The Gas Cooled Fast Reactor (GFR)

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Motivation

- ***Fast reactors are important for the sustainability of nuclear power:***
  - ***More efficient use of fuel***
  - ***Reduced volumes, heat loading and radiotoxicity of high level waste***
- ***Sodium cooled fast reactors are the shortest route to FR deployment, but:***
  - ***The sodium coolant has some undesirable features:***
    - ***Chemical incompatibility with air and water***
    - ***Difficult to carry out inspection and repair***
    - ***Avoiding sodium boiling places a restriction on achievable core outlet temperature***
- ***Gas cooled fast reactors do not suffer from any of the above:***
  - ***Chemically inert, very stable nucleus, void coefficient is small (but positive), single phase coolant eliminates boiling and optically transparent.***

Motivation

- **But …**
  - **Gaseous coolants have little thermal inertia -> rapid heat-up of the core following loss of forced cooling;**
    - » **Compounded by the lack of thermal inertia of the core structure (no moderator) + high power density**

Advantages and Disadvantages of GFR

Advantages:

- ***Low (+ve) coolant void coefficient***
- ***Operation at high or very high temperatures***
- ***Strong Doppler effect***
- ***Transparent coolant***
- ***Nuclear stability of the coolant – no activation products***
- ***Chemical stability – no dissociation and chemically inert***
- ***Negligible corrosion/erosion of reactor structures***
- ***Passive decay heat removal to an independent heat sink***

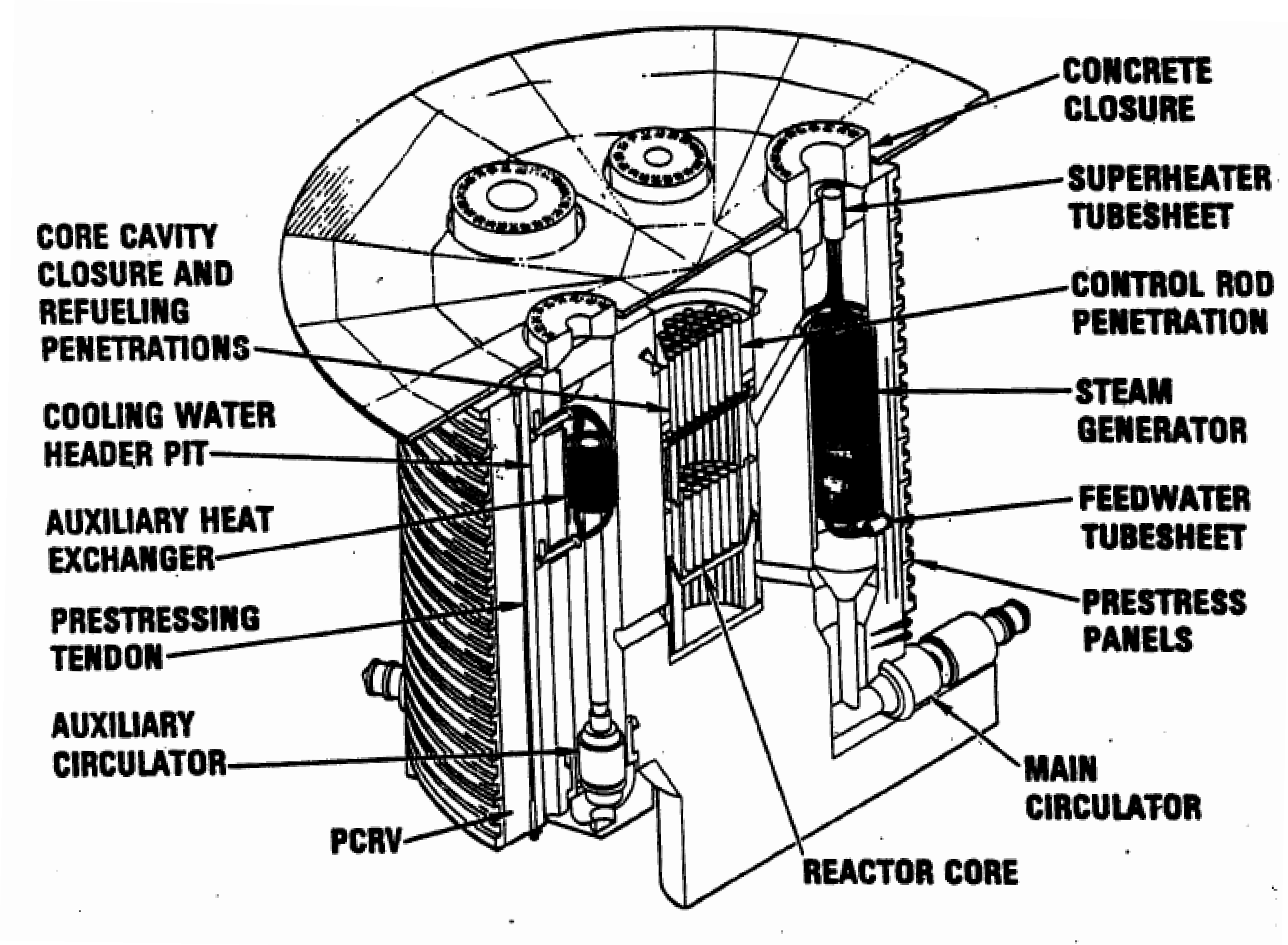
Disadvantages:

- ***Pressurised system***
- ***High coolant pumping power***
- ***High power density, high temperature fuels are required***
- ***Low thermal inertia gives short grace times, and …***
- ***It is difficult to remove decay heat by passive means in depressurised conditions***
  - ***so multiple layers of engineered safety features are required***

Gas cooled fast reactor concepts: a partial historical perspective

- ***US, General Atomics – The GCFR programme***
  - ***Started in the 1960's***
  - ***Capitalised upon High Temperature (thermal) Reactor (HTR) experience:***
    - ***Peach Bottom and Fort St Vrain***
  - ***Funded by US DOE***
  - ***Collaboration with European partners***
- ***Helium cooled reactor with a multi-cavity pre-stressed concrete pressure vessel. Featured a vented fuel pin fuel element design to reduce fuel clad stresses.***

General Atomics GCFR concept



Germany: the Gas Breeder Memorandum

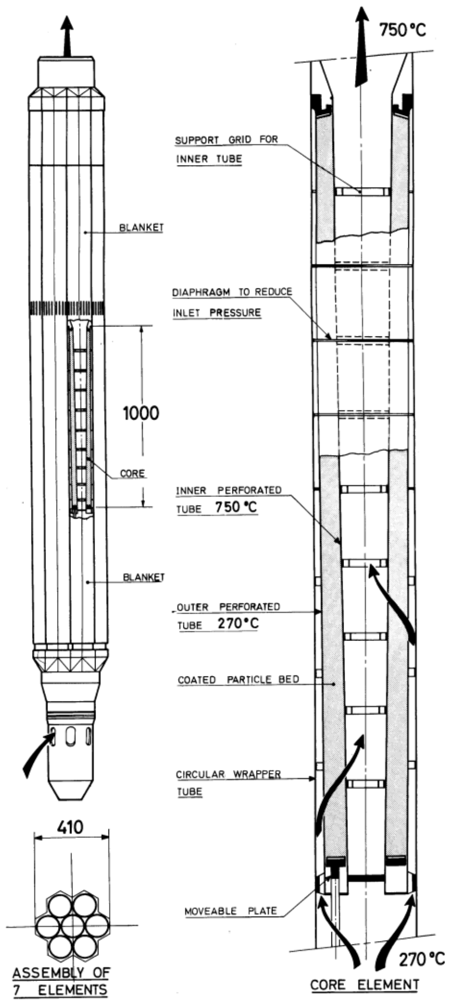
- *Germany: the Gas Breeder Memorandum (1969)*
  - *The German research centres at Karlsruhe and Jülich, together with industrial partners,*
  - *Defined three concepts, all cooled by helium,*
  - *Fuel assemblies extrapolated from sodium cooled fast reactors,*
  - *Pre-stressed concrete pressure vessels*
  - *Steam cycle,*
  - *Some work was carried out on coated particle fuels and direct cycle power cycles.*

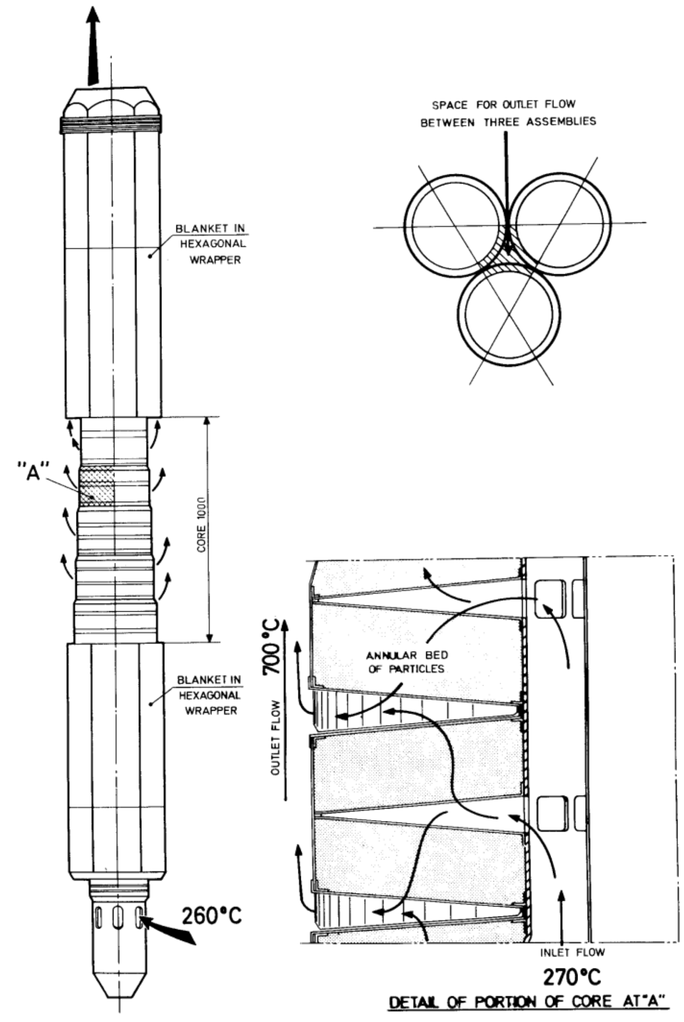
Europe: the Gas Breeder Reactor Association (1970 - 1981)

A number of organisations joined to form the Gas Breeder Reactor Association. Four designs were developed:

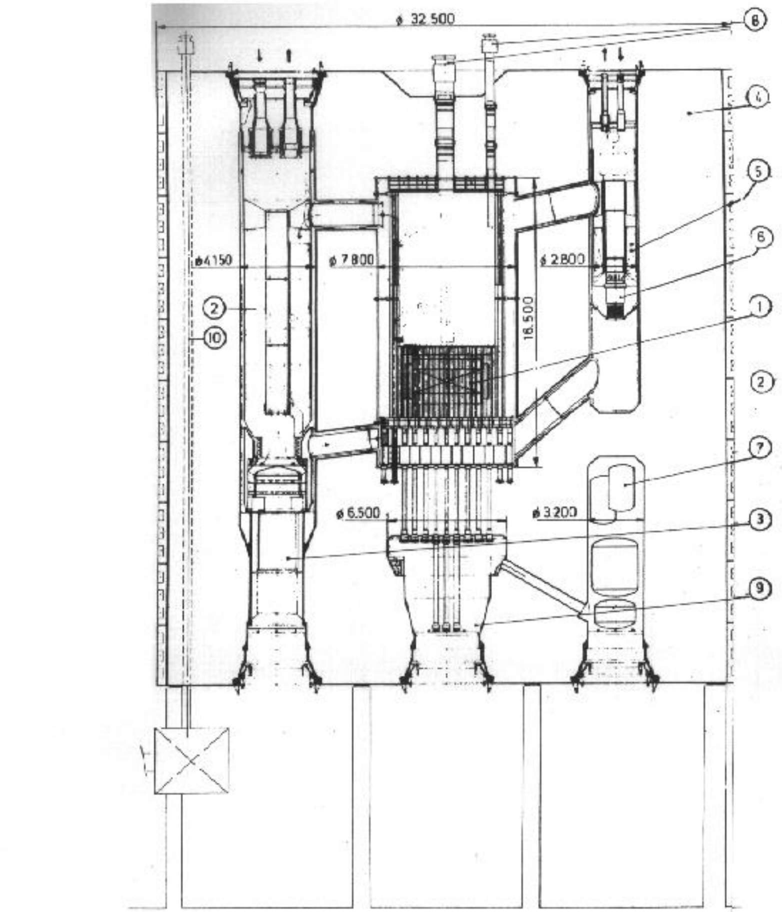
- *GBR-1, a 1000MWe helium cooled reactor with metallic clad pin fuel*
- *GBR-2, 1000MWe reactor using coated particle fuel, slightly elevated outlet temperature, helium coolant,*
- *GBR-3 1000MWe reactor using coated particle fuel, CO_2 coolant*
- *GBR-4 design was developed to avoid complexities of the particle bed fuel elements.*
  - *Rib-roughened metal-clad fuel pins held in spacer grids.*

GBR-2 (left) and GBR-3 (right) particle bed fuel assemblies





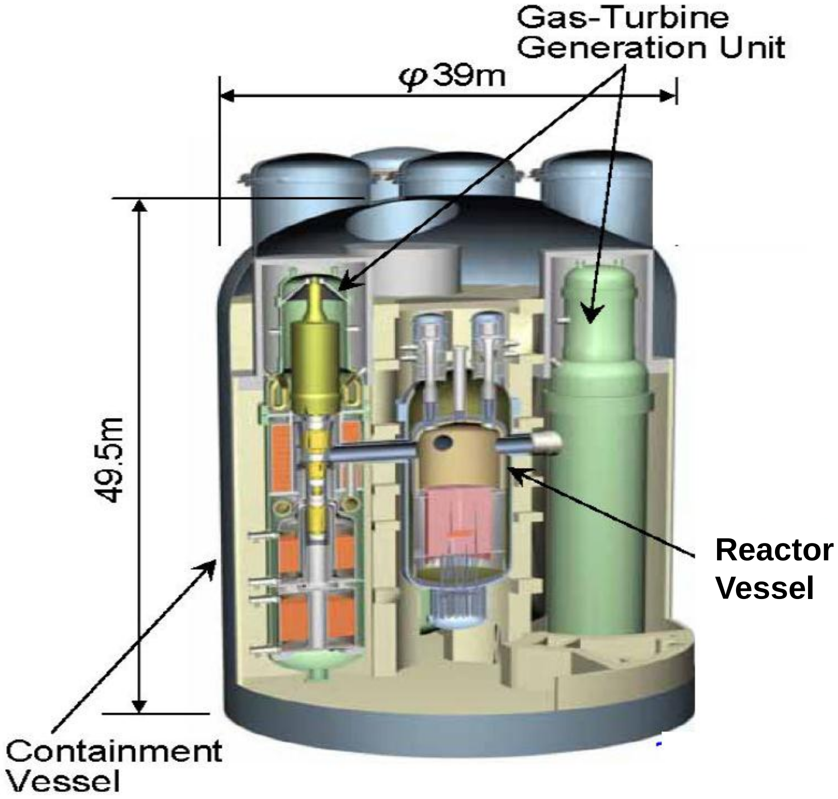
GBR-4 reactor layout

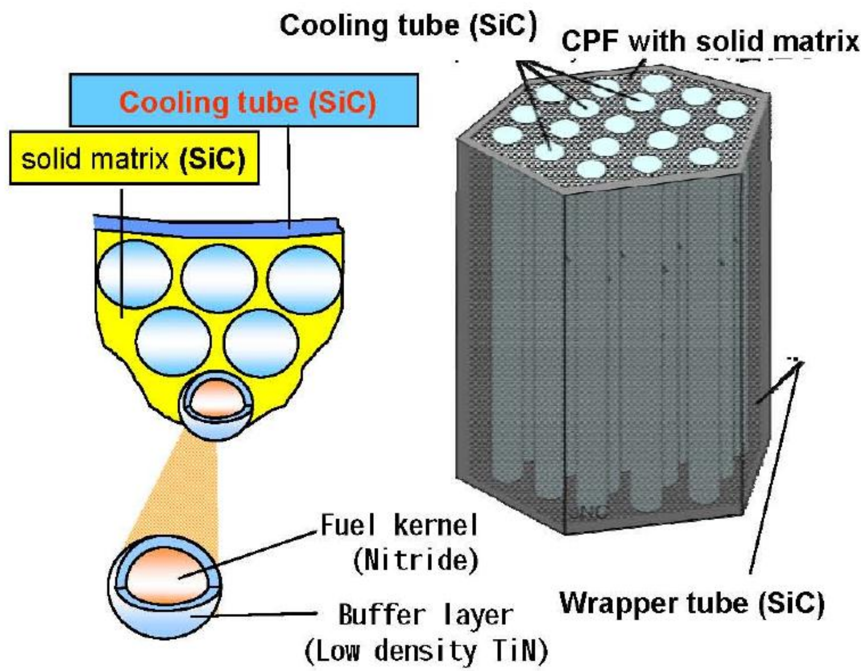


1 REACTOR CORE
2 MAIN STEAM GENERATOR
3 MAIN CIRCULATOR SET
4 PRESTRESSED CONCRETE VESSEL
5 EMERGENCY COOLER
6 EMERGENCY CIRCULATOR SET
7 FUEL VENTING PLANT AND He PURIFICATION WELLS
8 REFUELLING STANDPIPES
9 LOWER CAVITY
10 SPENT FUEL TRANSFER TUBE

Japan: Coated Particle Fuels (1960s – present day

- *JAEA investigated both block fuel containing coated particles and packed bed (GBR-2 type) fuel elements.*





CPF with solid matrix

Sub-assembly

The early GIF years – The exploratory phase

Participants US, France, Switzerland, Japan, UK & Euratom shared the analysis of six evaluation cases:

- ***Case 1 – 600 MWth, high temperature high power density, high density dispersed (plate) carbide fuel, direct cycle EC***
- ***Case 2 – As Case 1 but with a moderate temperature indirect S-CO2 cycle EC***
- ***Case 3 – 2400 MWth, high temperature, high power density, moderate density dispersed carbide fuel (plate), direct cycle***
- ***Case 4 – As Case 3 with SiC-clad pin fuel (carbide)***
- ***Case 5 – 2400 Mth, high temperature, moderate power density, particle fuel (nitride), direct cycle energy conversion***
- ***Case 6 – 2400 MWth, high temperature, moderate power density, SiC-clad oxide fuel, direct cycle***

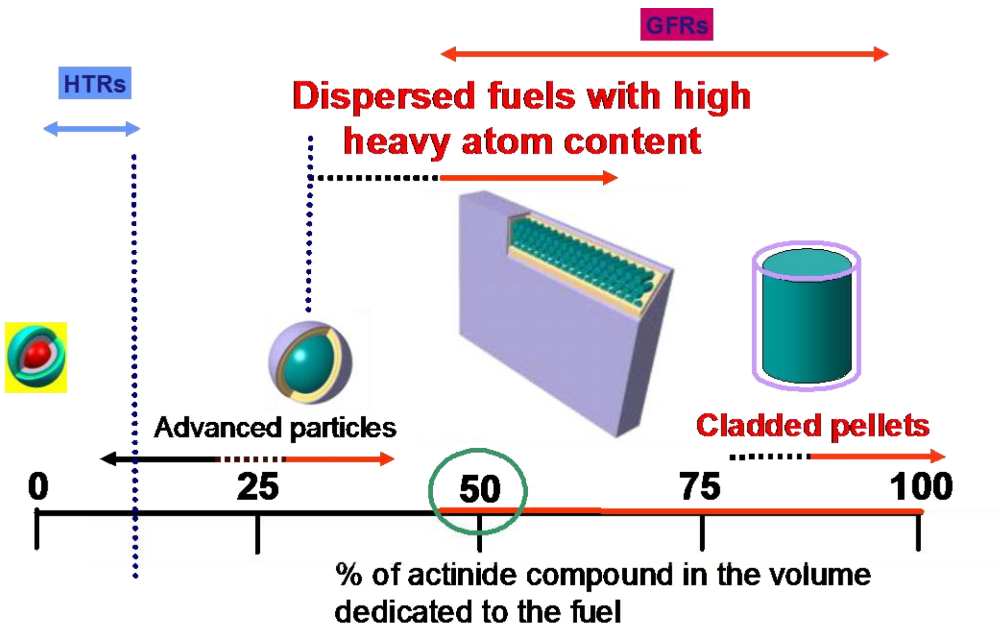
Core performance comparison

	Case 3 (carbide plate) (FR)	Case 4 (carbide pin) (US)	Case 5 (nitride, particle) (JP)	Case 6 (oxide, pin) (UK)
Fuel feasibility	?	?	?	? 🙂
Fuel temp.	🙂	🙂	🙂	☹️
Core pressure drop	🙂	🙂	☹️	😐
Pu inventory	🙂	🙂	😐	😐
Breeding gain	😐	🙂	☹️	😐
He void	😐	☹️	🙂	☹️

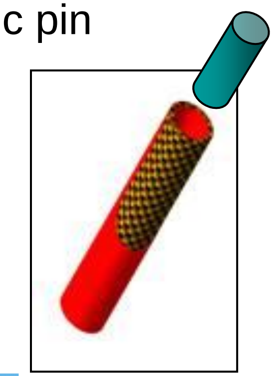
Outcome of exploratory phase down-selection

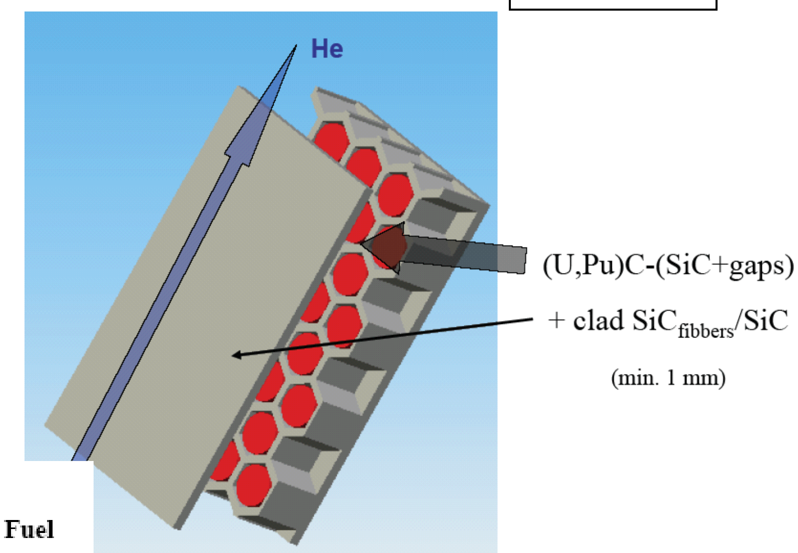
- 600 MWth cores (Case 1 and Case 2) rejected on the basis of not meeting breeding ratio ≥ 1.0 (without breeding blankets)
- At 2400 MWth, Case 5 (particle fuels) could not meet breeding gain objective without the use of breeder blankets
- Case 3 was initially selected for study in the conceptual phase as the reference, but the direct cycle option was soon dropped in favour of an indirect helium-nitrogen Brayton / steam combined cycle.
- CerCer plate fuel option was later dropped in favour of SiC-SiCf ceramic matrix composite pin

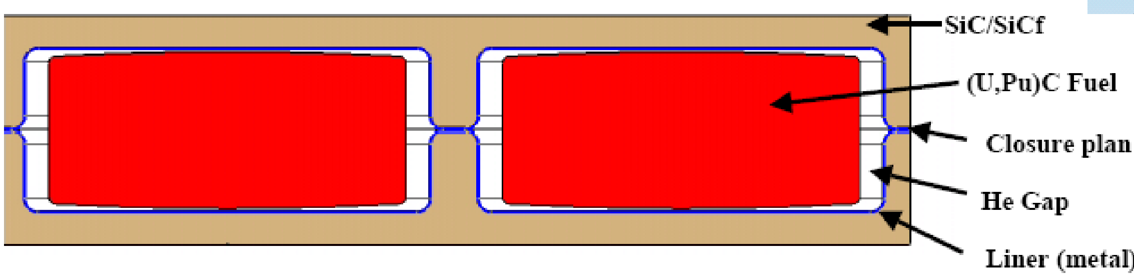
Potential GFR fuel forms



Ceramic pin





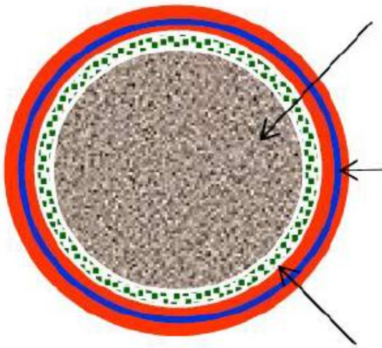


Ceramic plate

Current Fuel Pin Concept (CEA)

Although the plate type concept is attractive, fabrication difficulties appeared which lead to focus first on the more classical pin concept

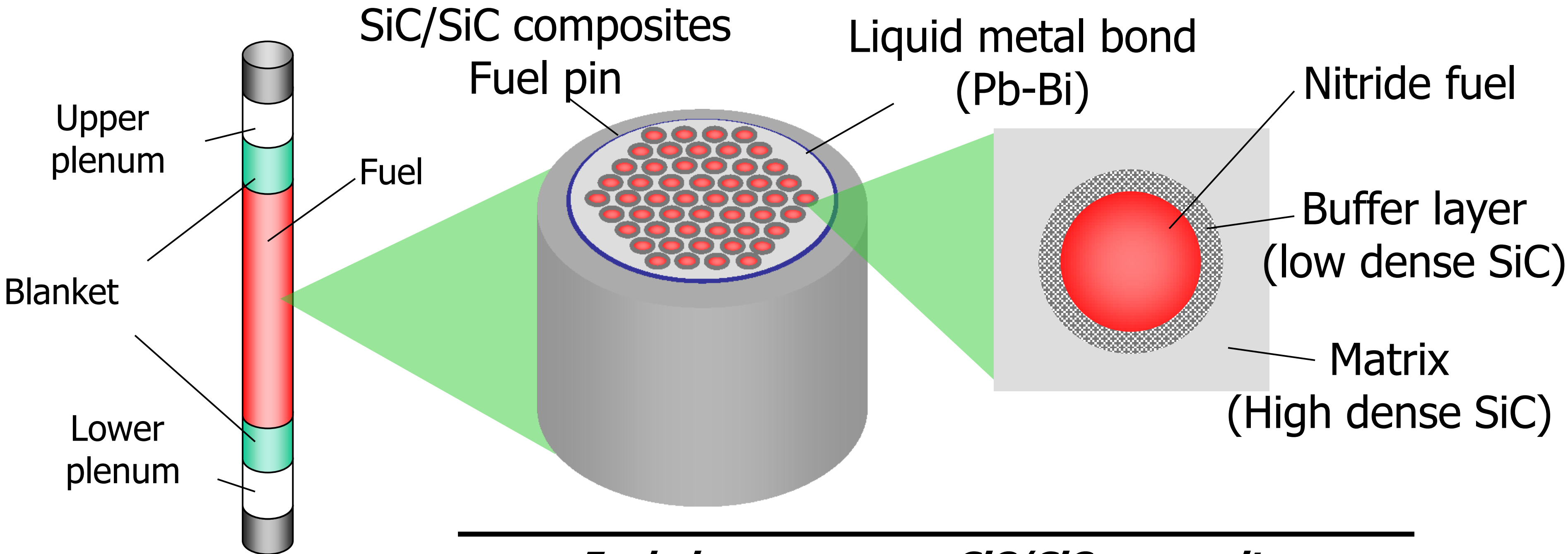
- a ceramic matrix composite cladding comprising a sandwich of SiC cladding and a thin internal metallic liner to ensure the leak tightness of the pin,
- a “buffer” , porous carbon structure placed between the pellet and the cladding allowing higher heat exchanges and moderate clad/pellet mechanical interaction.



The concept lives on as the basis for much current global work on Accident Tolerant Fuels (ATF) for light water reactors – **GFR’s gift to the world !**

… but work on coated particle fuels for GFR continues here in Japan …

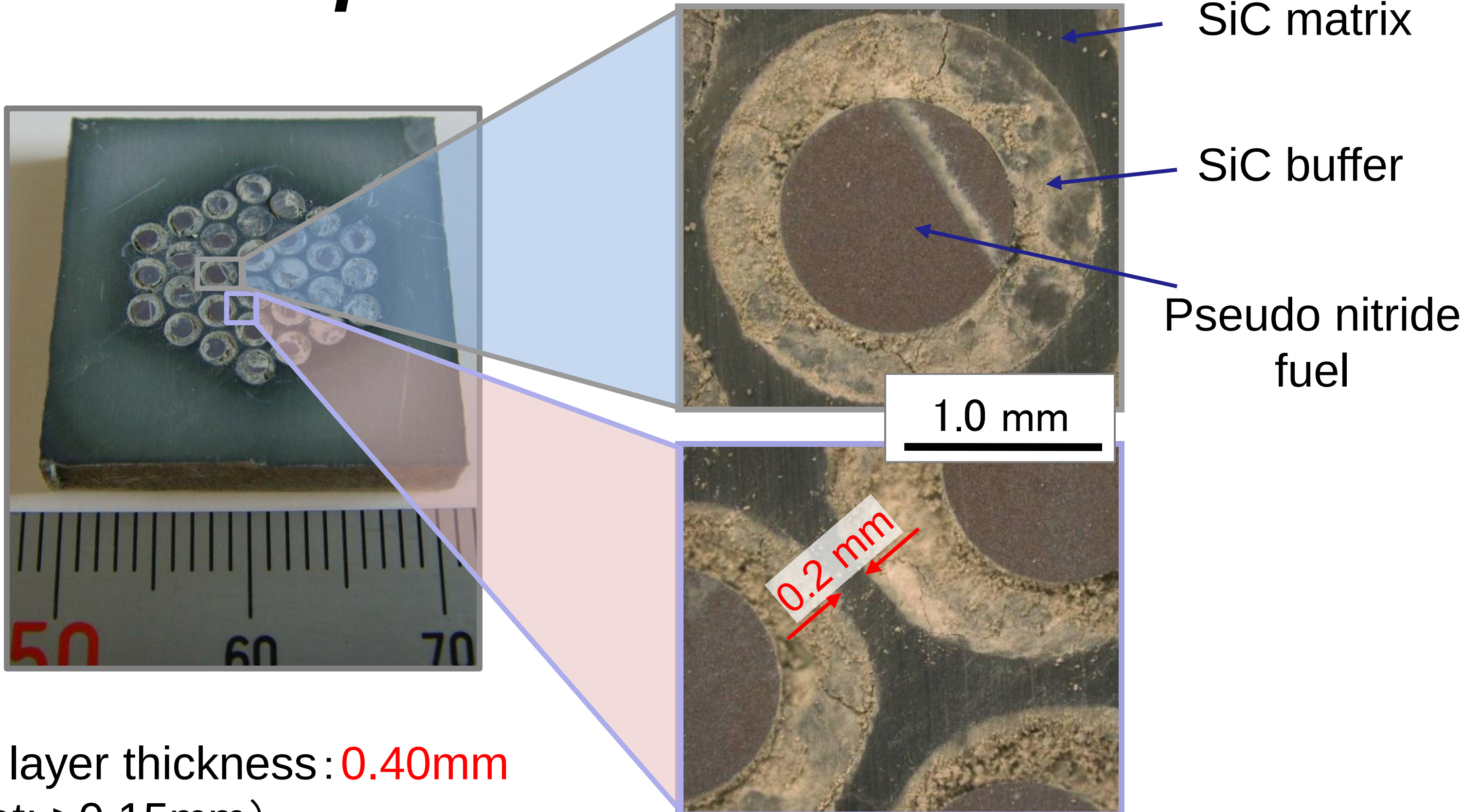
GFR Core Design Concept Using Fuel Pin



Fuel pin	***SiC/SiC composites***
Bond material	***Liquid metal (Pb-Bi)***
Fuel matrix	***High dense SiC (> 95%TD)***
Fuel buffer layer	***Low dense SiC (~ 50%TD)***
Fuel	***Nitride fuel***

Kyoto University

Fabricated Composite Fuel



- Buffer layer thickness：0.40mm
  （Target: >0.15mm）
- SiC matrix thickness：0.22mm
  （Target: <0.23mm）
- Buffer layer density：20%
  （Target: <50%）

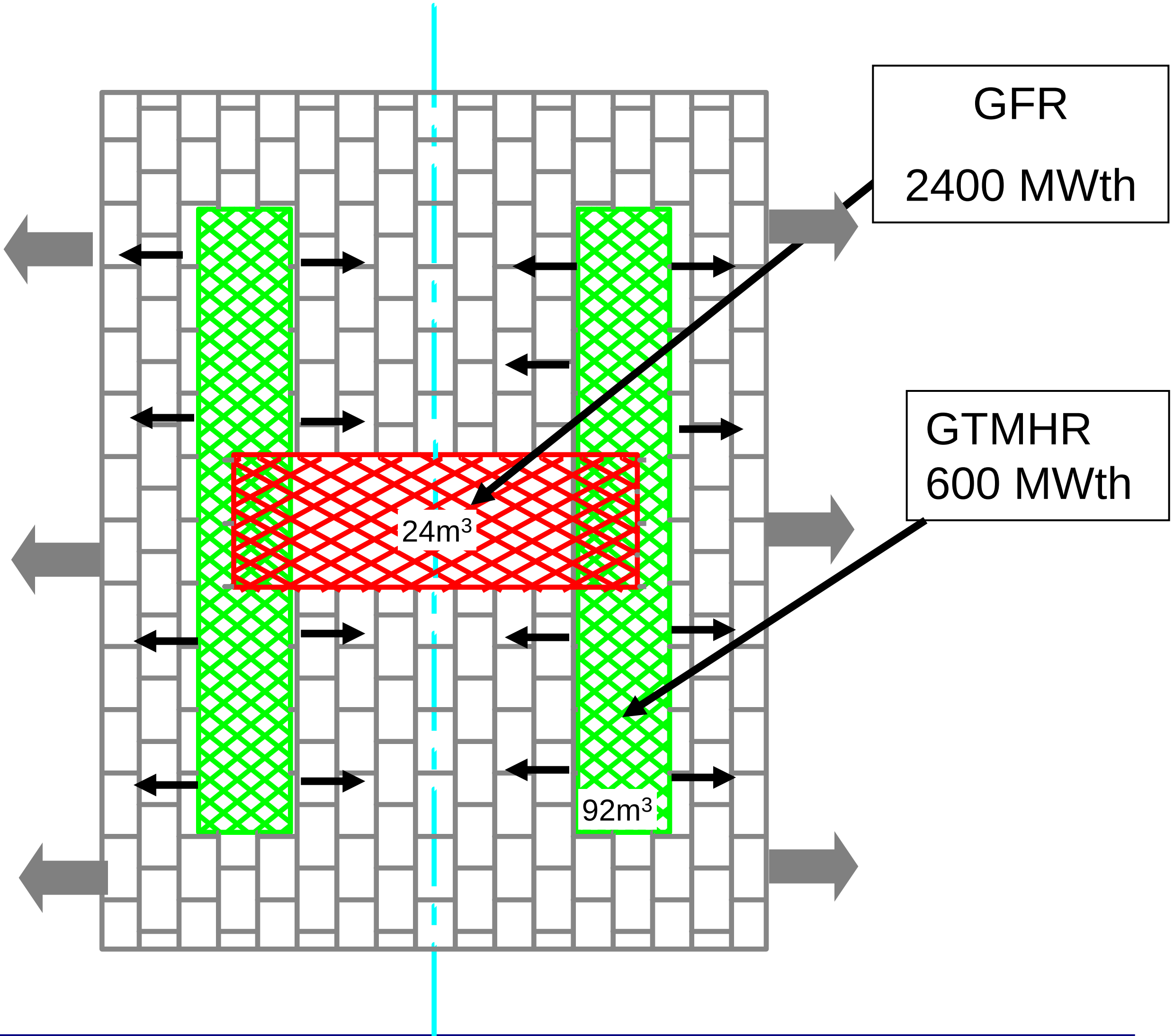
All technical targets were cleared with sufficient margin!

Kyoto University

GFR Fuel – the future (or possible futures)

- ***The "sandwich clad" fuel pin design appears to be viable***
- ***Work has been done on non-active thermal testing and irradiating the individual components.***
- ***Next steps are:***
  - ***To demonstrate end-cap sealing***
  - ***To produce rodlets***
  - ***To irradiate rodlets and to carry out PIE***
- ***It would be good if advantage could be taken from parallel work on accident tolerant fuels for light water reactors.***
- ***Coated particle fuels look like a good alternative but we would need to drop the proliferation resistance objective of having no breeder blankets***
  - ***Is it possible to retain PR objective with breeder blankets by spiking the these with minor actinides ?***

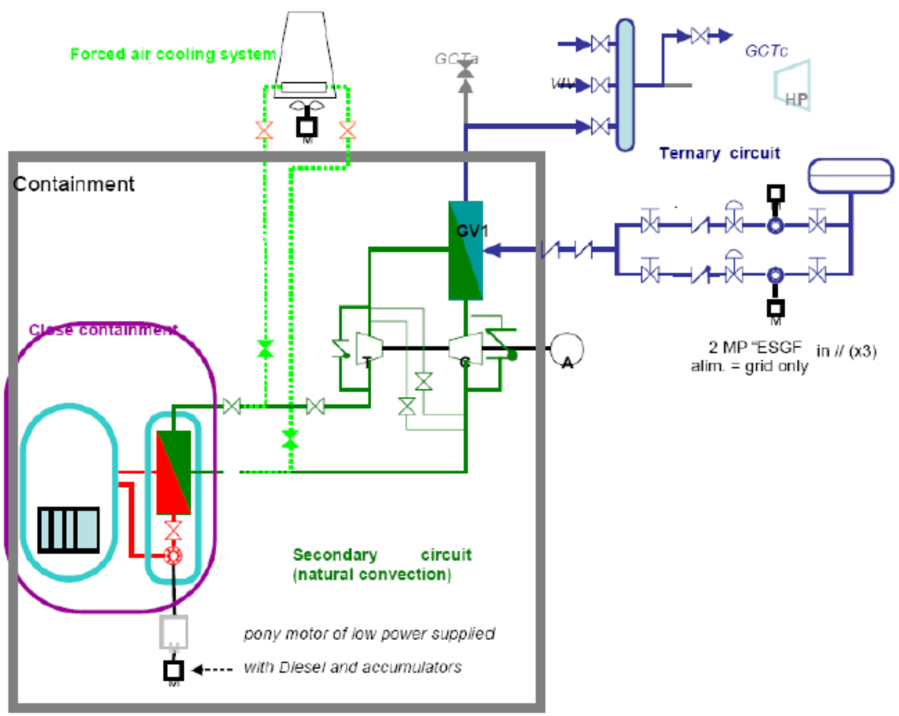
Comparison of passive heat conduction paths and power densities for GT-MHR and GFR2400 cores

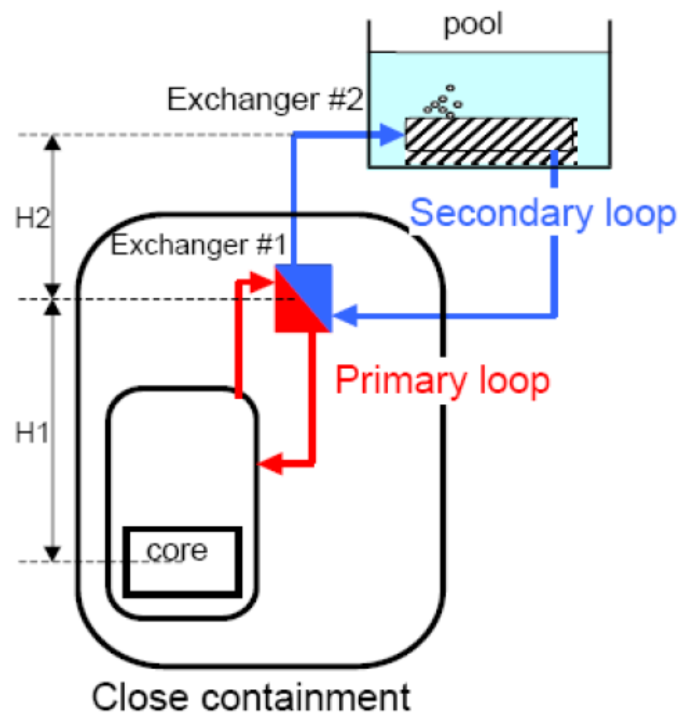


GFR Safety Aspects

Decay heat removal relying on gas circulation in the Primary circuit

- Using at first normal circuits operated in forced or natural circulation
- Using dedicated DHR loops operated in forced or natural circulation

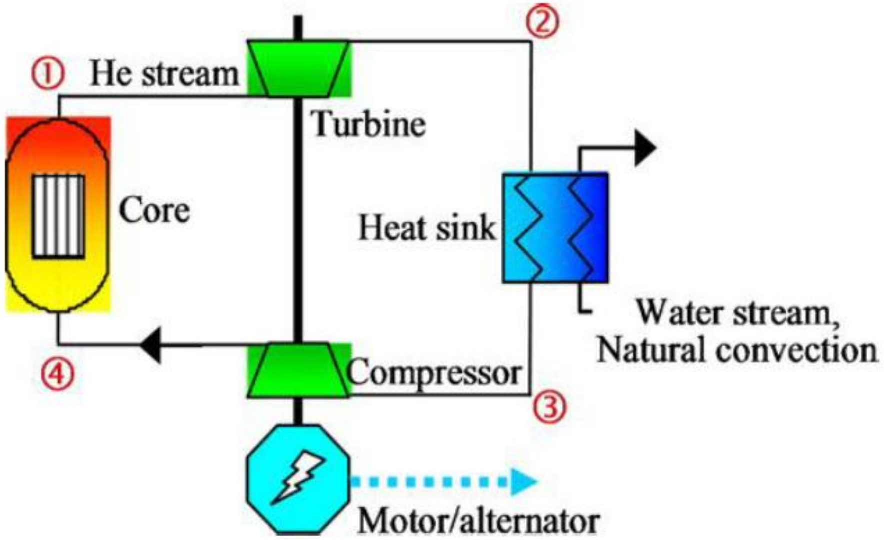




GFR Safety Enhancement

Still various open innovative design options

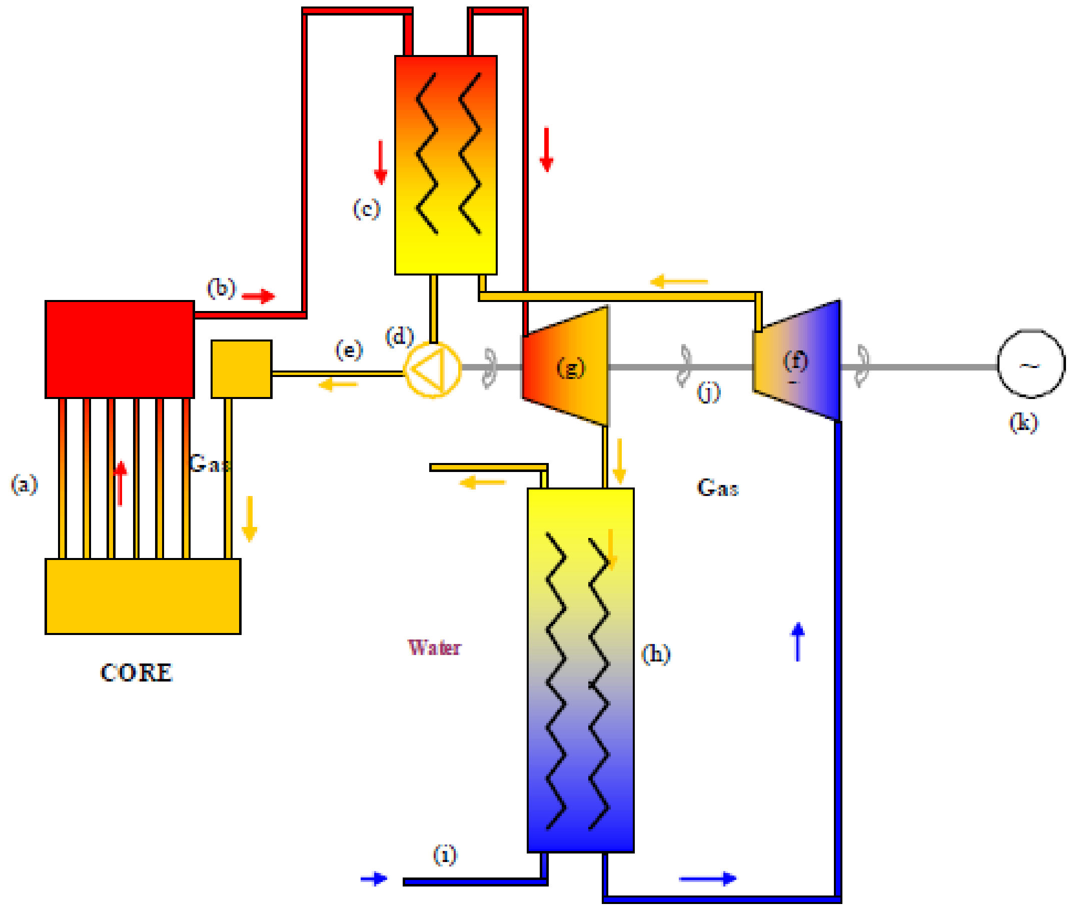
- **DHR system design**: the concept of autonomous Brayton cycle for DHR is promising; it should be incorporated in the existing DHR architecture as an extra protection line in the prevention of severe accidents.



Principle scheme of the autonomous DHR loop: the primary gas circulation is ensured by a small turbo machine driven by the residual heat of the core

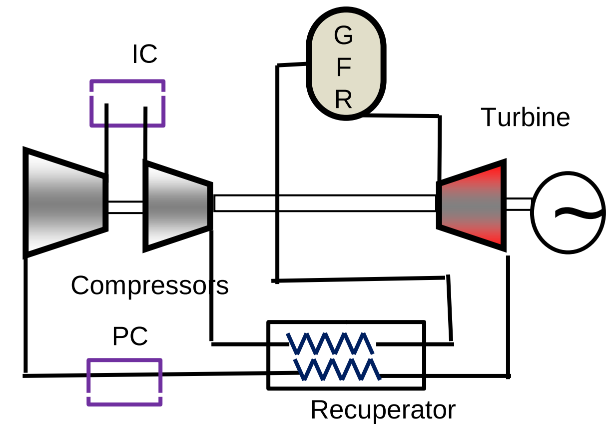
Alternative scheme – direct drive primary circulators

- Alternative design of the primary gas circulator systems
  - -- the primary circulators are driven by the 3 turbogenerators of the secondary circuits
  - -- decay heat removed through the normal heat removal path
  - -- Need to be able to provide power to drive the heat sink – an alternative heat sink using natural convection is preferred

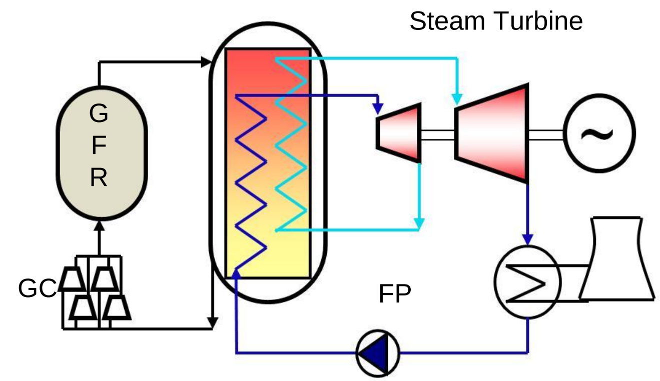


N. Tauveron, F. Bentivoglio. Preliminary design and study of an innovative option for gas fast reactors. Proc. ICAPP11. Nice, France, May 2-5, 2011

Power conversion system options

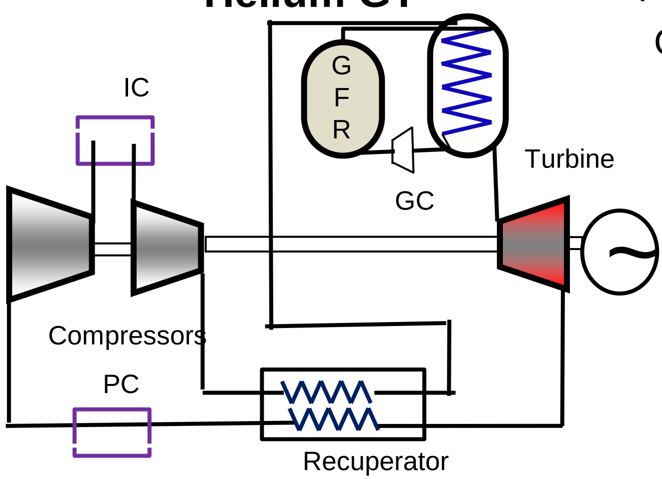


Direct Recuperated Helium GT

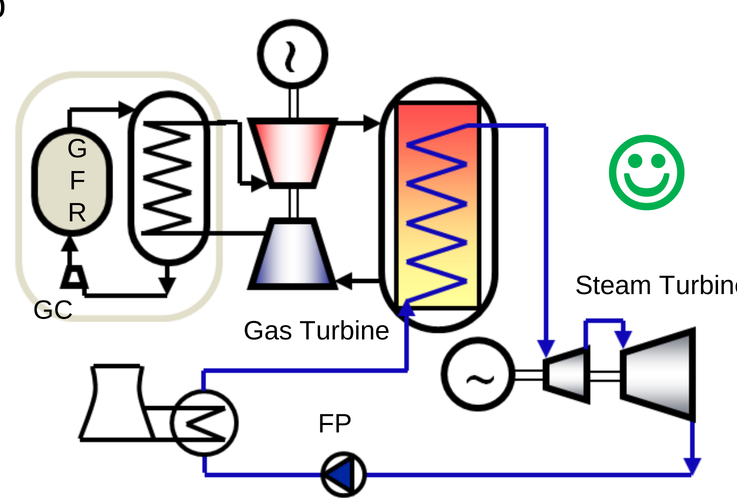


Indirect Pure Steam Cycle

PC – pre-cooler
IC – Intercooler
FP – Feed water pump
GC – Gas circulators



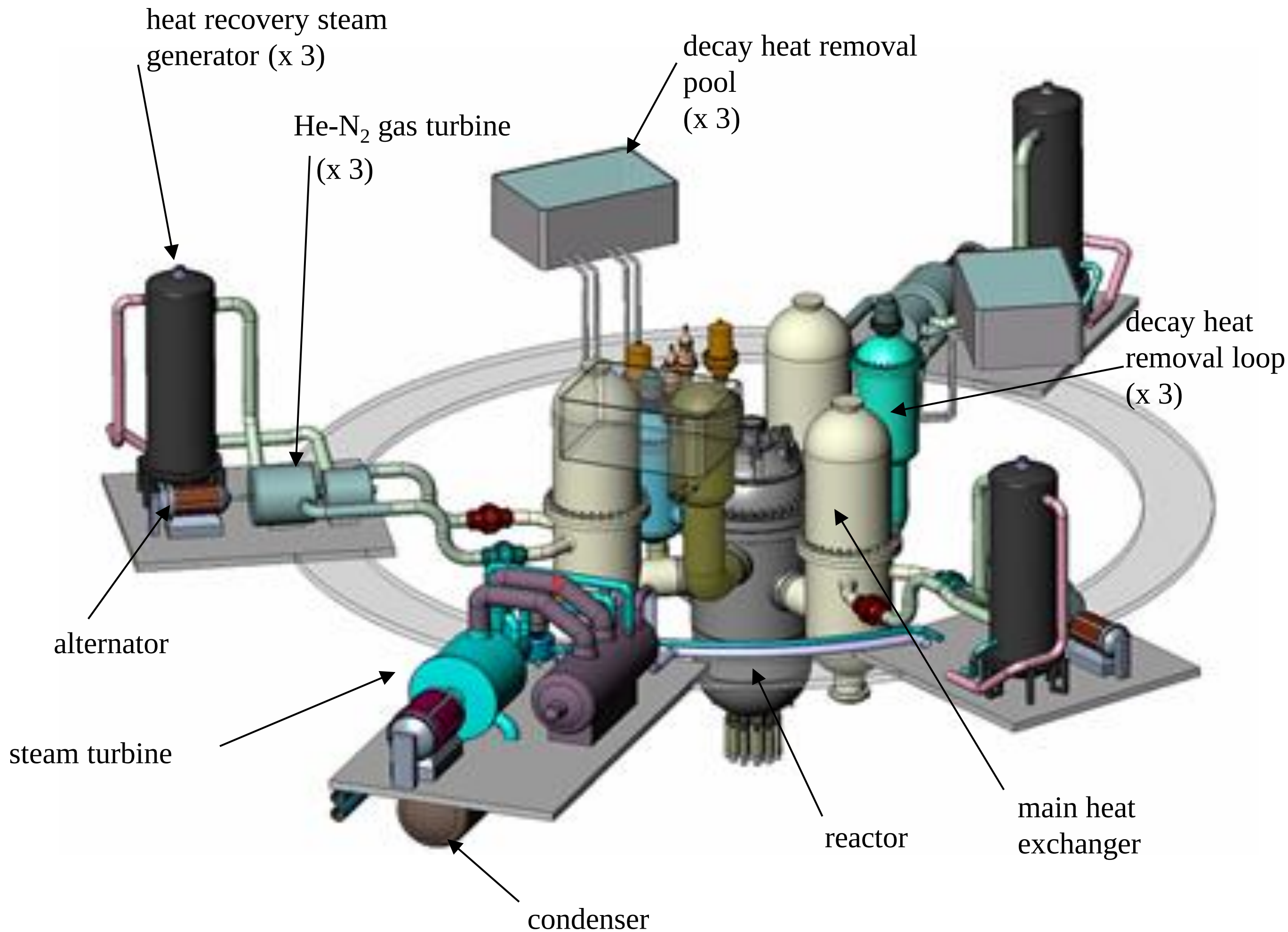
Indirect Recuperated Helium GT



Indirect CCGT

Images courtesy of
Chris Neeson, Rolls-Royce plc

Power conversion system (indirect combined gas~steam cycle)



Status of GFR System Cooperation

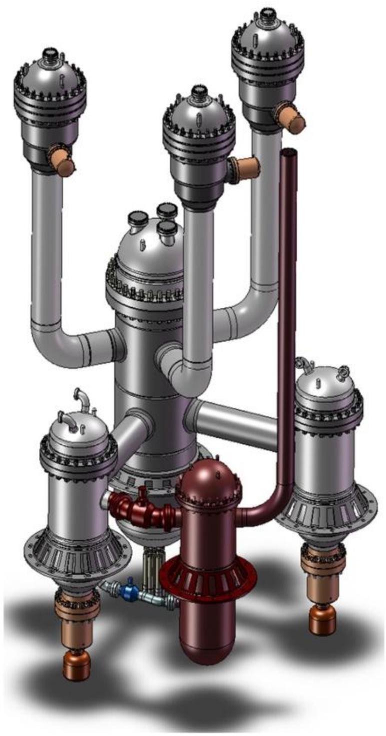
GFR System Arrangement signed by Euratom, France, Switzerland and Japan

- *France – very limited effort which has been dedicated to supporting the V4 ALLEGRO consortium*
- *Switzerland – No national funding for GFR R&D*
- *Japan – No national funding for GFR R&D and efforts re-directed post-Fukushima, but Kyoto University is contributing to fuel development.*
- *Euratom: FP7 GoFastR project ended in February 2013:*
  - *Work surrounding establishment of ALLEGRO in the FP7 ALLIANCE project. Minor physics tasks in FP7 ESNII+,*
  - *There was a poor match between first call for in the Horizon 2020 programme and the needs of GFR*
    - » *Next Horizon 2020 call will be published at the end of 2015 for projects starting in 2017*

ALLEGRO – The GFR Demonstrator

Main IHX, based on design of HTTR IHX by JAEA

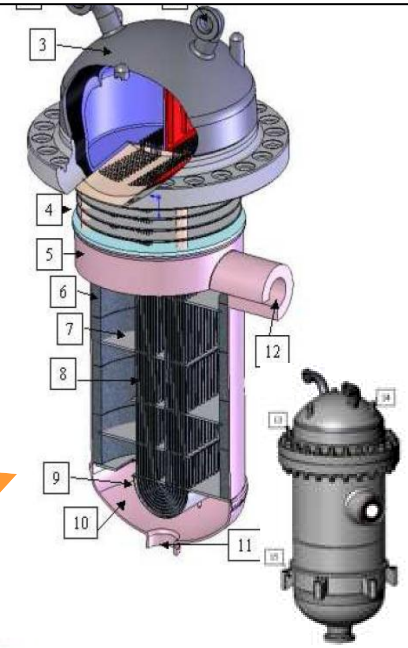
GFR

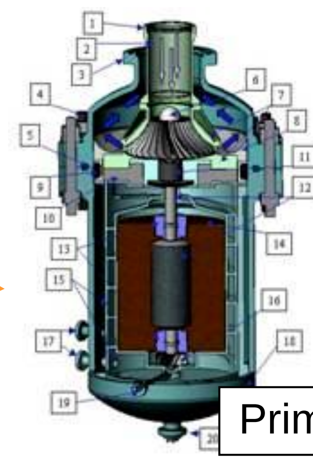


Reactor vessel

Length : 14m

Diameter : 3.20 m





Primary Blower

The new ALLEGRO strategy - 1

A new strategy for developing the ALLEGRO reactor is under preparation, starting from April 2014. The main components of this strategy are as follows:

- *To reduce ALLEGRO power from 75 MWth to around 10 MWth and to find the optimum core configuration;*
- *To optimize nitrogen injection (launch time, duration) and the backup pressure in guard containment;*
- *To increase main blowers inertia to avoid short term peak temperature for the LOCA+ blackout case and/or to develop a design with a gas turbine in the secondary side coupled to the primary blowers (this is the solution also advised for GFR).*

As a consequence of potential fuel supply difficulties it was also decided to use UO_2 pellets in AIM1 cladding instead of MOX pellets.

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The new ALLEGRO strategy - 2

•*Ideas on high temperature remained unchanged.*

•*The design should ensure the possibility of increasing reactor power (eventually up to 75 MWth) if safety considerations allow for it.*

•*The initial core (UO_2 / AIM1) will be replaced by ceramic clad fuel whenever the development and qualification of this fuel will have been completed.*

•*A new system Roadmap is under preparation to cover all design, safety and experimental aspects of ALLEGRO development.*

Conclusions

- *The GFR concept is not new, having been explored by a number of countries since the 1960's*
- *GFR can be considered as a longer term fast reactor concept that will provide an equivalent of VHTR that can sustain a self-sustaining closed fuel cycle.*
- *Progress in the early days of the GIF was good with six partners all contributing to the exploratory phase.*
- *Formal signing of the system arrangement reduced the number of partners to four, and effort has continued to decrease to to a shifting of priorities back to SFR, and a refocusing of R&D funding following the Fukushima accident.*
- *Viable concepts for fuel and cladding have been developed.*
- *Work remains to be done on refining the safety architecture such that the safety goals can be met in a cost effective manner.*

Conclusions (2)

- *Work continues in the V4G4 consortium on developing ALLEGRO to be a GFR demonstrator – funded at a fairly low level by the European Commission and the Governments of the V4 member states.*
- *ALLEGRO concept has been re-worked to start with a much smaller core 10MWth c.f. 75MWth, starting with UO_2 fuel as opposed to MOX*
- *There are synergies with the VHTR system that can be exploited if the GFR partners can get funding to collaborate, such as:*
  - *Pressure boundary materials and design,*
  - *Main heat exchangers and power conversion*
  - *Oil-free gas circulators and other helium circuit components.*
- *The future of the GFR system itself depends upon the will of the signatories to continue – whether this will remains will be demonstrated in 2016 when the current System Arrangement expires.*

Acknowledgements

I would like to acknowledge the support of the members of the GFR Sytem Steering Committee and CDS & FCM PMBs both present and past:

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  - *Konstantin Mikityuk (PSI), Alfredo Vasile (CEA), Koji Sato (JAEA), Akos Horvath (MTA_EK), Henri Paillere (Secretariat)*
- *GFR SSC - EG Liaison: Frank Carre*
- *Past SSC Chairs:*
  - *Kevan Weaver (INL), Jaques Roualt (CEA), Pascal Anzieu (CEA)*
- *And many more …*
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- *Apologies to all I have forgotten to mention and to those whose names for whom have forgotten the spelling !*