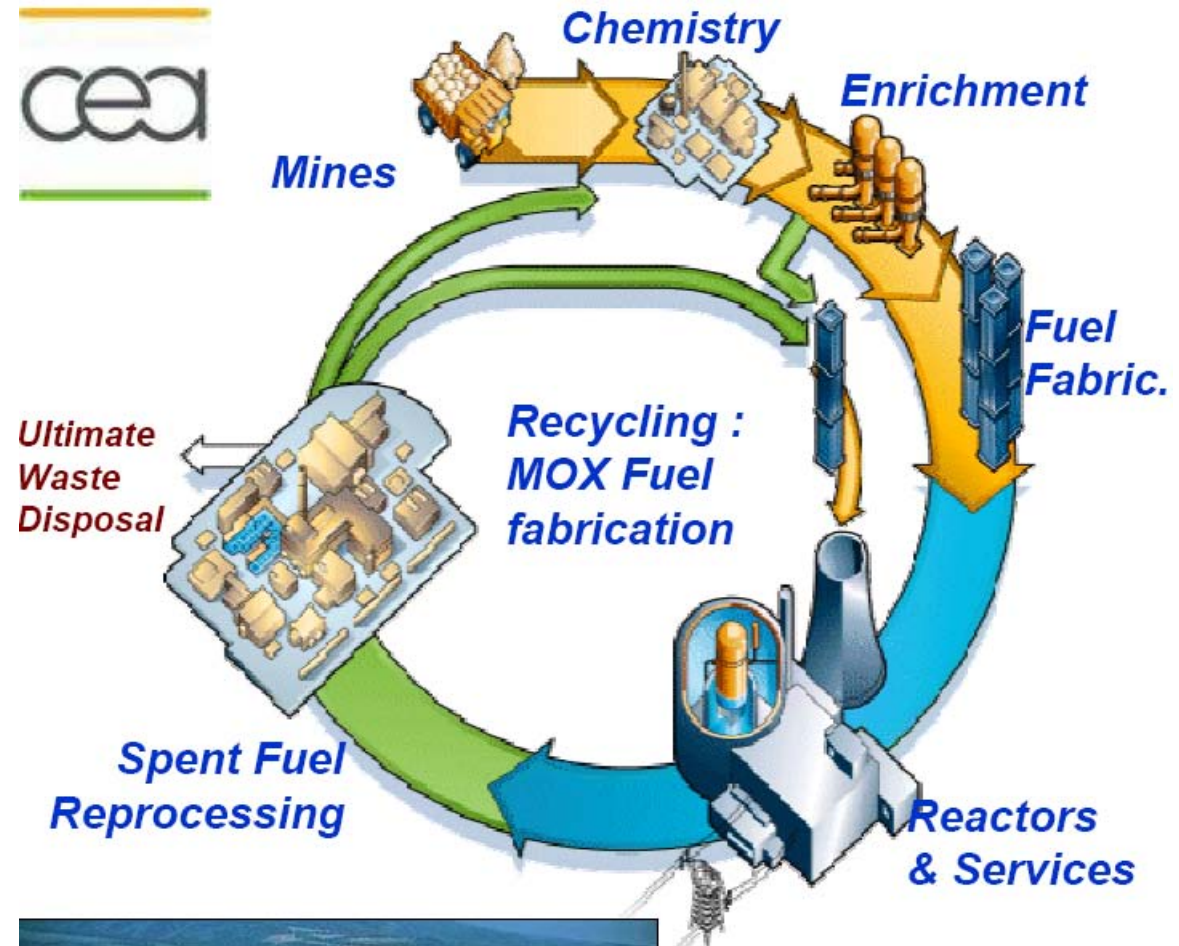
The bonus – the ability to transmute: minor actinide burning to reduce the radiotoxicity of waste



Closed fuel cycle (Example is for MOX recycle in LWRs)

A closed fuel cycle is a necessity for a fast reactor fleet

Reprocessing and fuel re-fabrication facilities are central parts of a fast reactor-driven nuclear park.

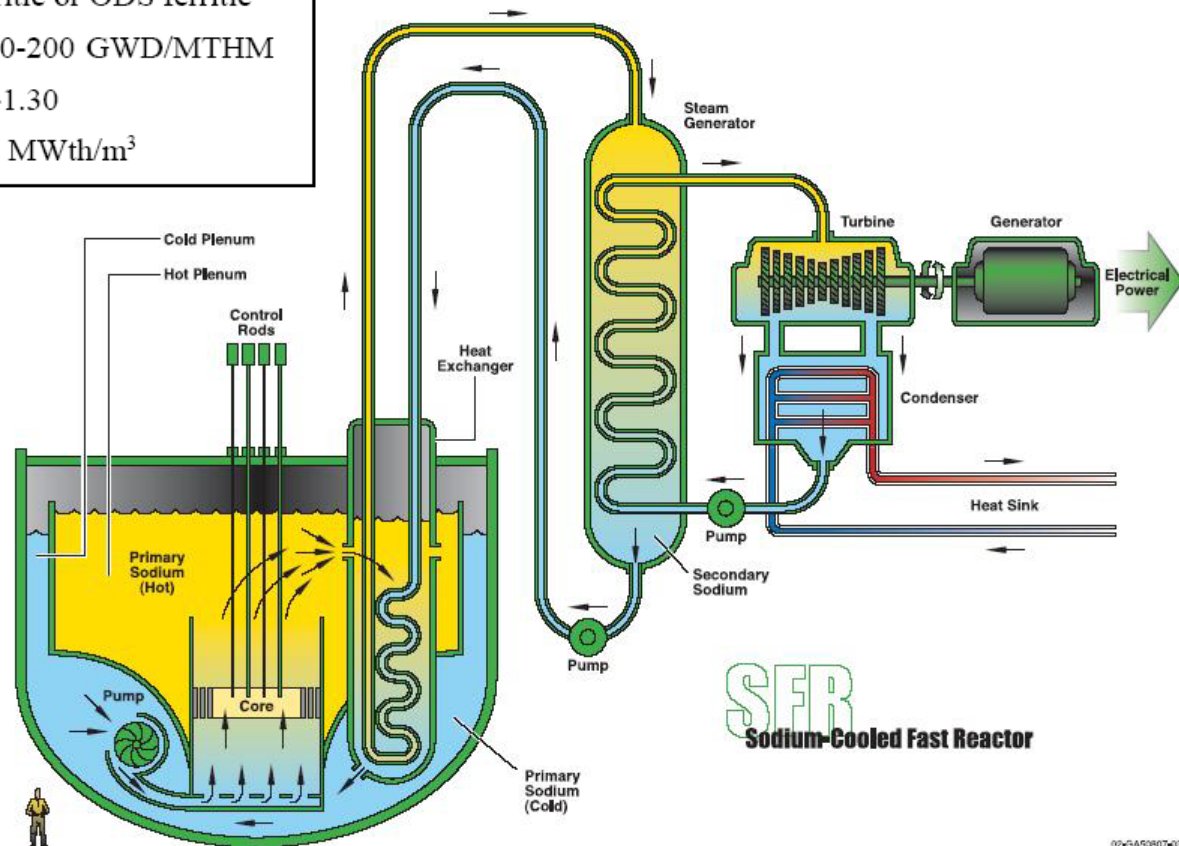


The Technology



Sodium-cooled fast reactor (SFR)

Reactor Parameters	Reference Value
Outlet Temperature	530-550 °C
Pressure	~1 Atmospheres
Rating	1000-5000 MWth
Fuel	Oxide or metal alloy
Cladding	Ferritic or ODS ferritic
Average Burnup	~150-200 GWD/MTHM
Conversion Ratio	0.5-1.30
Average Power Density	350 MWth/m ³



SFR
Sodium-Cooled Fast Reactor

UK fast reactors

Dounreay Fast Reactor (DFR) – metal fuel, highly enriched U235/U238 fuel, sodium-potassium eutectic liquid metal coolant, 72MWth (1959-1977).

Prototype fast reactor (PFR), also at Dounreay – mixed oxide fuel, Pu/U238, sodium liquid metal coolant, 600MWth (1974-1994).



Both now shut down and partially decommissioned.

French fast reactors

Rapsodie (at Cadarache) – Pu/U238 mixed oxide fuel, sodium-cooled, 24MWth (later 40MWth), (1966-1983)

Phenix (at Marcoule) – Pu/U238 mixed oxide fuel, sodium-cooled, 560MWth, (1973 -)



Superphenix (at Creys-Malville) – Pu/U238 mixed oxide, sodium-cooled, 2900MWth (1985 – 1996)

The need for a fast reactors to provide security of supply and management of plutonium and minor actinides is now enacted in French law.

- The ASTRID programme aims to deploy a Gen IV SFR demonstrator in the early 2020's for commercialisation by 2040.

Sodium-Cooled Fast Reactors in other Countries

USA – EBR I, Enrico Fermi, EBR II, Clinch River, FFTF

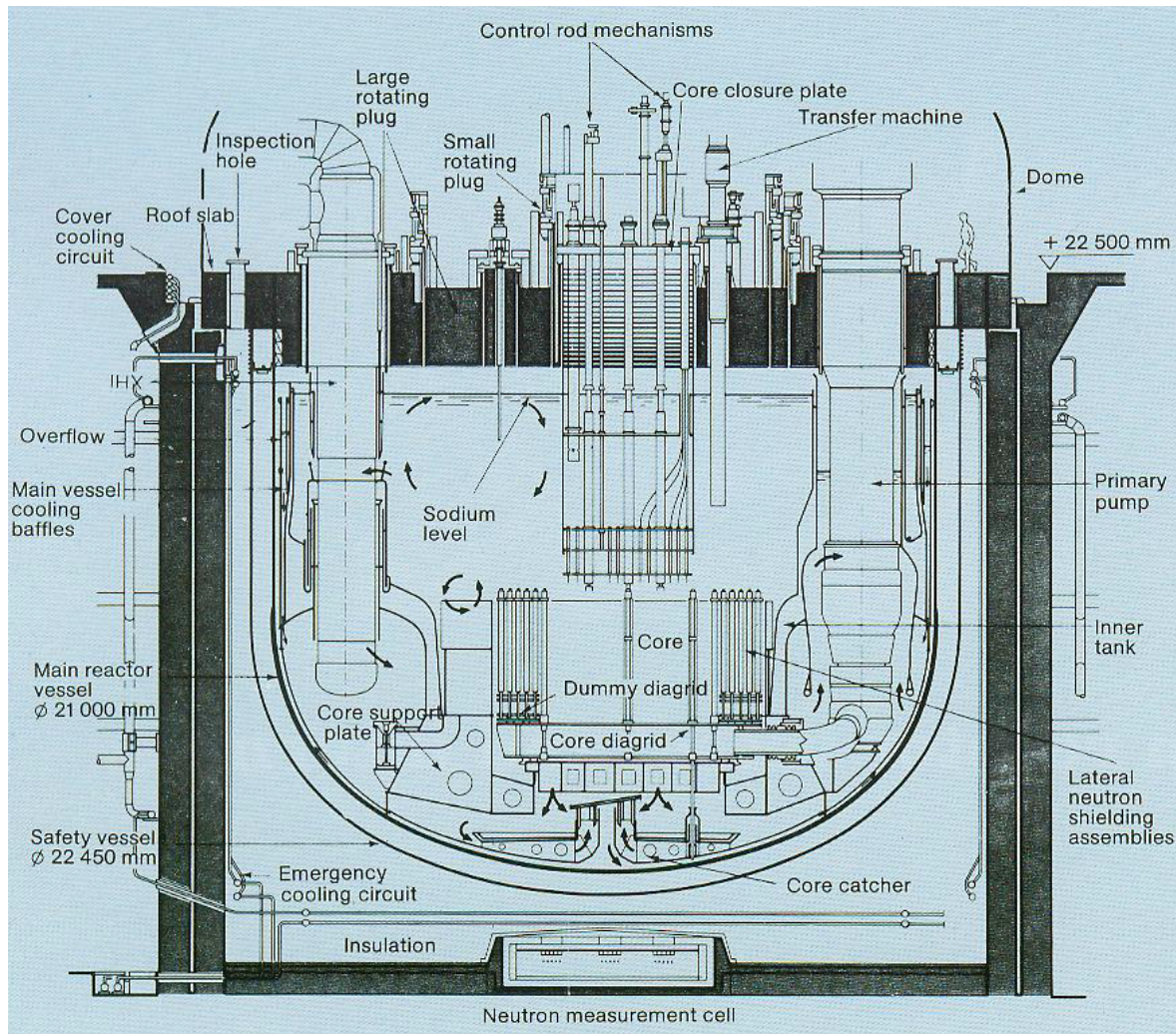
Russian Federation – BR5, BOR 60, BN 350, BN600

Japan – Joyo, Monju

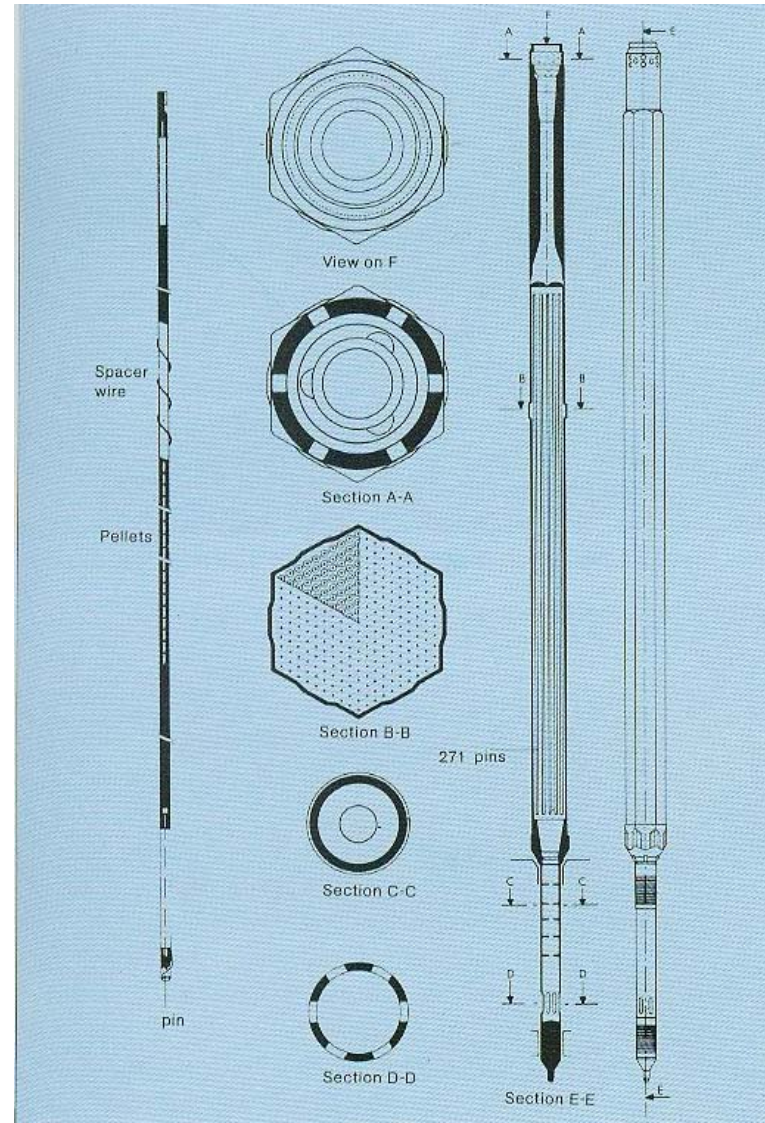


W. Germany – KNK II, SNR-300 (built but never operated)

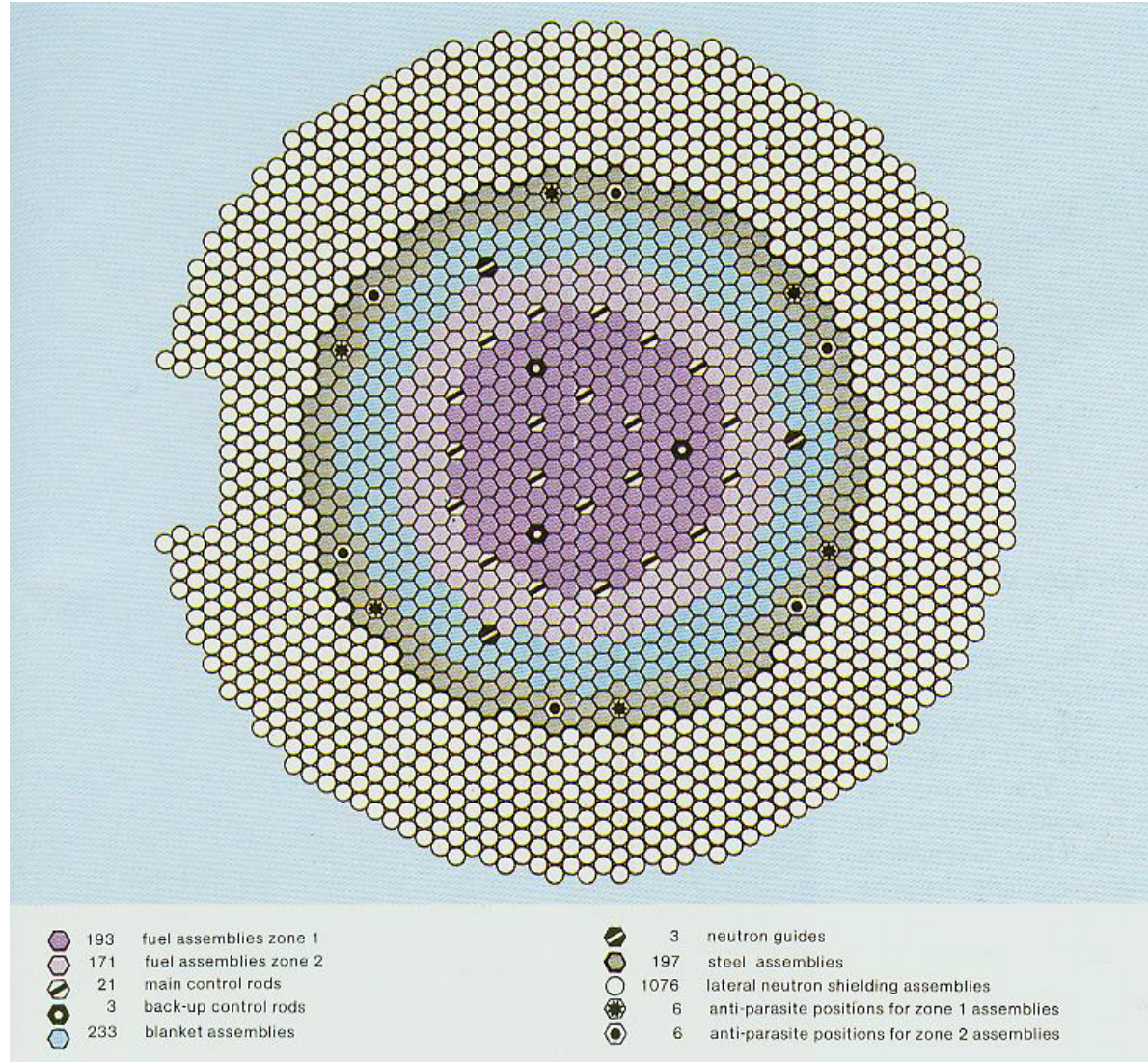
Superphenix



Superphenix fuel element



Superphenix core



Problems with the liquid sodium coolant

Reacts violently with water, need the intermediate heat exchange loop to prevent reaction with primary coolant.

High void worth – leads to large reactivity insertion if gas or vapour bubbles form in the coolant, or if the coolant is lost.

It is not possible to operate at higher temperatures because of sodium boiling.

Fast reactors – the future beyond SFR

The Generation IV programme has identified 3 fast reactor systems for further development:

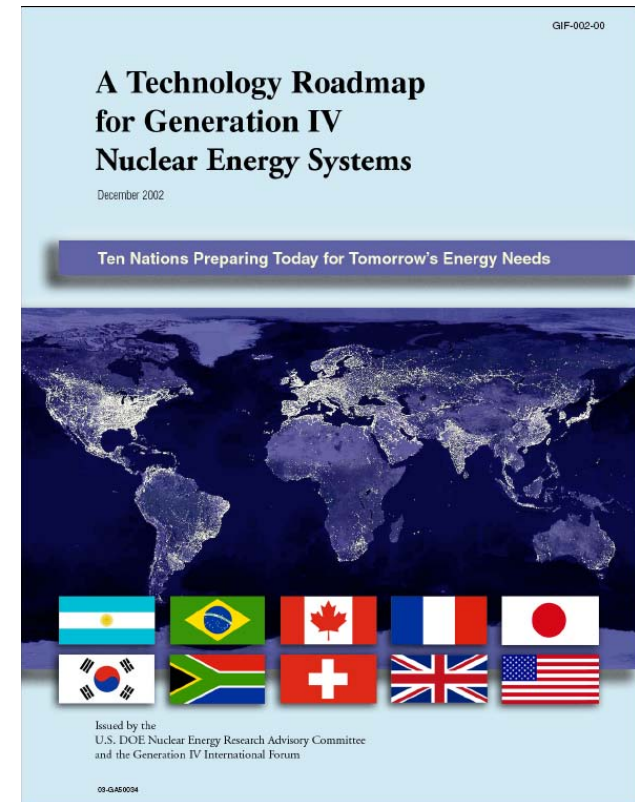
SFR - Sodium-cooled fast reactor

LFR - Lead-cooled fast reactor

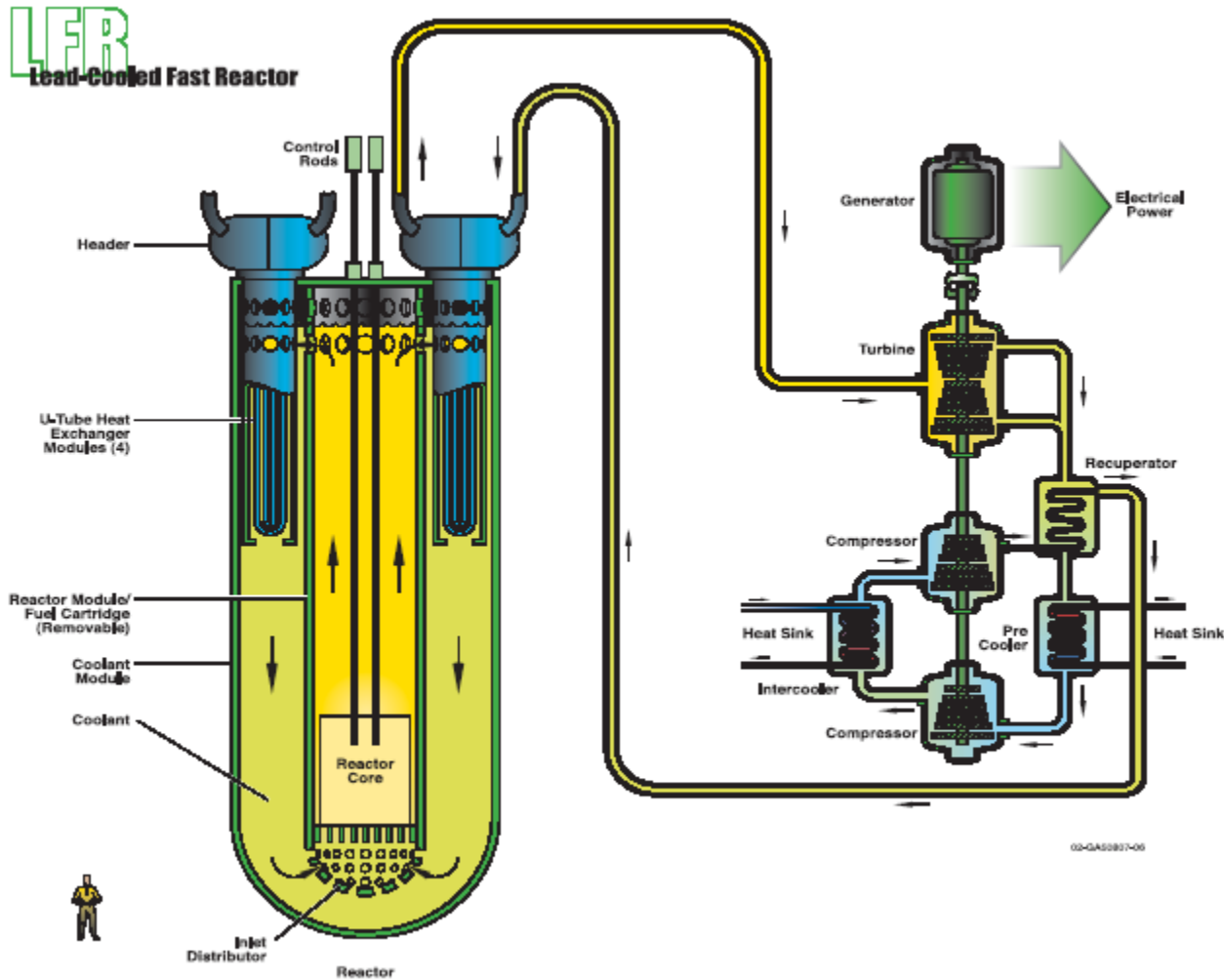
GFR - Gas-cooled fast reactor

Minor actinide destruction and plutonium management – sustainability and proliferation benefits.

+ the molten salt fast reactor (MSFR)



Lead-cooled fast reactor (LFR)



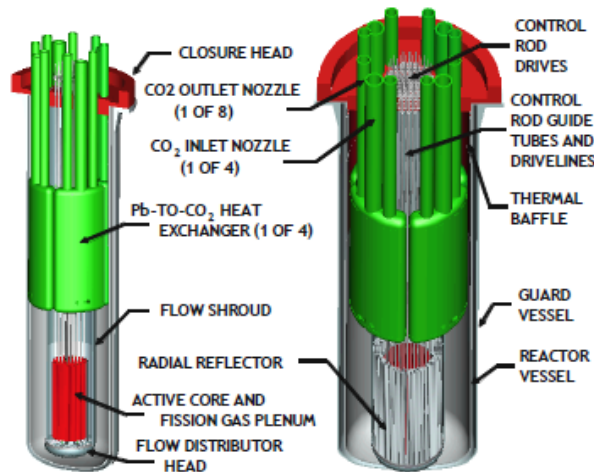
Proposed LFR Operating Parameters

Reactor Parameters	Reference Value			
	Pb-Bi Battery (nearer-term)	Pb-Bi Module (nearer-term)	Pb Large (nearer-term)	Pb Battery (far-term)
Coolant	Pb-Bi	Pb-Bi	Pb	Pb
Outlet Temperature (°C)	~550	~550	~550	750–800
Pressure (Atmospheres)	1	1	1	1
Rating (MWth)	125–400	~1000	3600	400
Fuel	Metal Alloy or Nitride	Metal Alloy	Nitride	Nitride
Cladding	Ferritic	Ferritic	Ferritic	Ceramic coatings or refractory alloys
Average Burnup (GWD/MTHM)	~100	~100–150	100–150	100
Conversion Ratio	1.0	$d \geq 1.0$	1.0–1.02	1.0
Lattice	Open	Open	Mixed	Open
Primary Flow	Natural	Forced	Forced	Natural
Pin Linear Heat Rate	Derated	Nominal	Nominal	Drated

Lead Cooled Fast Reactor Concepts

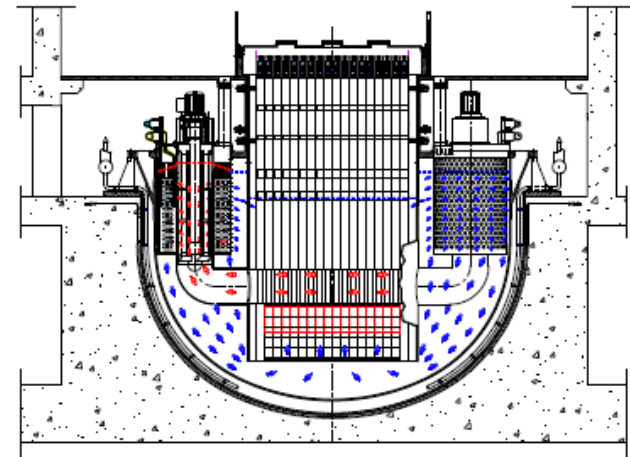
GIF LFR reference concepts

SSTAR (10 - 100 MWe)



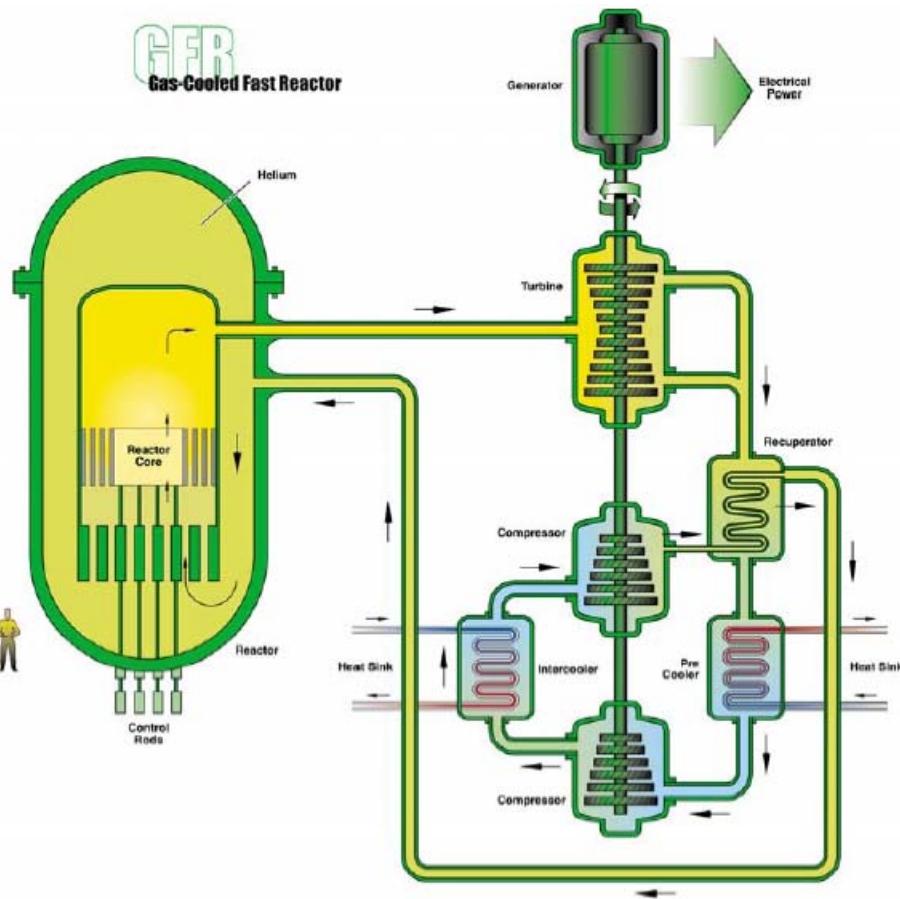
Natural convection cooled

ELSY (600 MWe)



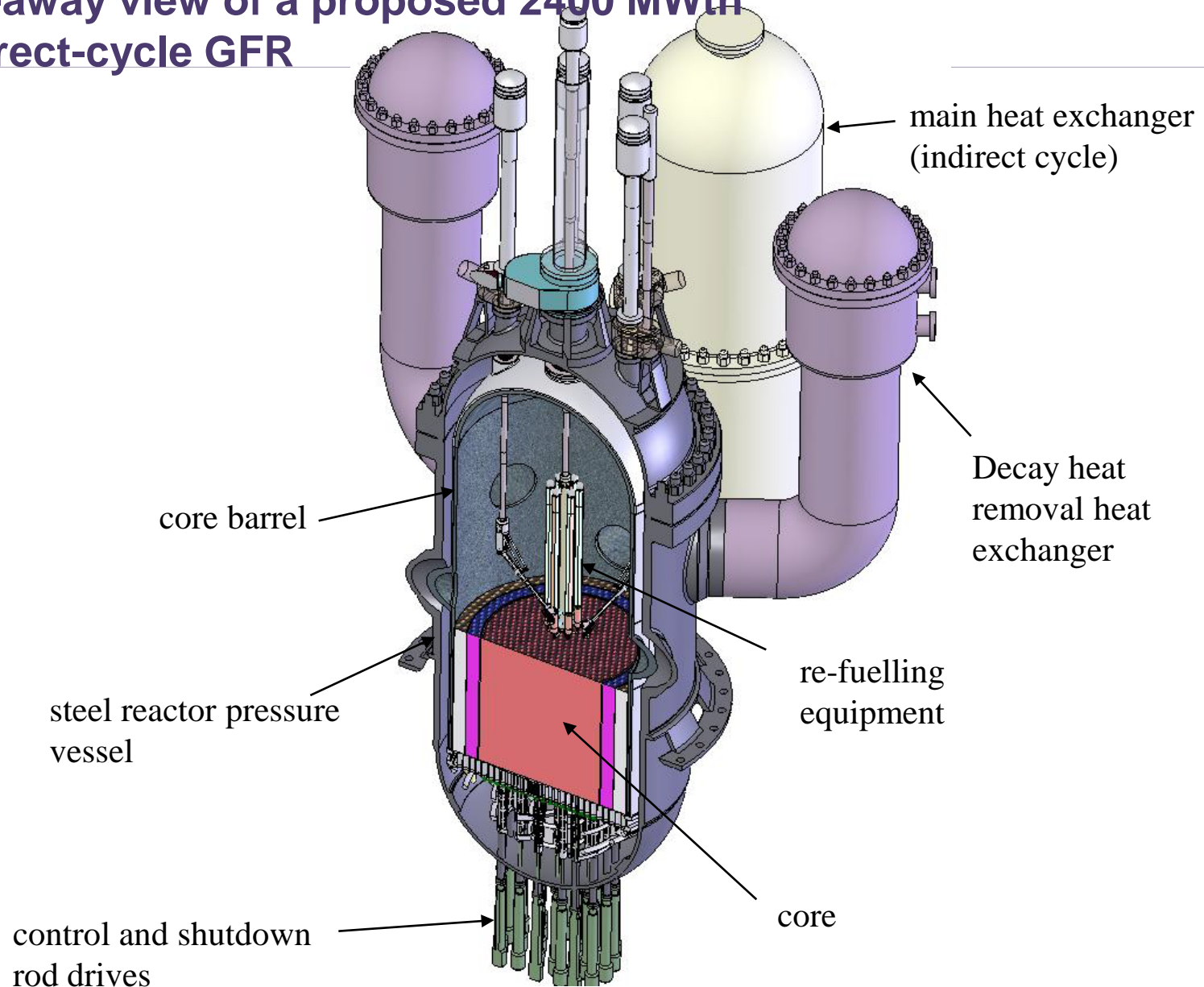
Forced convection cooled

Gas-cooled fast reactor (GFR)

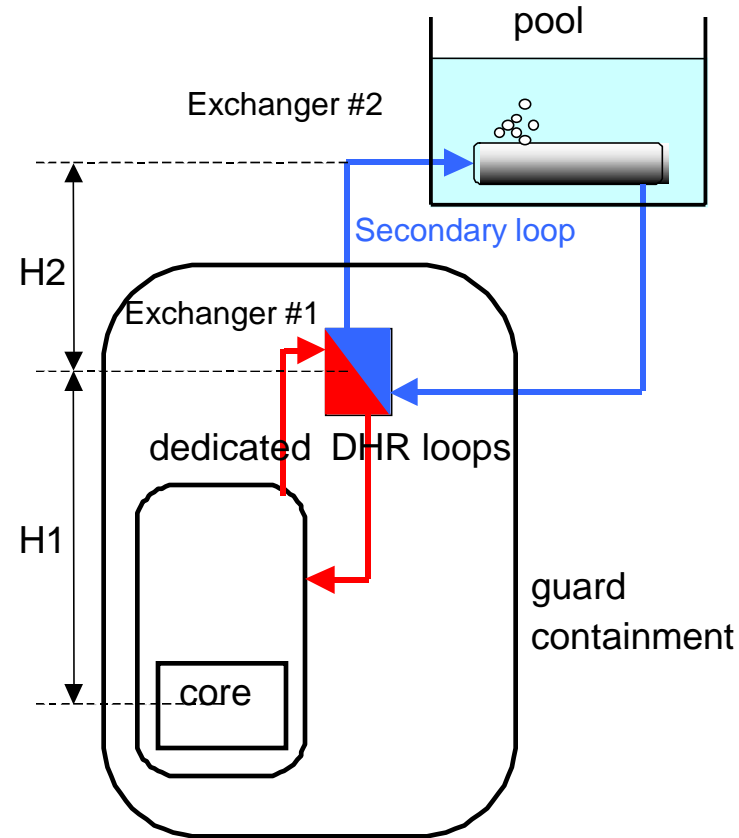


Reactor Parameters	Reference Value
Reactor power	600 MWth
Net plant efficiency (direct cycle helium)	48%
Coolant inlet/outlet temperature and pressure	490°C/850°C at 90 bar
Average power density	100 MWth/m ³
Reference fuel compound	UPuC/SiC (70/30%) with about 20% Pu content
Volume fraction, Fuel/Gas/SiC	50/40/10%
Conversion ratio	Self-sufficient
Burnup, Damage	5% FIMA; 60 dpa

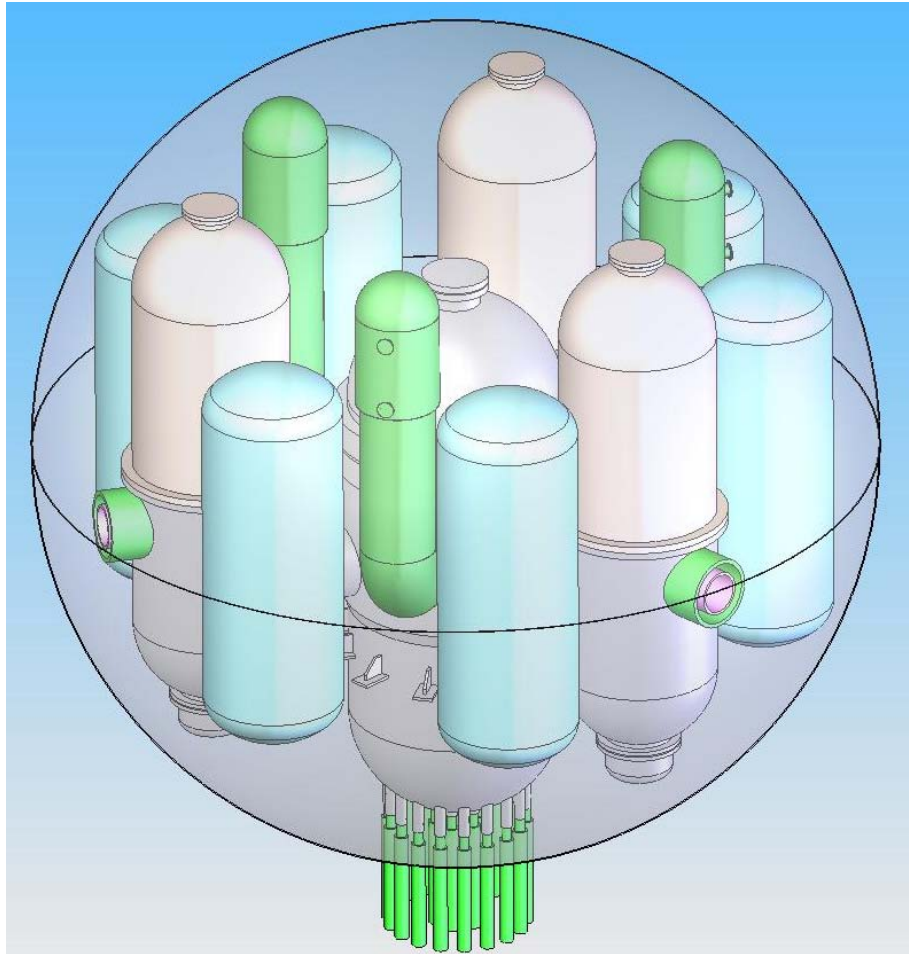
Cut-away view of a proposed 2400 MWth indirect-cycle GFR



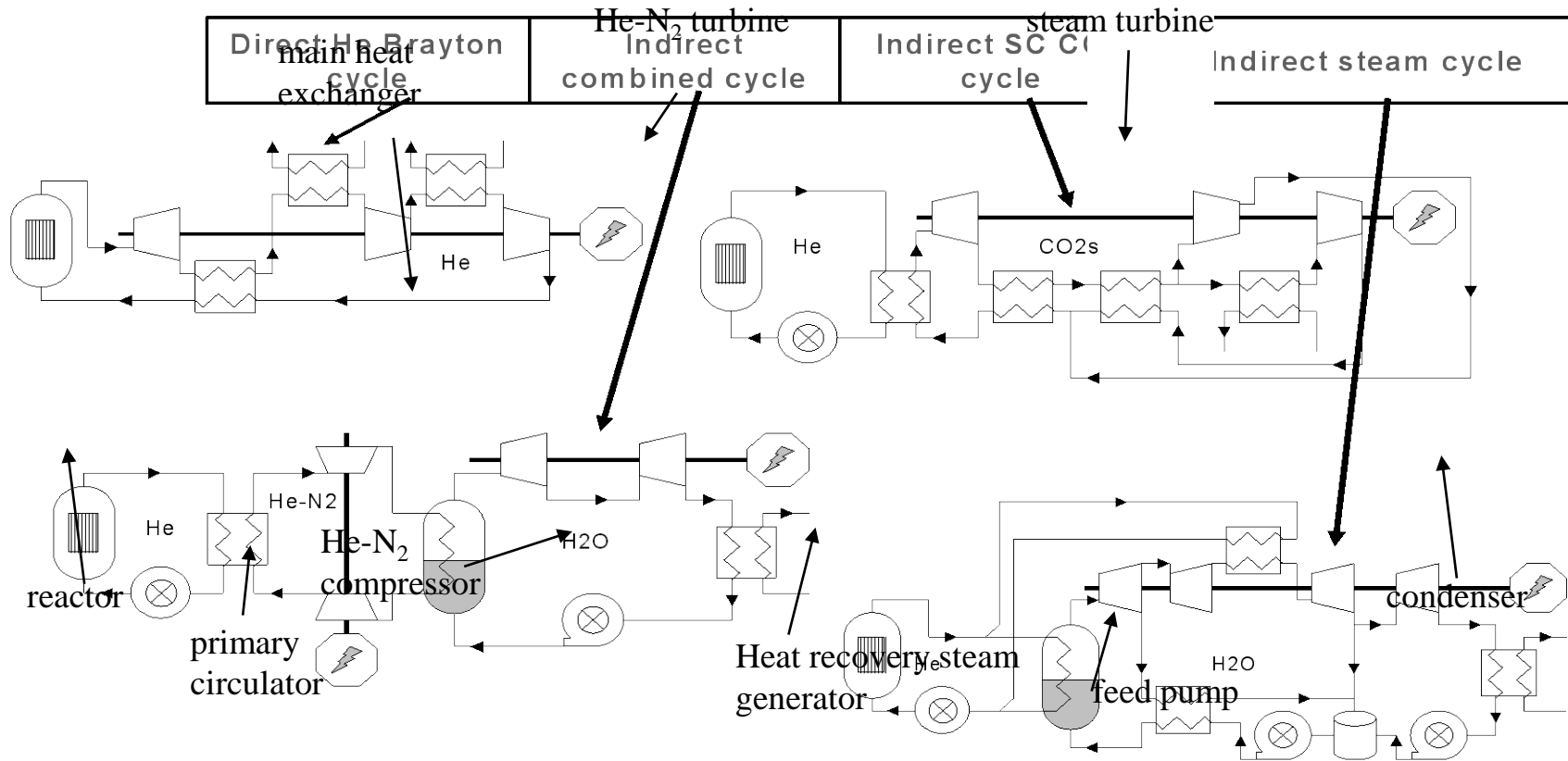
Schematic diagram of the DHR system in natural convection mode



2400 MWth indirect-cycle GFR inside a spherical “guard vessel”

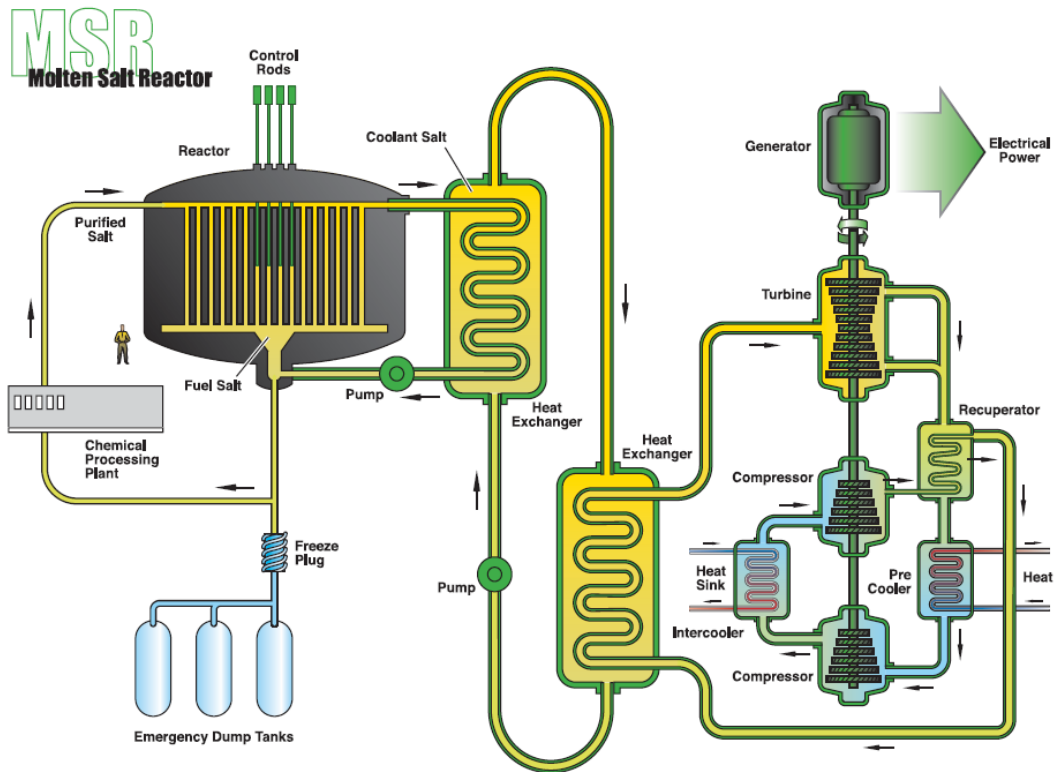


Current GFR concept - gas~steam turbine combined cycle



The indirect combined cycle is proposed for the ANTARES HTR and is the reference cycle for the GenIV GFR system

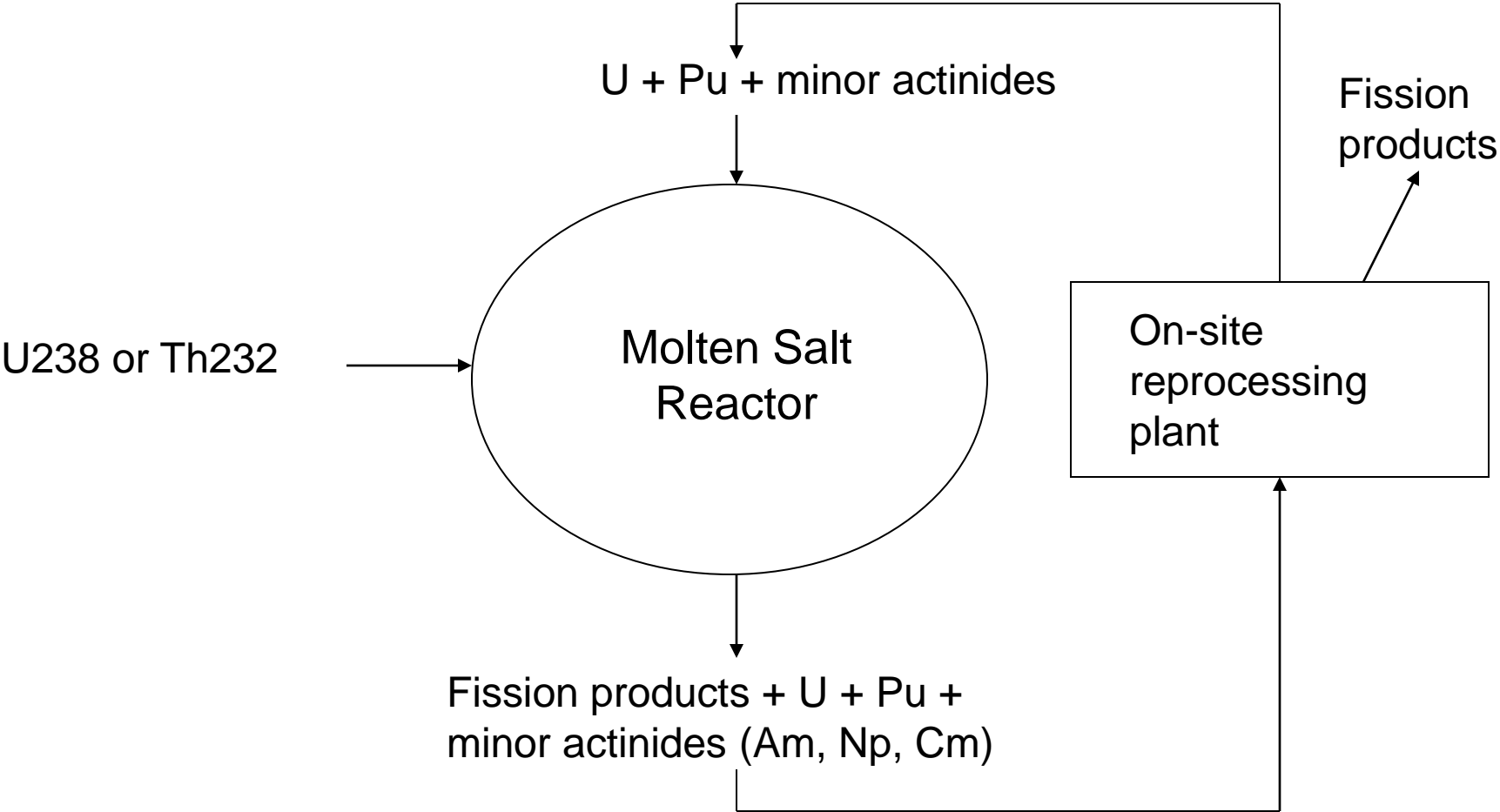
Molten Salt Reactor (MSR)



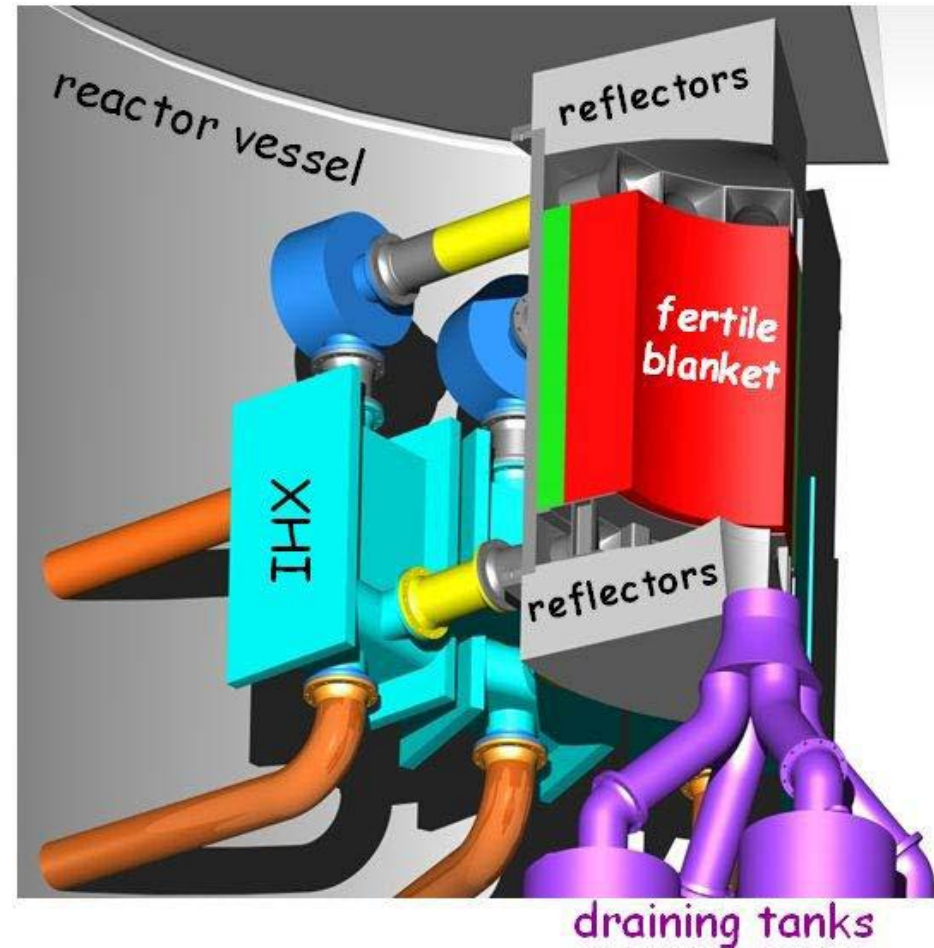
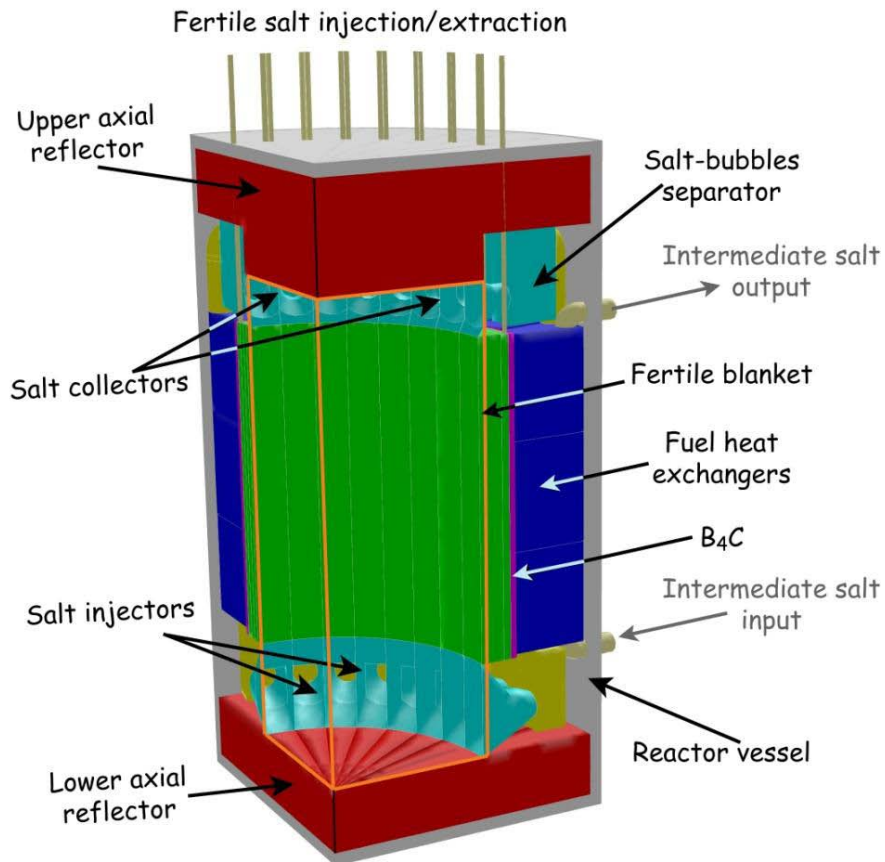
Reactor Parameters	Reference Value
Net power	1000 MWe
Power density	22 MWth/m ³
Net thermal efficiency	44 to 50%
Fuel-salt – inlet temperature	565°C
– outlet temperature	700°C (850°C for hydrogen production)
– vapor pressure	<0.1 psi
Moderator	Graphite
Power Cycle	Multi-reheat recuperative helium Brayton cycle
Neutron spectrum burner	Thermal-actinide

- Works with an epithermal neutron spectrum.
- The fuel is a liquid and the fuel is also the primary coolant.

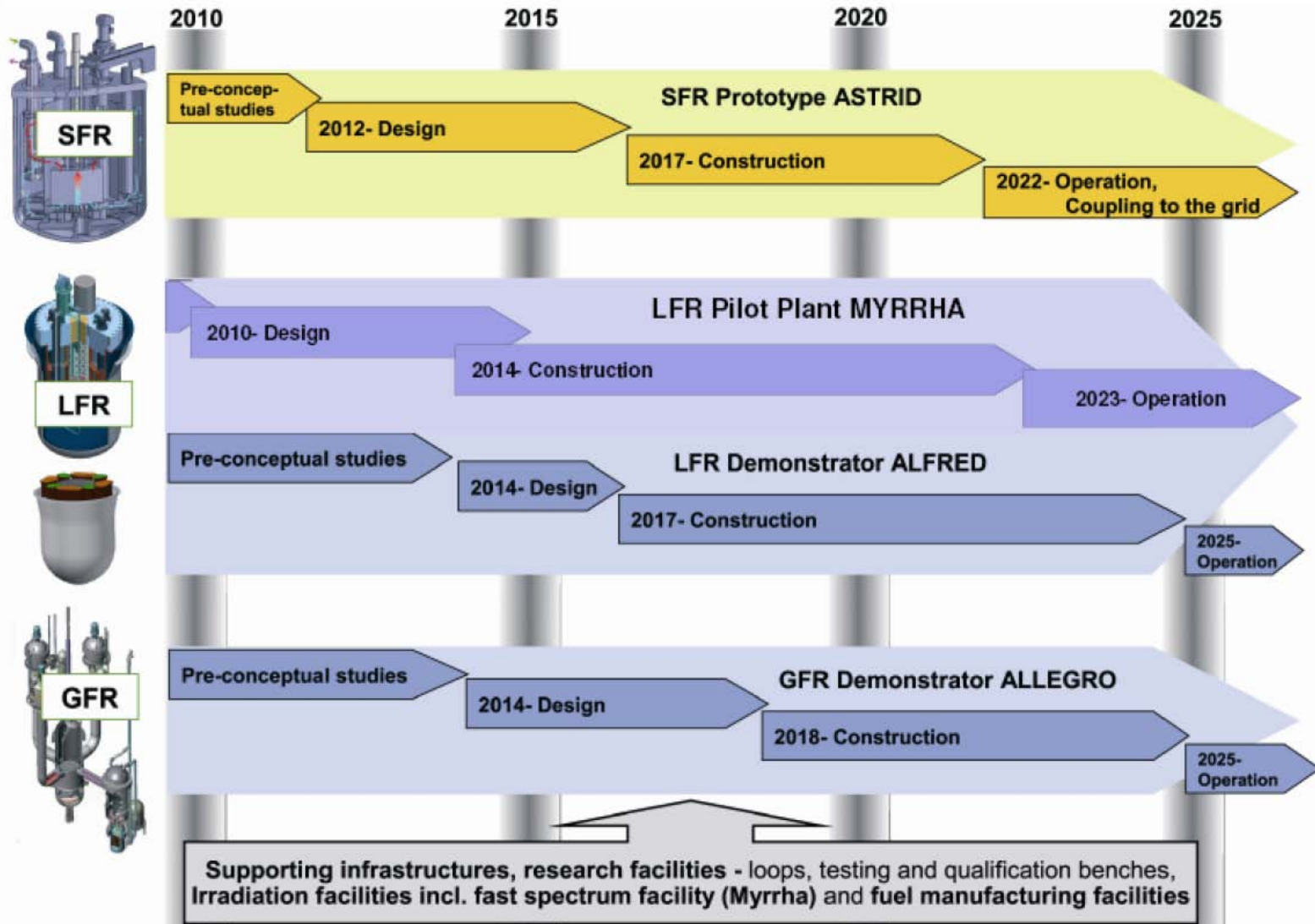
MSR – Closed On-Site Fuel Cycle (Equilibrium Conditions)



Molten Salt Fast Reactor (MSFR)



The European Sustainable Nuclear Industry Initiative (ESNII)



Conclusions

The case made for the development of Fast Reactors made in the 1940's and 1950's is still relevant today, even though;

- Expansion of the global reactor fleet has been slower than anticipated originally (after TMI-2 and Chernobyl) but has resumed.
- More uranium has been discovered, but uranium resource is still not large.

Without fast reactors, nuclear fission will simply be an interesting footnote in human history.

With fast reactors we can generate 4000 years of electricity (and other energy forms) using a small refinement of 1970's technology.

- A large fraction of the fuel we require in the UK is already above ground
- Using fast reactors, the UK is self-sufficient in plutonium and uranium-238 for at least for a few centuries.

Conclusions (continued)

Sodium cooled fast reactor technology is suitable for reviving an industrial capability for their construction at home and internationally

- We have a legacy of SFR design and construction experience
- No large (high) pressure components are require (except for steam generator water/steam headers)

The EC is supporting the development of all three fast reactor technologies (SFR, LFR and GFR) and accelerator driven systems (ADS).

We have the opportunity to re-engage as partners with France in the development of ASTRID and the development of a subsequent commercial fleet

(Rolls-Royce and AMEC have both signed MoUs with CEA to collaborate on the development of ASTRID)

Questions

