Nuclear Cogeneration Industrial Initiative

Prismatic HTGR

Dominique Hittner

www.nc2i.eu

NC2I is one of SNETP's strategic technological pillars, mandated to coordinate the demonstration of high temperature nuclear cogeneration.

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The core

What is a Prismatic HTGR?

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- Fuel:
  - The base element is the TRISO particle
  - Assembling in two steps:
    - *Mixing of TRISO particle and graphite based matrix → compacts (small cylinders)*
    - *Compacts inserted in channels of prismatic blocks*
- Core composed of a regular pattern of prismatic blocks
  - Possibility of having an annular core
    - *Lower radial power peak (tops off the radial power distribution)*
    - *More graphite available in accident conditions as a cold sink*
  - Refuelling in batch

Two Types of HTGR Fuel Assemblies and Cores

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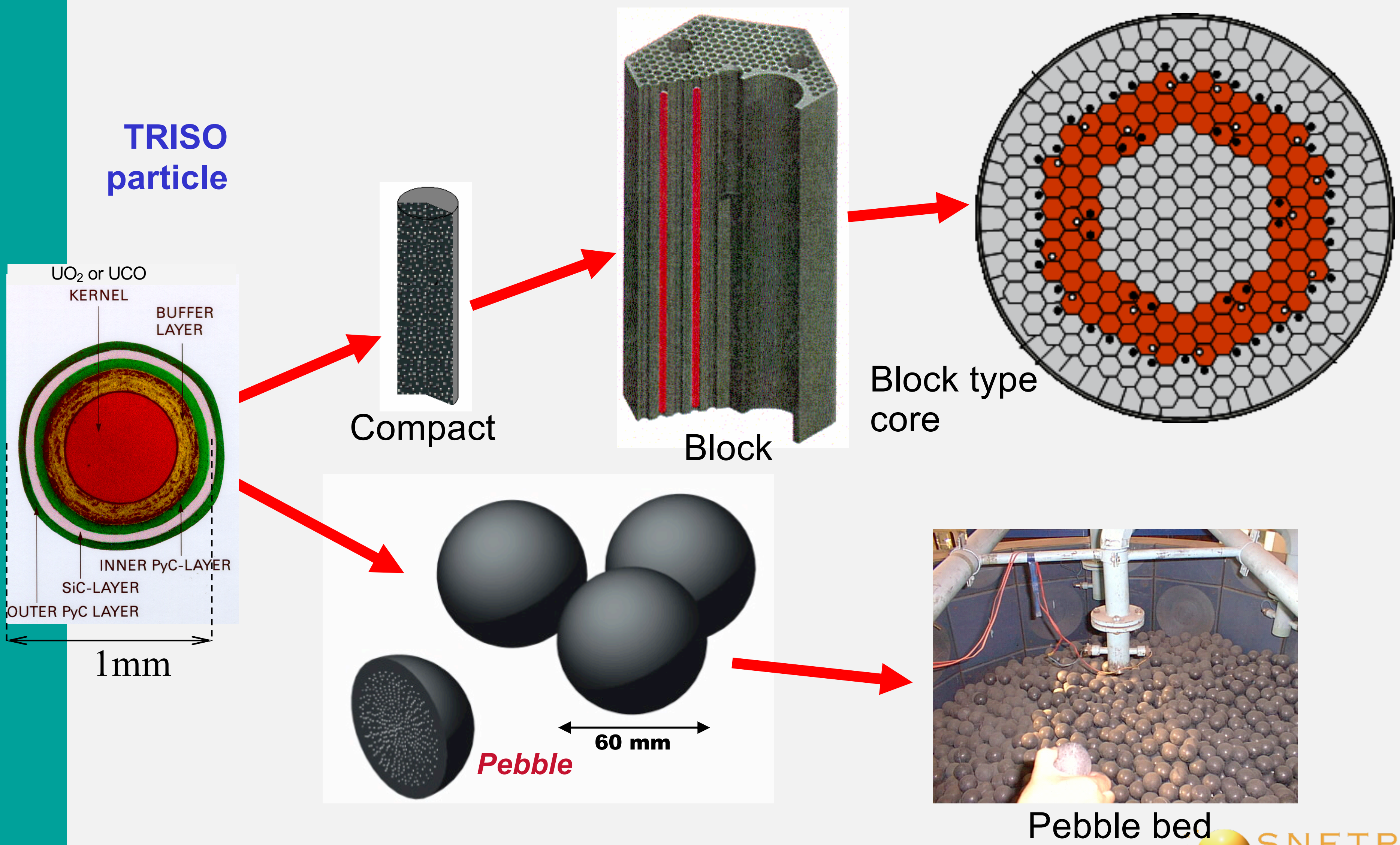

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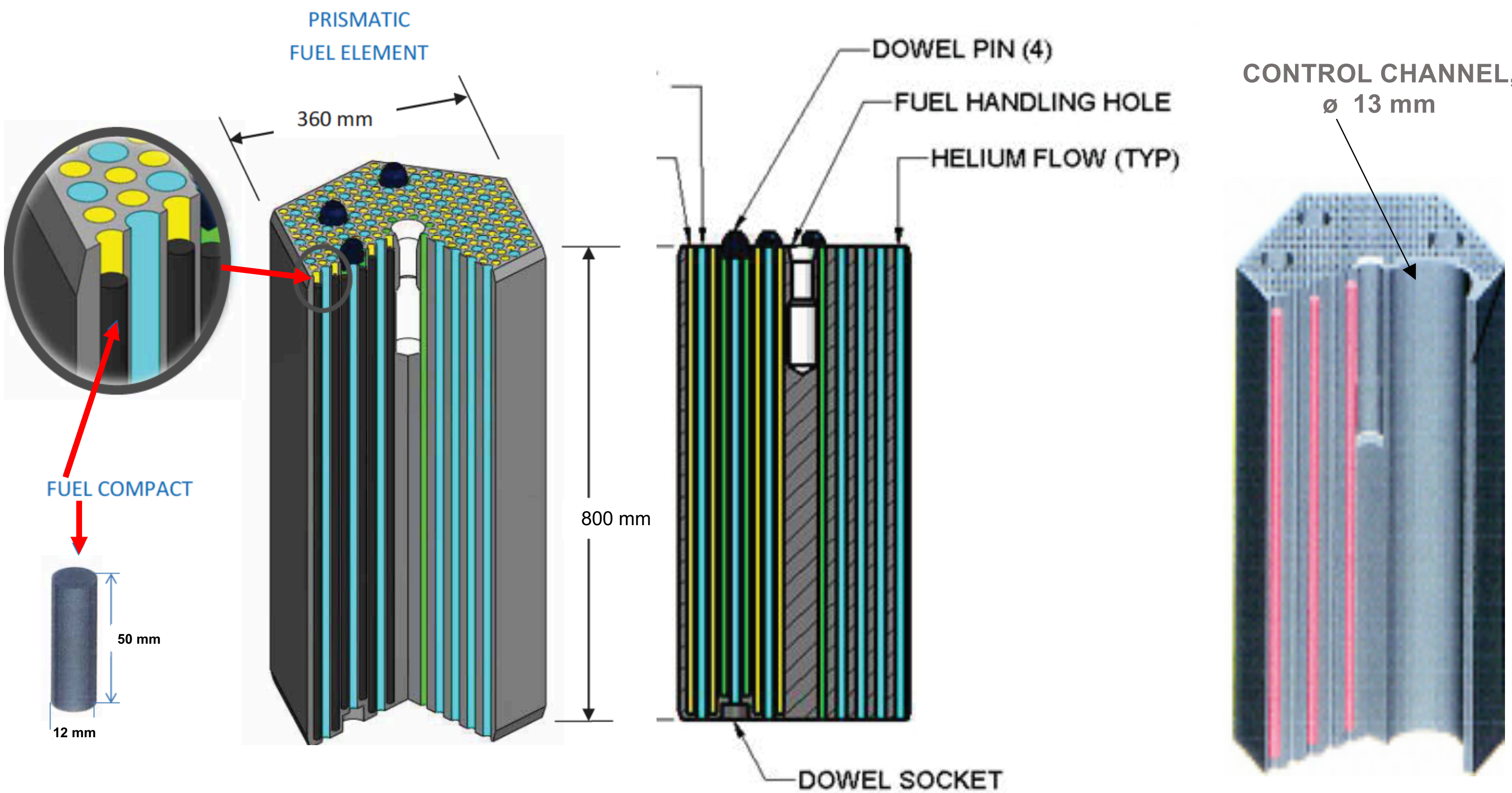
Prismatic Blocks



Block design: Fuel Rod/ Coolant hole Pattern Optimised

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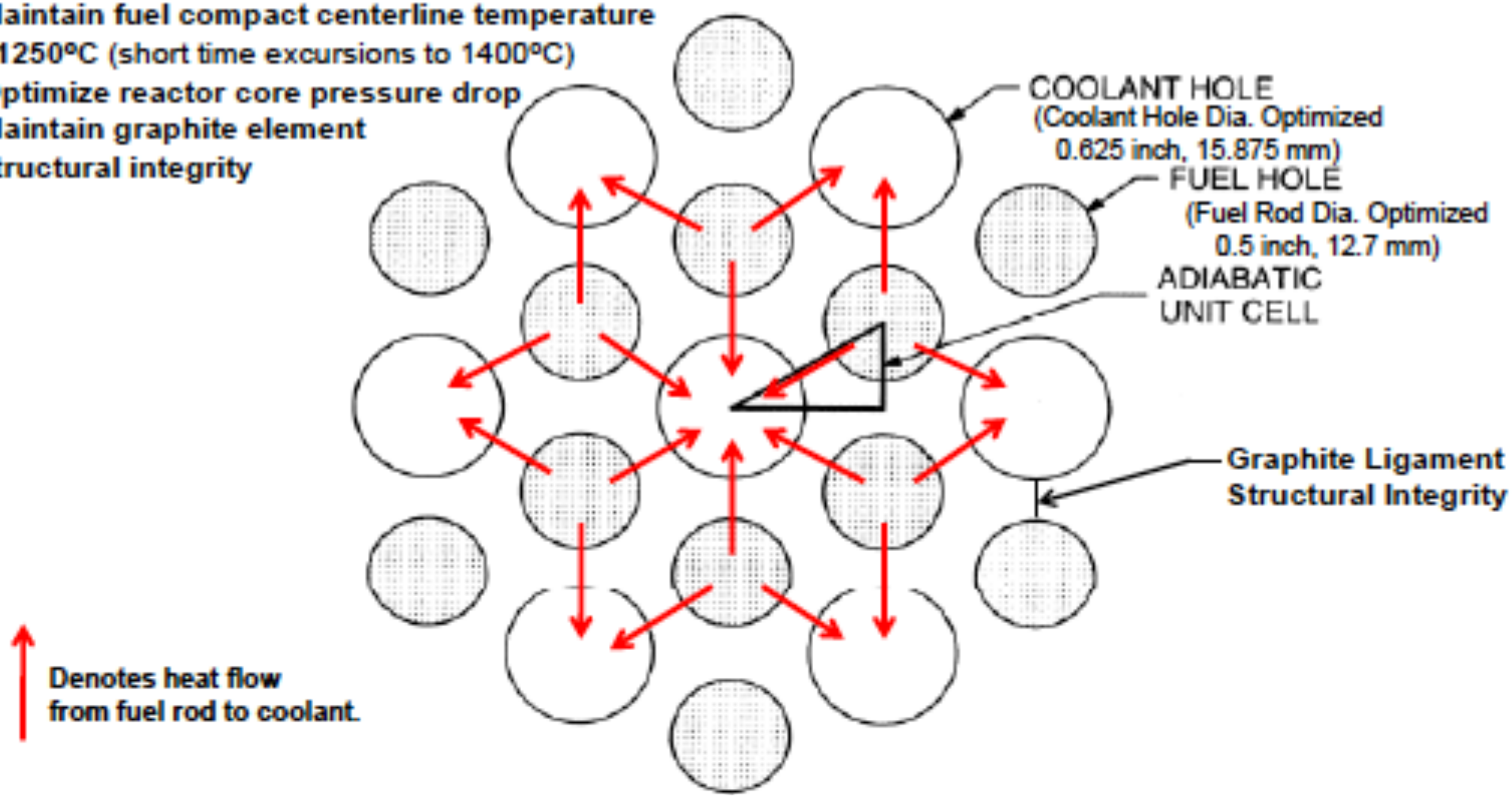
Objectives:

- Remove heat as close to source as possible
- Maintain fuel compact centerline temperature <1250ºC (short time excursions to 1400ºC)
- Optimize reactor core pressure drop
- Maintain graphite element structural integrity



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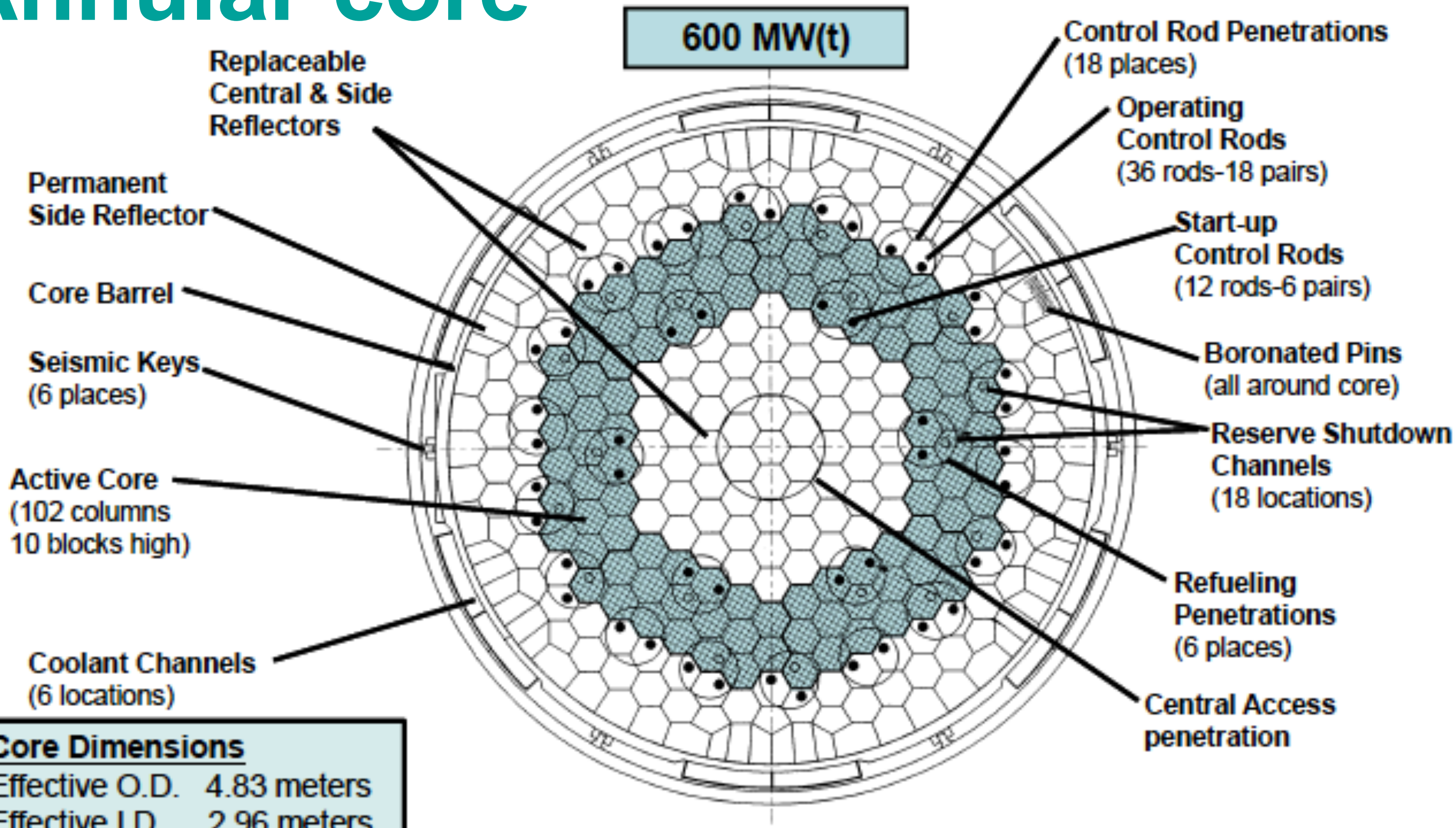
Annular core



Core Dimensions	
Effective O.D.	4.83 meters
Effective I.D.	2.96 meters
Height	7.93 meters

Radially, around the core:

- Replaceable reflector prismatic blocks
- Permanent reflector blocks
- The metallic core barrel contains the graphite core

Specific features of prismatic core reactor physics

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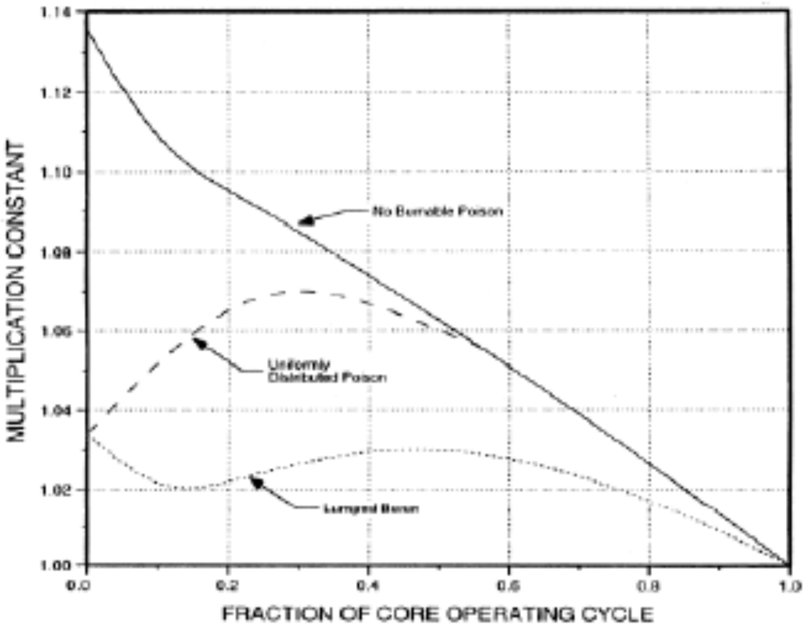
- Large reactivity in a fresh core, to be compensated
  - Control rods (not only in graphite reflectors, but also in the core)
  - Burnable poisons
    - *Use of fixed lumped boron poison for reactivity control*

Self shielding of the lumped boron (B4C) used to control poison burnout and core reactivity behavior over a fuel cycle to minimize control rod requirements



- Fuel and burnable poisons loadings can be varied radially within core annular rings and axially within fuel columns (zoning) to minimise power peaks
- High Pu burning capacity

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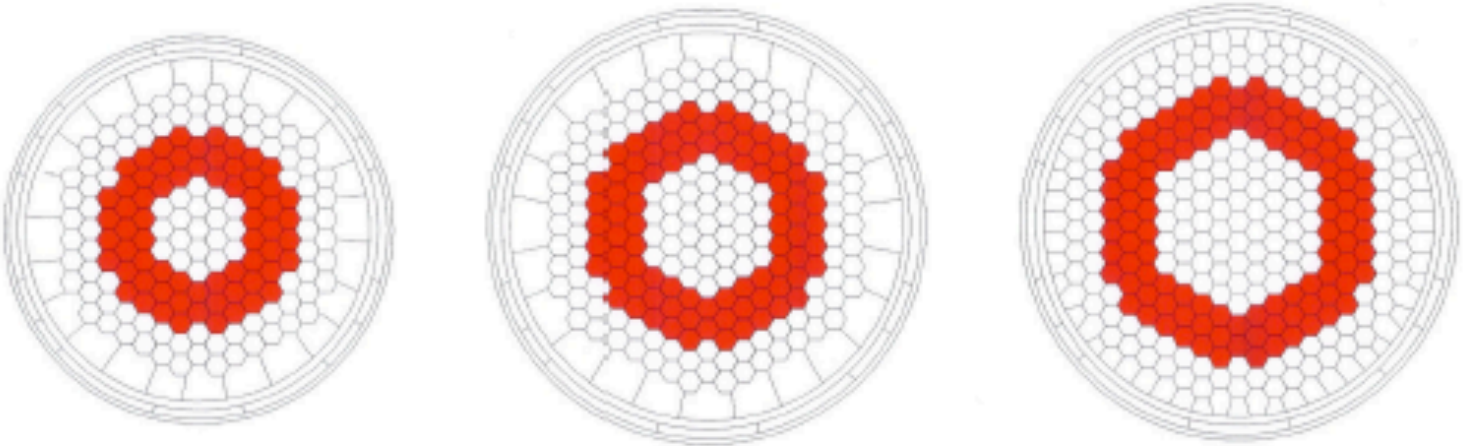
Optimisation of the core design

1600°C Fuel Temperature Limit Determines Central Reflector Size

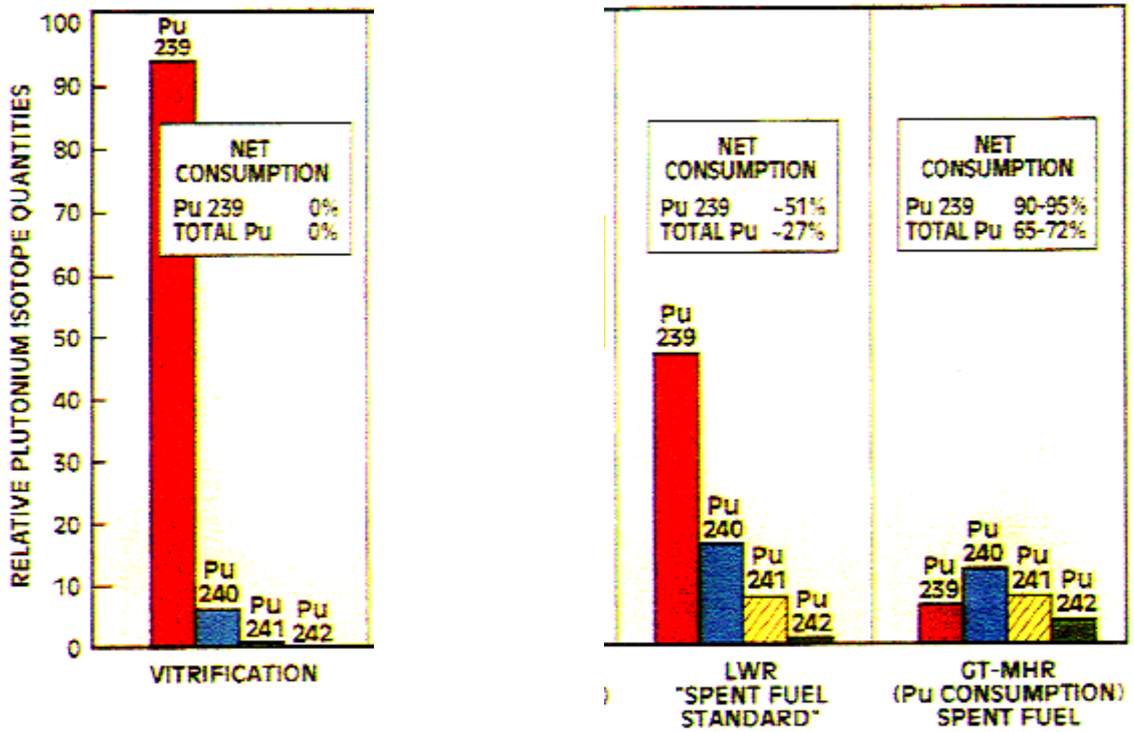
350 MW(t)	450 MW(t)	600 MW(t)



350 MW(t)	450 MW(t)	600 MW(t)
66 Columns	84 Columns	102 Columns
660 Elements	840 Elements	1020 Elements
3.60 m Core Dia.	4.32 m Core Dia.	5.04 m Core Dia.
6.21 m Vessel Dia.	6.93 m Vessel Dia.	6.93 m Vessel Dia.
5.95W/cc	6.01W/cc	6.60W/cc
0.5303MW/FE	0.5357MW/FE	0.5882MW/FE

Pu burning performance of HTGR

PLUTONIUM DESTRUCTION CAPABILITY OF DISPOSITION OPTIONS (ONCE-THROUGH REACTOR CYCLE)



GENERAL ATOMICS

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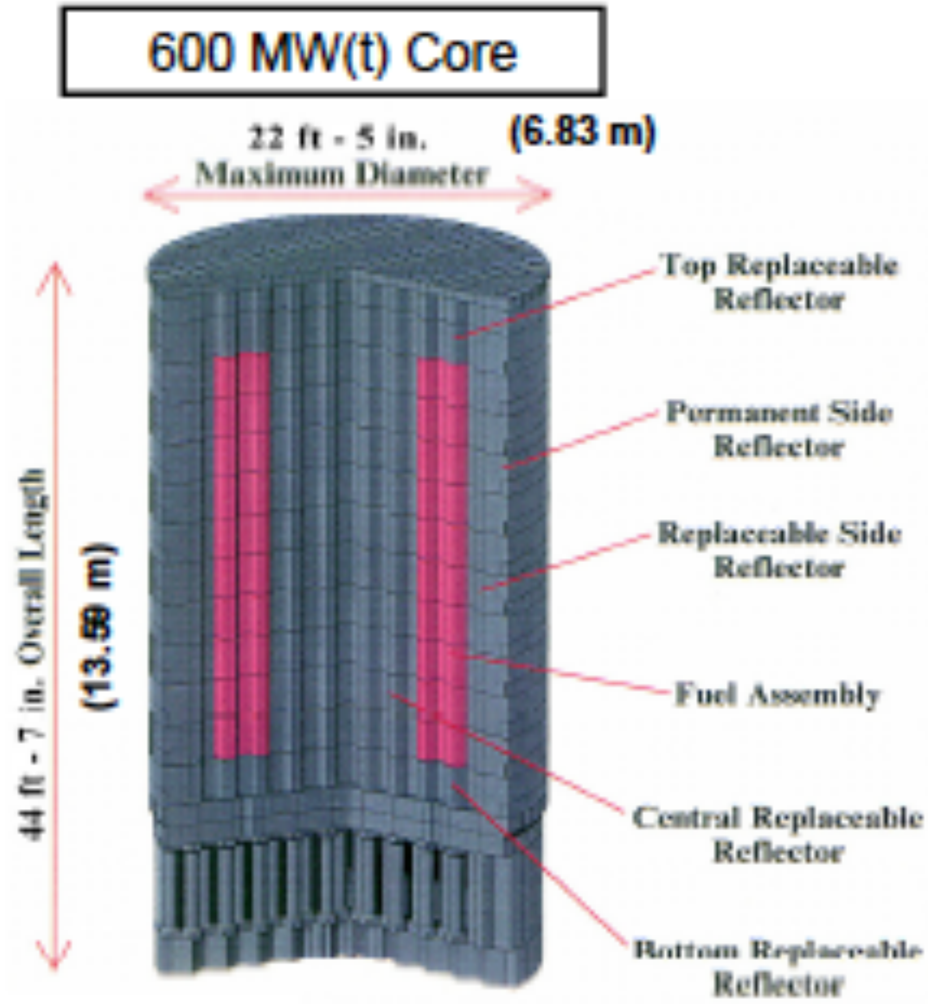
Graphite core structure

- Fuel assembly blocks stacked into columns and doweled together
- Gaps between graphite columns allow refuelling
- Restrained vertically by metallic core support
- Core columns free to expand/contract vertically
- Restrained horizontally at top and bottom
- Contained by core barrel & bottom plate



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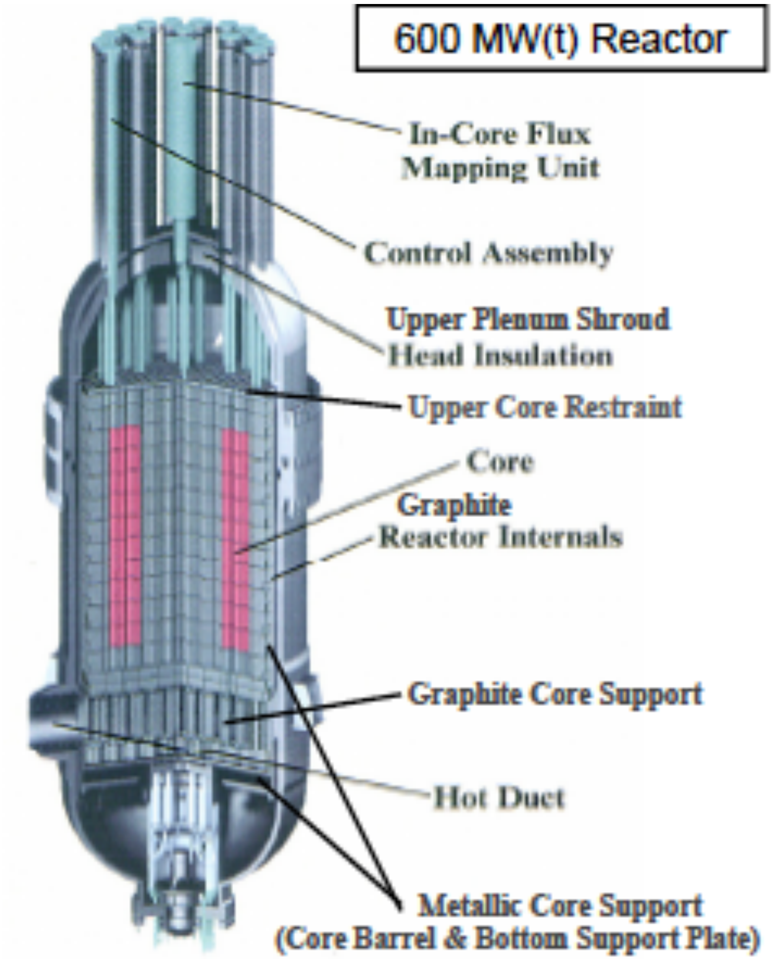
Internals

Reactor Internals

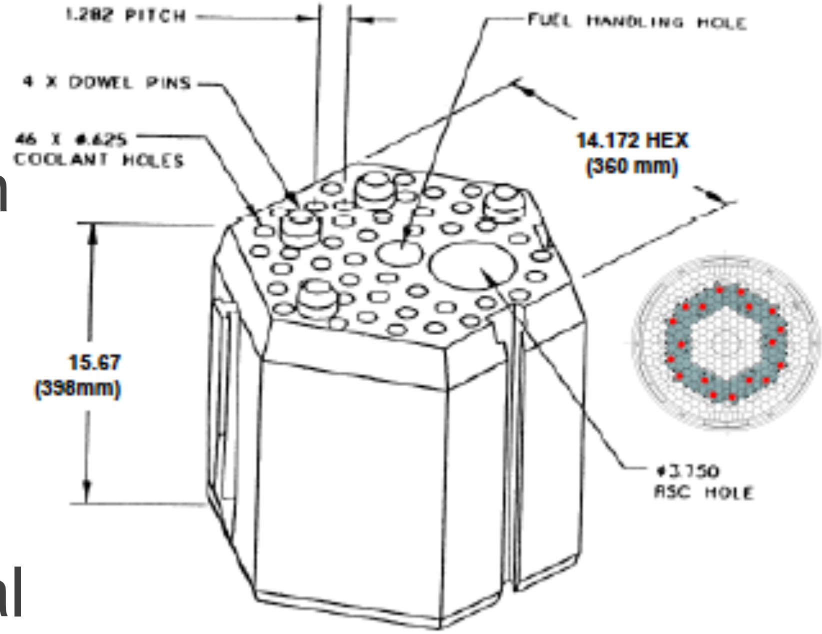
- They include
  - Permanent graphite reflector (lateral and bottom)
  - Bottom support plate
  - Core barrel
  - Upper core restraint
  - Upper plenum shroud

  } Metallic (bottom support plate, core barrel, upper core restraint, upper plenum shroud)
- They must
  - Accommodate core dimensional changes (thermal & irradiation) and duty cycle transients
  - Withstand 0,3 g earthquake
  - Operate for a 60 years lifetime



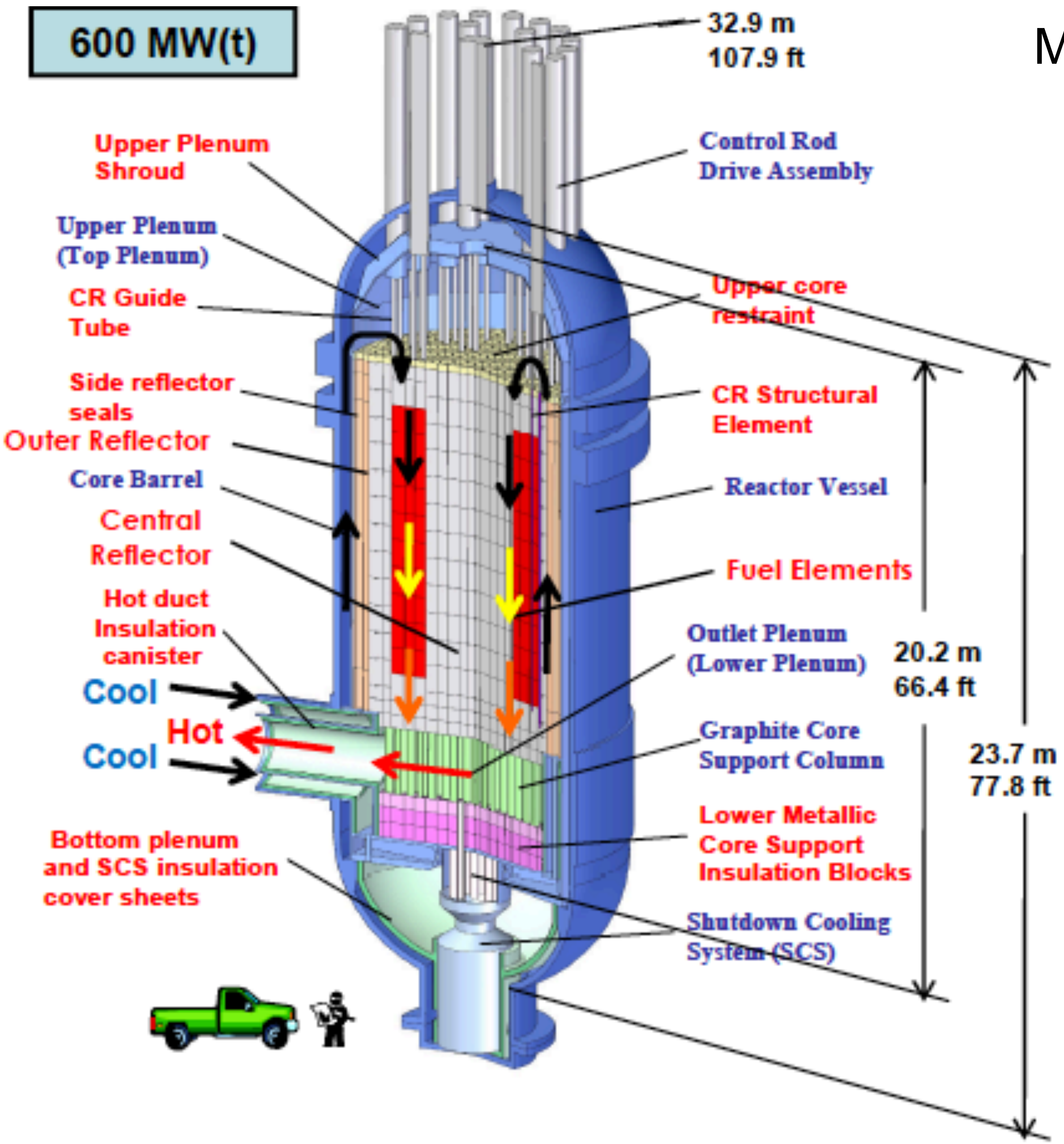
Upper Core Restraint Element

- "T" keys interlock elements
- Allow free thermal expansion of fuel column vertically and horizontally around the fuel column centreline
- Restrains column centreline translation at top in horizontal direction



- Provides interface with coolant channels, rod & RSS guide tubes
- Material: Hastelloy XR (alternate: SiC/SiC or C/C composites)

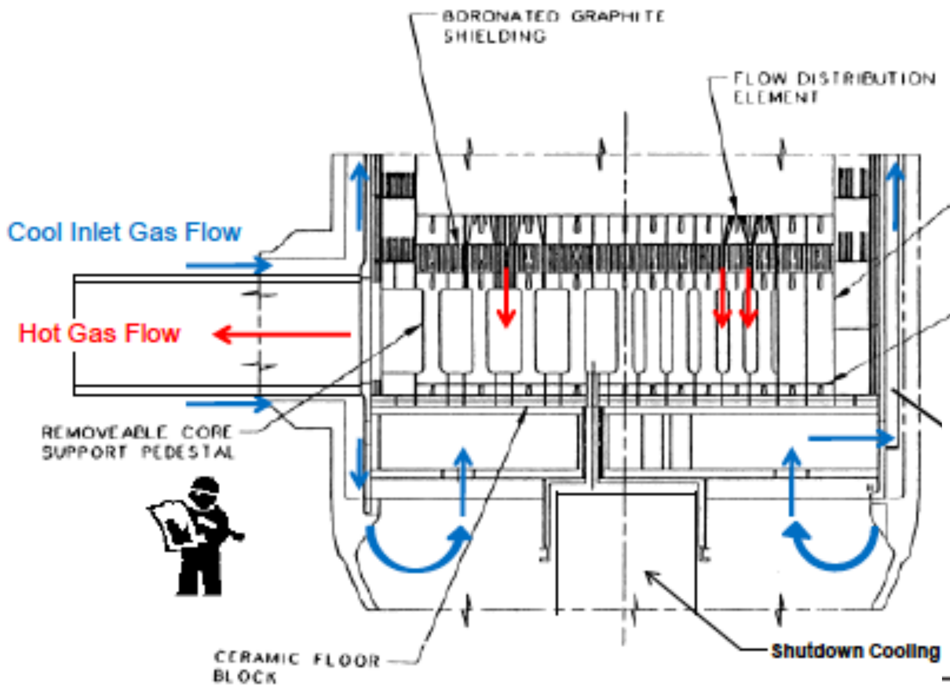
The reactor

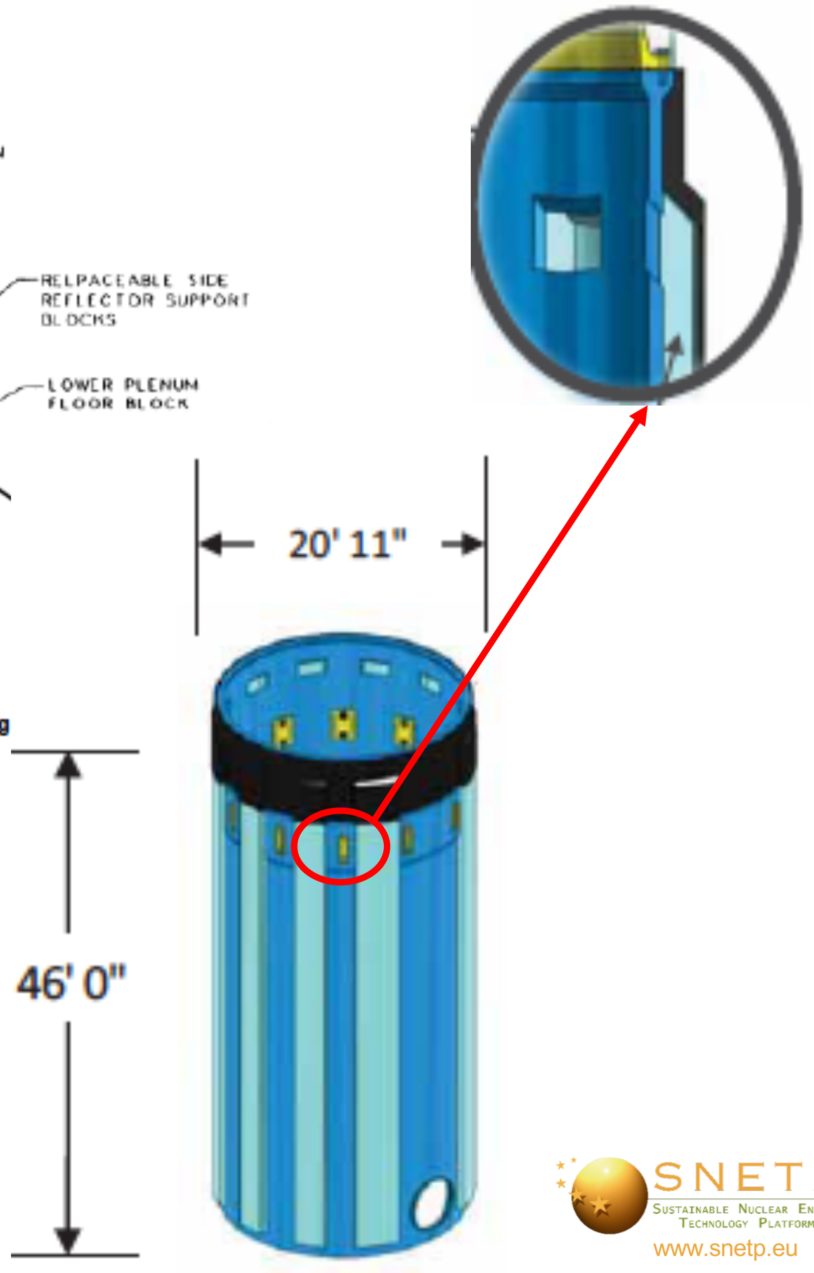


Main design challenges:

- To cool the vessel and metallic internals by cold He
- To avoid hot streaking in the outlet plenum
- To insert 48 control rods, 12 Reserve Shutdown guide tubes in the vessel head
- To reload the core without opening the vessel

Cooling metallic structures

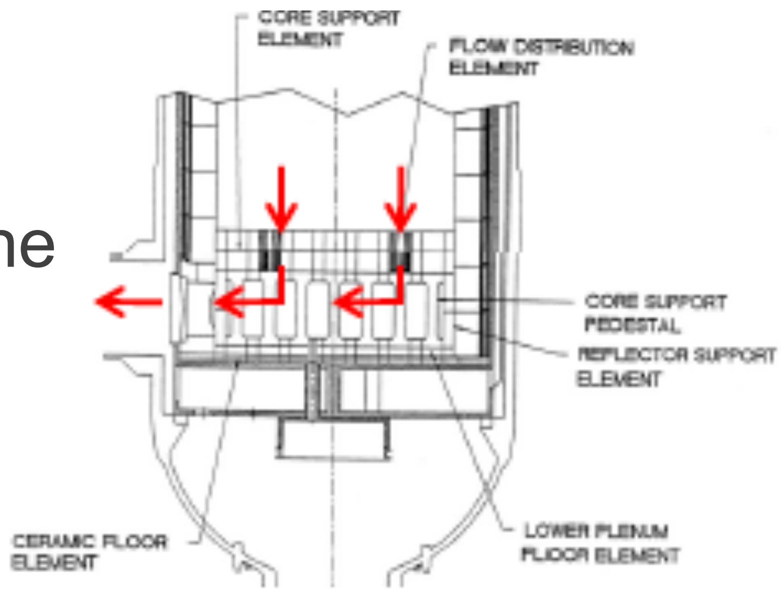




Core bypass flow

- Defined as any flow that bypasses coolant holes:
  - Gaps between columns
  - Control rod channels
  - Reactor shutdown channels

Core outlet flow (1)

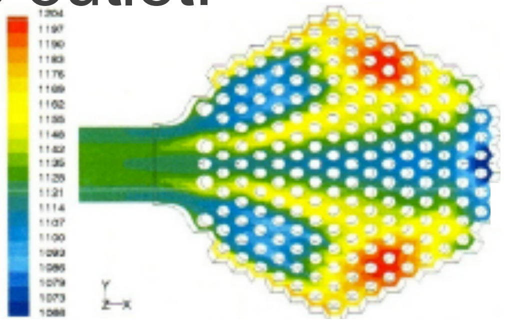


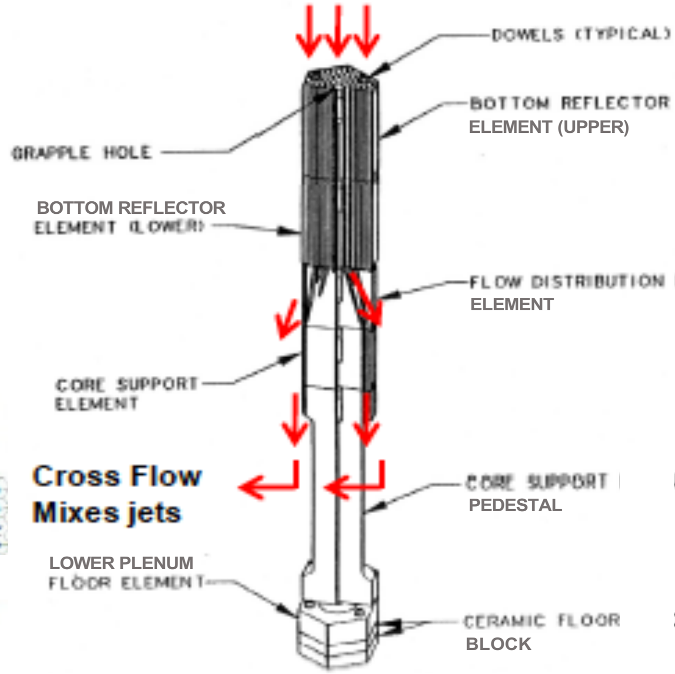
- The main flow going through the core makes a 90° turn to enter the outlet plenum
- There is a difference of temperature that can reach 400°C between hot streaks from fuel coolant channels and cold streaks from bypass channels (control channels, gaps between blocks)
- Insufficient mixing of these streaks will induce temperature fluctuations that can propagate to components downstream

⇒Failure risk of structures due to thermal fatigue (e.g. break in the fixation of the insulation of the hot gas duct of THTR)

Core outlet flow (2)

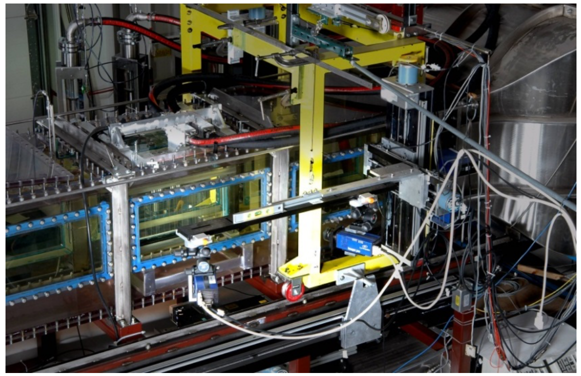
- Increasing turbulence and early mixing of hot and cold streaks is necessary at core outlet.
- Optimisation is performed by CFD calculation





- Validation of CFD calculation of temperature fluctuations requires testing:
  - INL Matched Index of Refraction Facility (MIR)
  - OSU HTTF facility

HTTF



MIR

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Reactivity control

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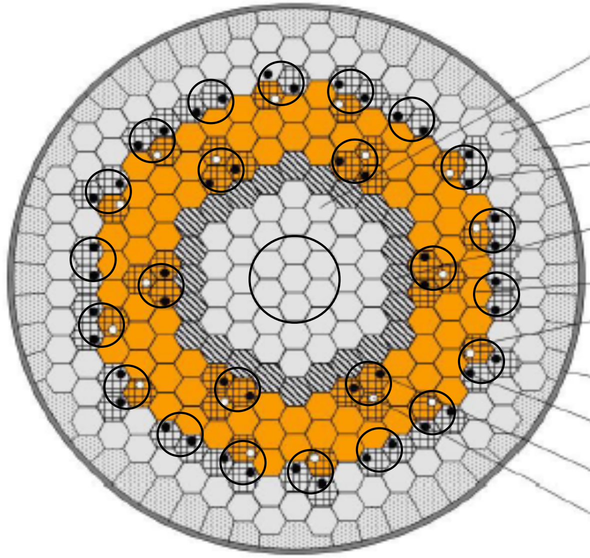
Reactivity control



- Large negative temperature coefficient intrinsically shuts reactor down
- Principle of reactor control
  - Two independent and diverse systems of reactivity control for reactor shutdown are required
    - *Control rods*
    - *Reserve Shutdown System (RSS)*
  - Each system capable of maintaining subcriticality
  - One system capable of maintaining cold shutdown during prismatic refuelling

⇒60 control drives to be accommodated on the vessel head, without jeopardising the integrity of the primary boundary

☞ Gathering the control positions into clusters of 2 or 3 positions with mechanisms grouped in the same housings.

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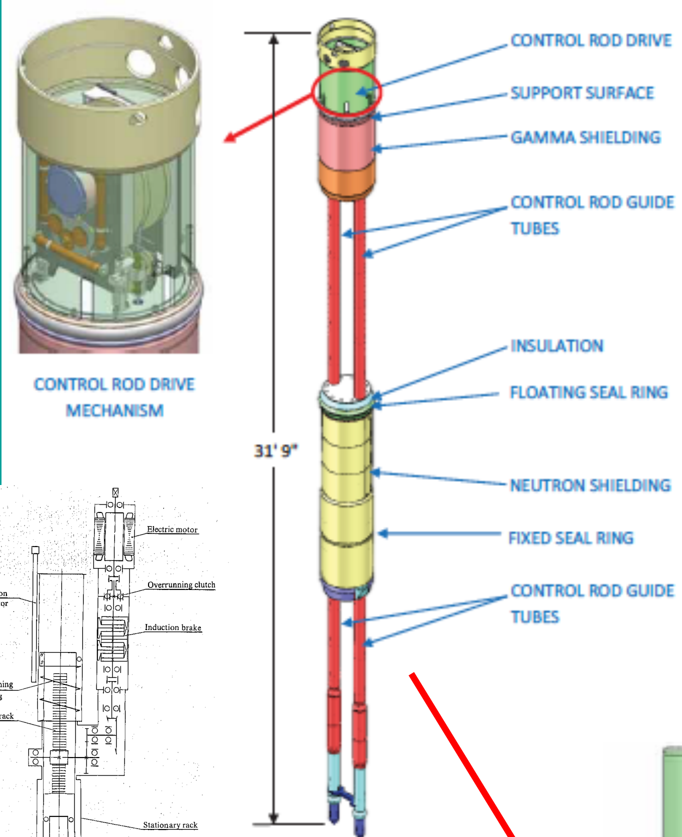
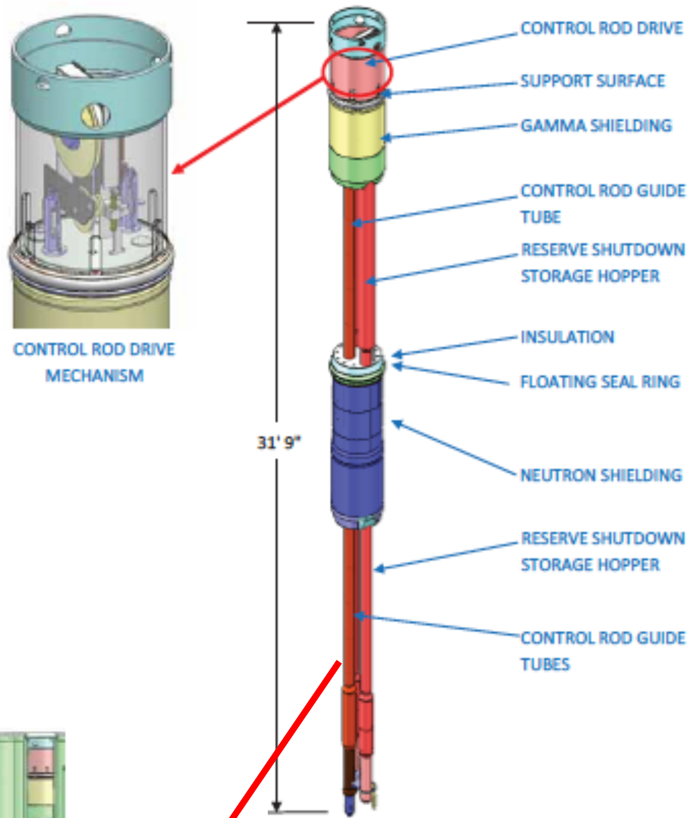
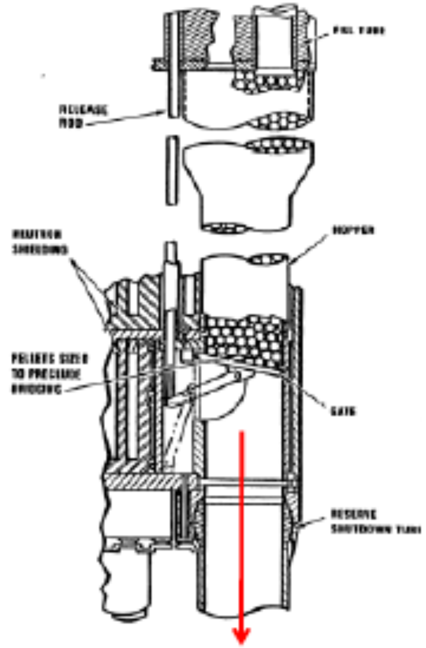
Control drives



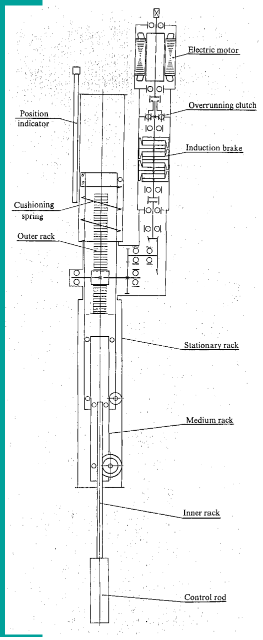
Control drive for 2 control rods



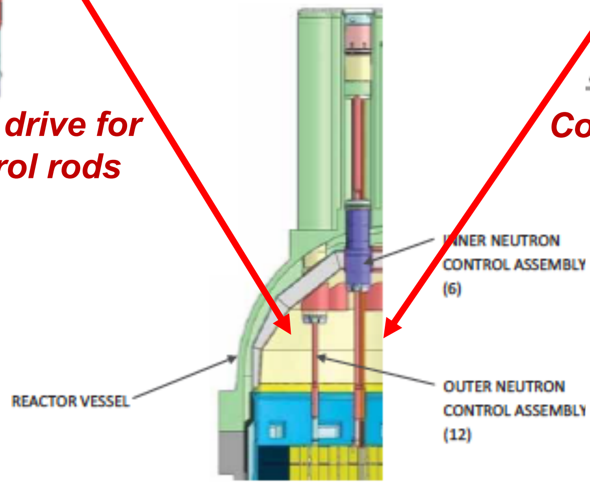
Control drive for 1 control rod and 2 RSS



Reserve Shutdown system (RSS)



Alternative control rod drive system



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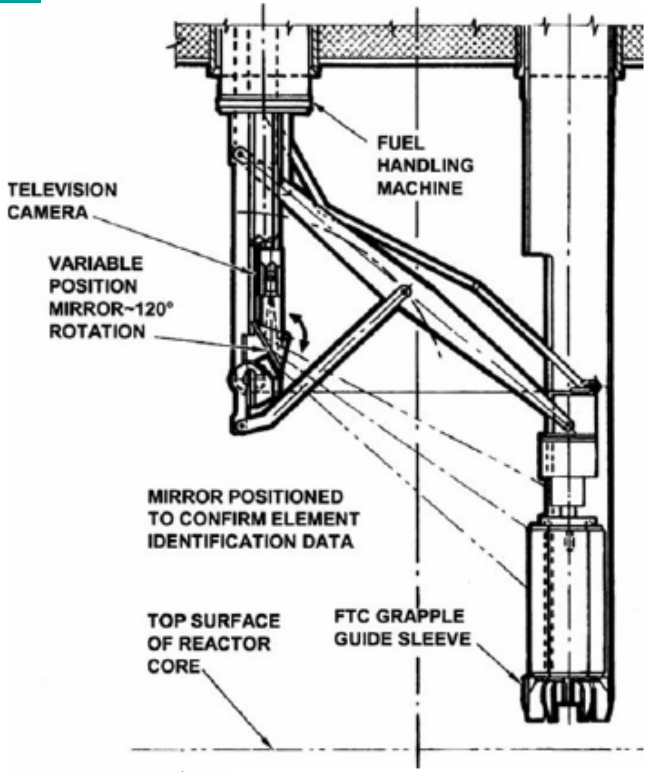
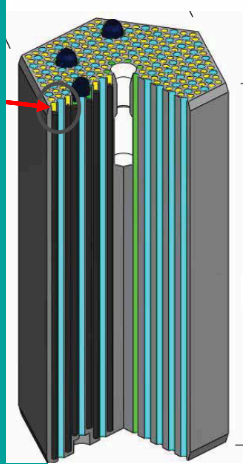
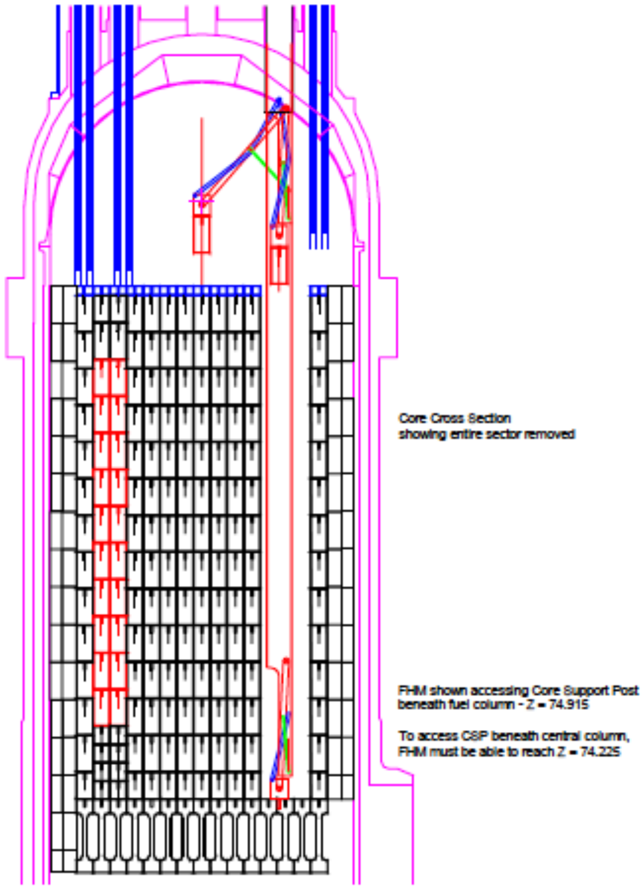
Fuel handling

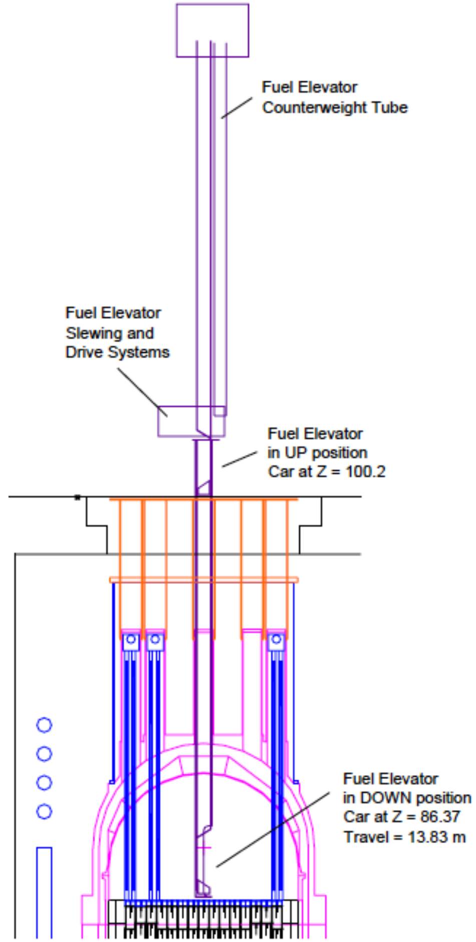
Fuel handling (1)







Fuel handling machine (FHM)



Fuel elevator (FE)

- The control rods and guide tubes are withdrawn from a sector of the reactor head above 1/6 of the core
- The FHM is introduced in one emptied control rod position and the FE in the central hole of the vessel head
- 1/6 of the core is unloaded, the FHM is moved out and control rod reintroduced.

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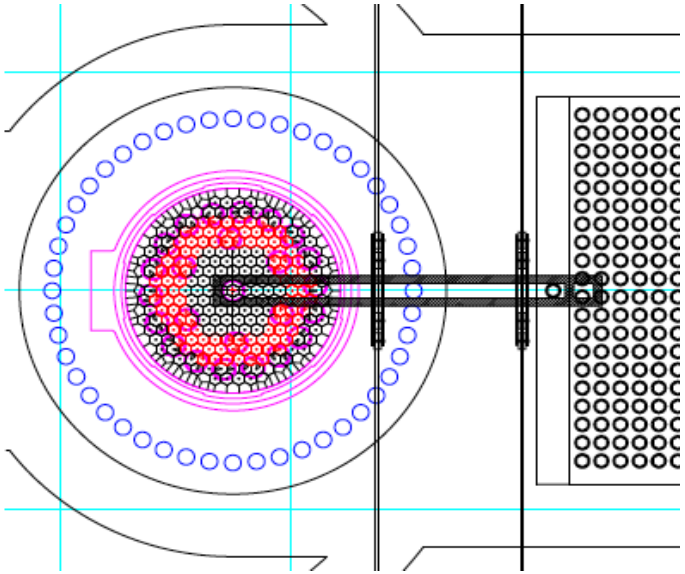
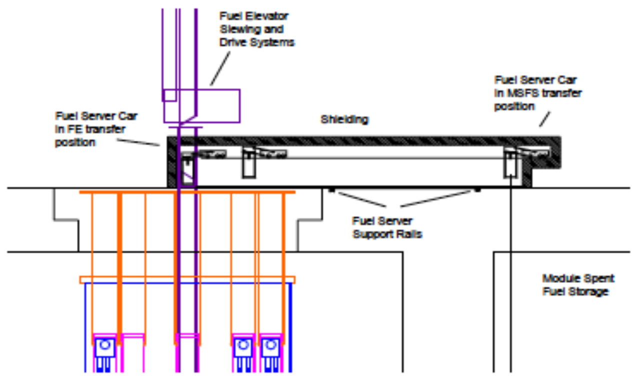
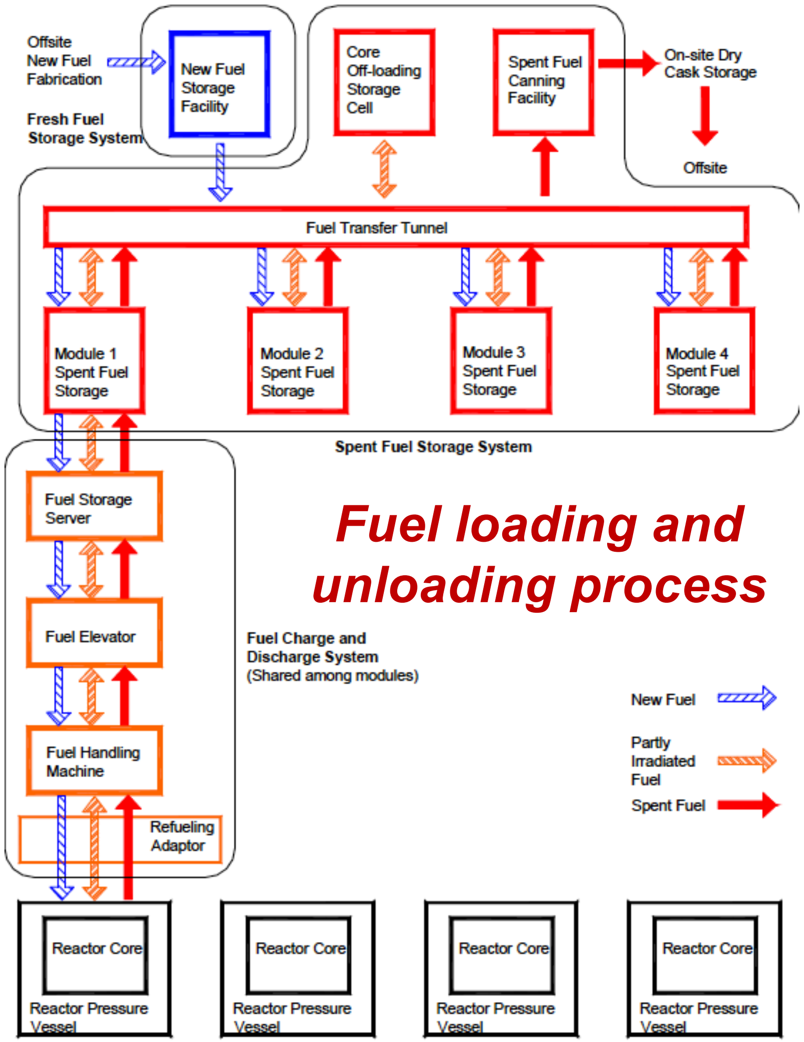
Fuel handling (2)





Fuel Storage Server



Fuel loading and unloading process

Power conversion systems and their components

Gas or steam thermodynamic cycle?

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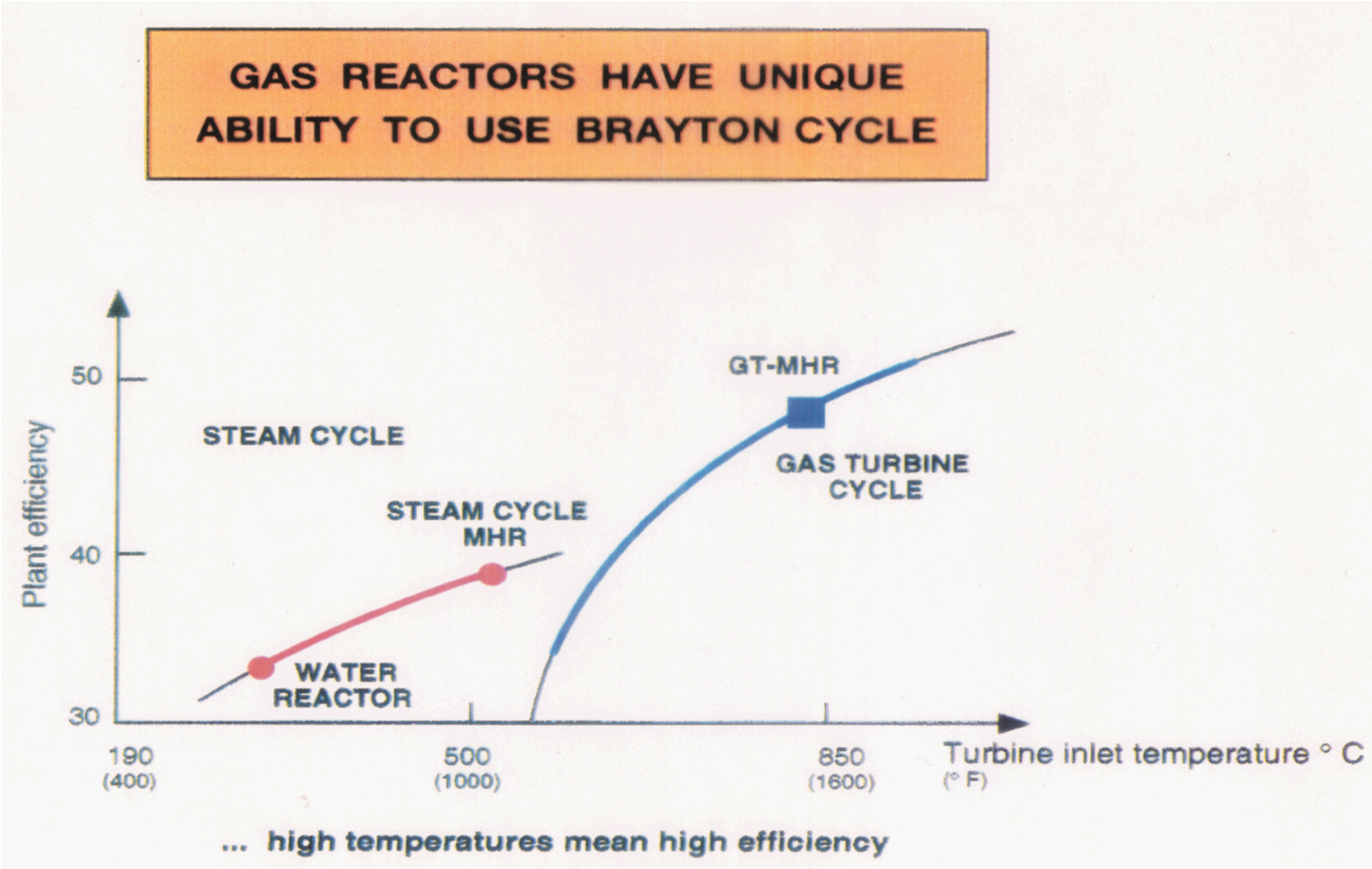

- ☞ Super-critical steam cycle improves the thermal efficiency of the steam cycle, but increases the impact of a water ingress

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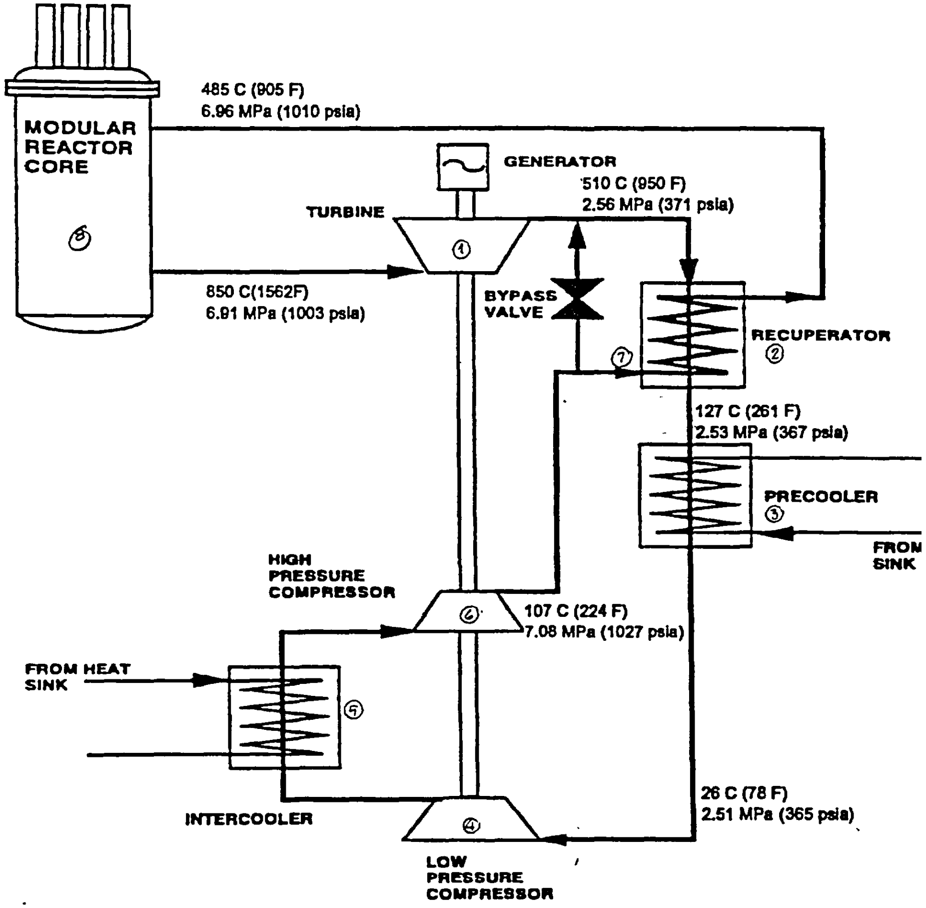
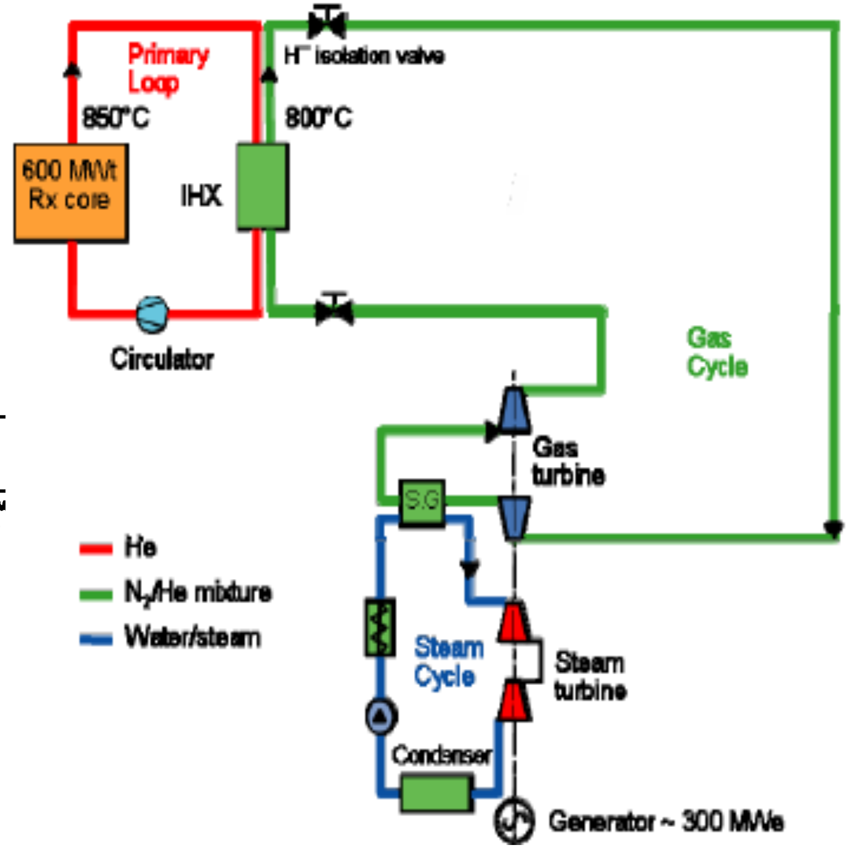
Gas cycle: direct or indirect? (1)

Main merit of gas cycle: no risk of massive air ingress



Direct recuperated Brayton cycle



Indirect combined cycle

Gas cycle: direct or indirect? (2)

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	Direct	Indirect
Integration of the power conversion system in the nuclear primary containment	Yes	No
Turbo-compressor	Specific for helium, use of magnetic bearings preferred	Industrially available components
Primary circulator	N.A.	He circulator to be developed, preferably with magnetic bearings
Heat exchanger	Recuperator	Intermediate heat exchanger (IHX)
	Plate technologies are preferred (compactness)	
	Must resist to high pressure differences	Must resist to high temperature gradients
Electricity generation	Higher efficiency due to higher temperature (~ 50˚C))?	Possibility of optimising the efficiency by added bottom steam cycle (combined cyle)
Heat applications	Limited	Extended

Direct cycle: integration of the power conversion system in the primary containment

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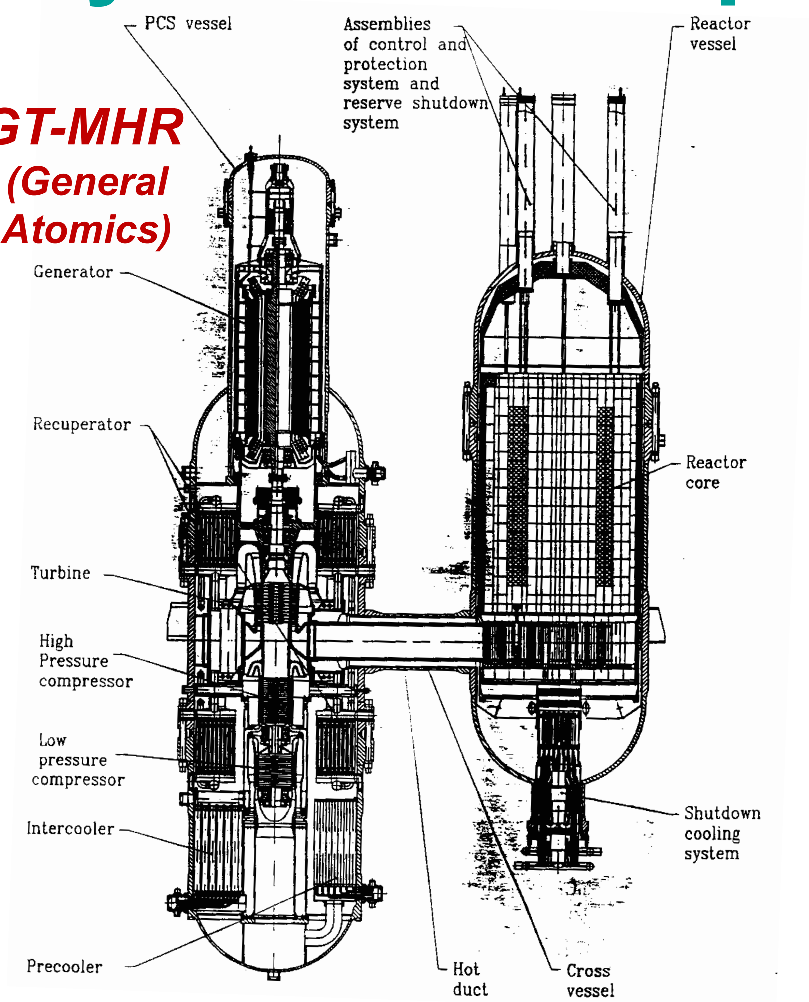
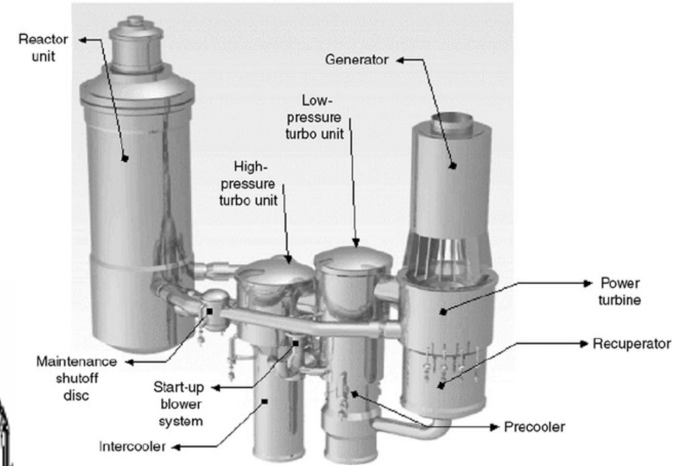
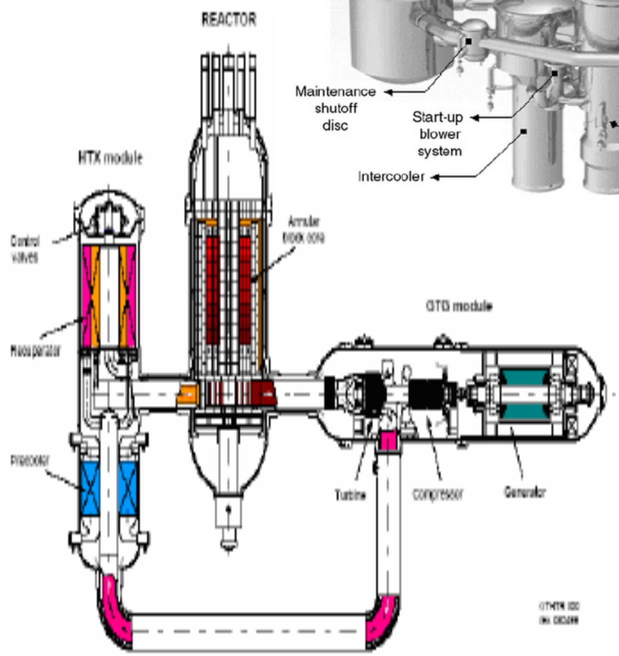
GT-MHR
(General Atomics)



- Max. integration ⇒ max. compactness
- Vertical turbo-machine with magnetic bearings
- Easiness of maintenance?

PBMR
(South Africa)





GTHTR 300
(JAEA)

- Less integration ⇒ bigger reactor building
- Horizontal turbine
- Easier maintenance
- Justification of ducts

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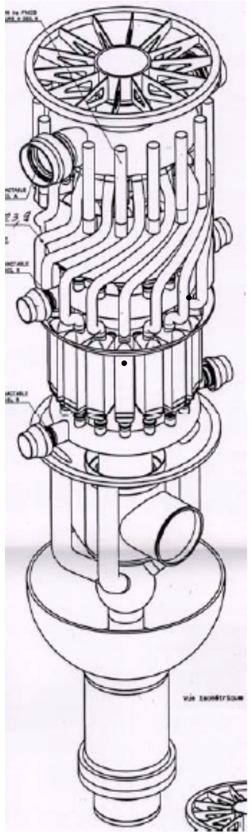
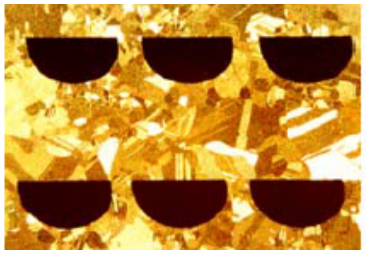
Heat exchangers for gas cycles

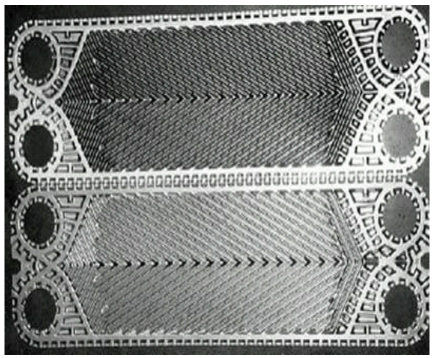
- Use of plate heat exchanger technologies to keep reasonable size of components
- Widely used in industry, but challenges for the specific application:
  - To nuclearize designs and manufacturing
  - Materials (800H, Ni based materials)
    - *Corrosion issues with He impurities*
    - *Solving fabrication problems (welding, forming…)*
  - Integration of many plate modules into a heat exchanger



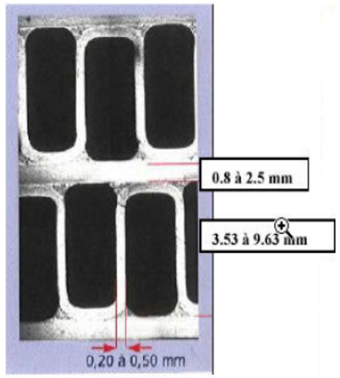
Integration of 38 plate-finned modules with He distribution into a 600 MW heat exchanger



Chemically etched, diffusion bonded plates



Stamped plates



Finned plates

Steam generator for steam cycle

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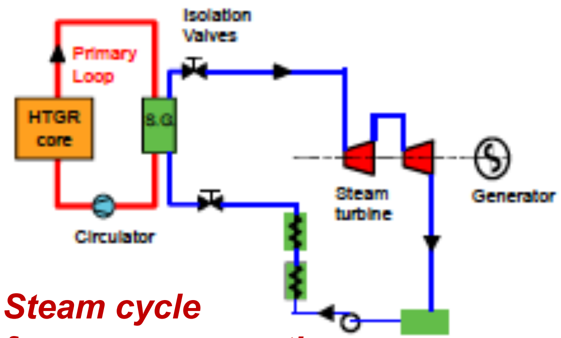
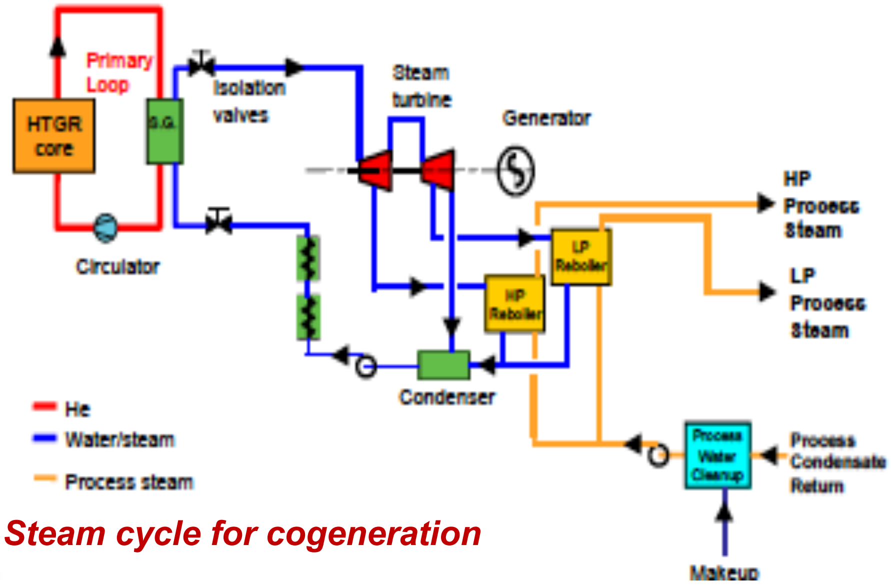
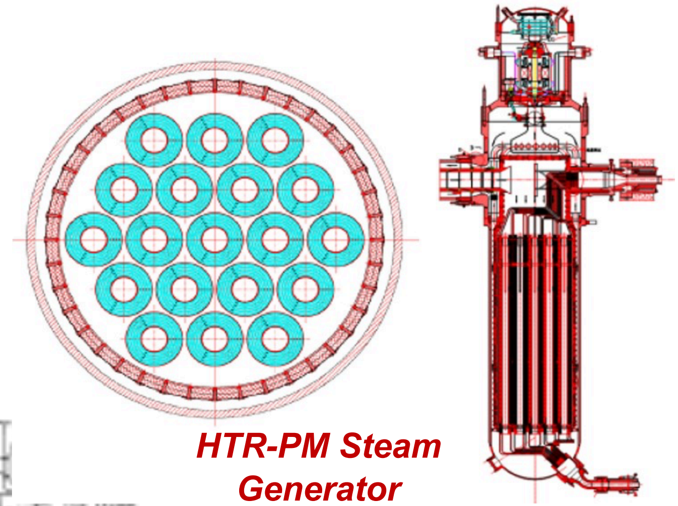


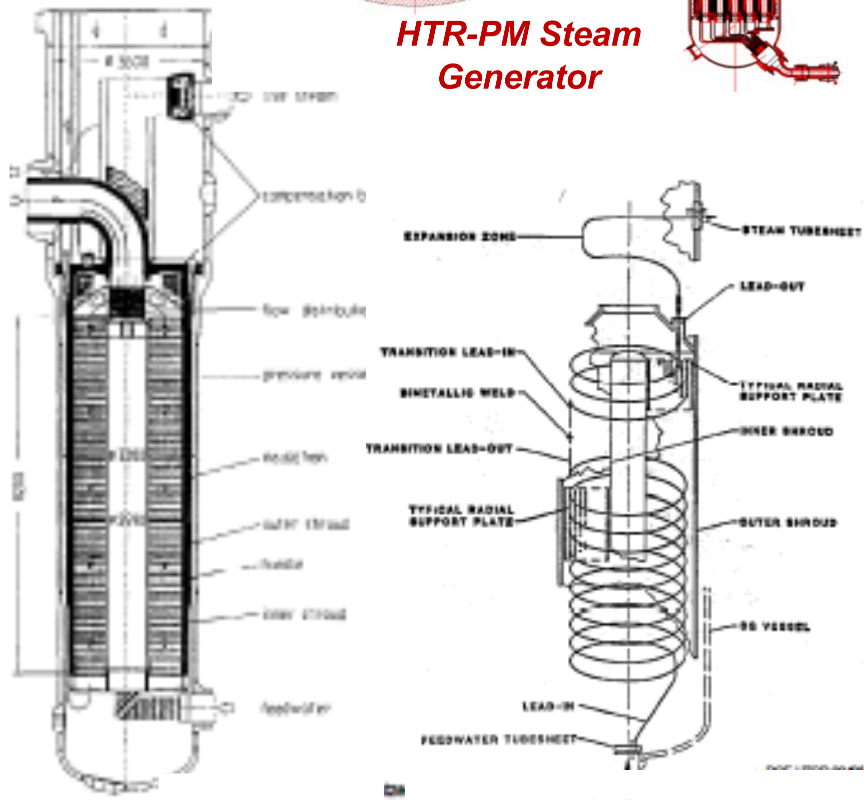
Steam cycle for power generation



Steam cycle for cogeneration



HTR-PM Steam Generator



Steam Generator (MHTGR-HTR-Modul)

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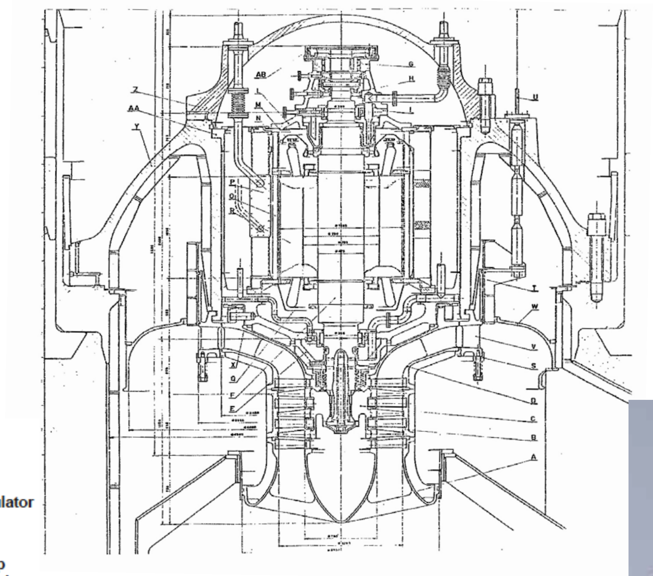
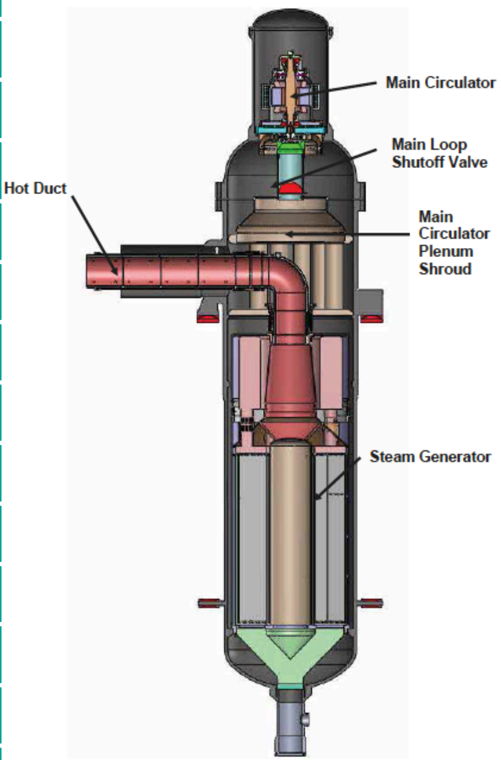
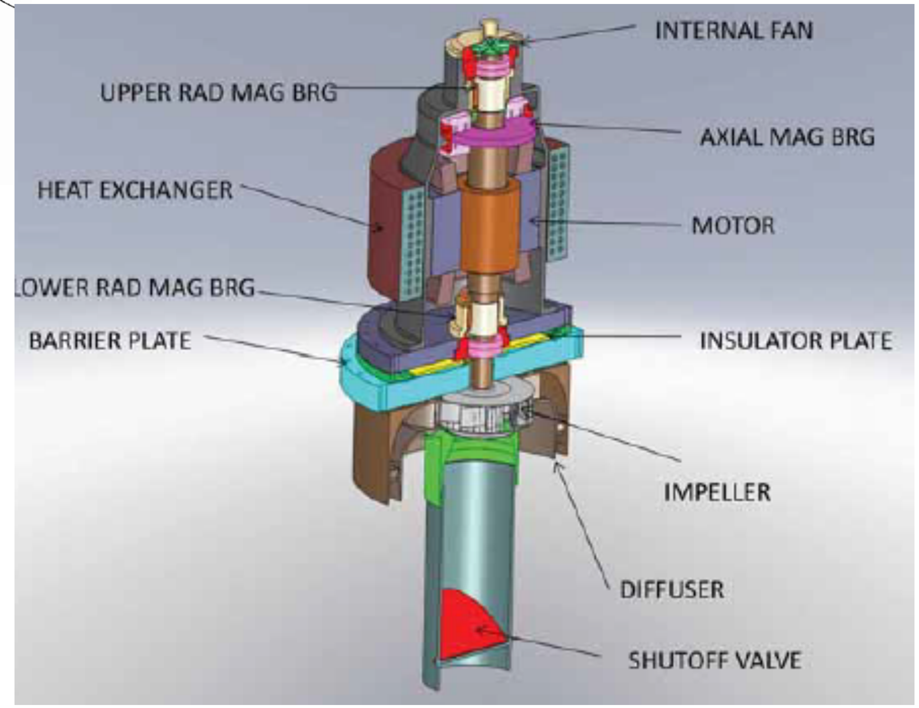
HTGR circulator for steam and indirect gas cycles





- Bearings (magnetic)
- Cooling of the motor and the bearings
- Thermal insulation



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Prospects for evolution: an example, the MMR™

A new approach for simplified micro-modular HTGR: the MMR™

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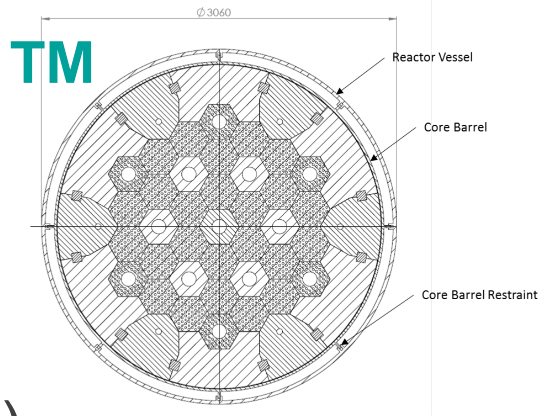


- Very low power: 15 MWth
- Prismatic core

⇒With very low power density (1,24 MW/m³), still transportable by road (vessel ø ~ 3 m)

- ⇒ Sufficient fuel for a core lifetime of 20 years
- ⇒ Very large margins in accident (no heat-up of the fuel)

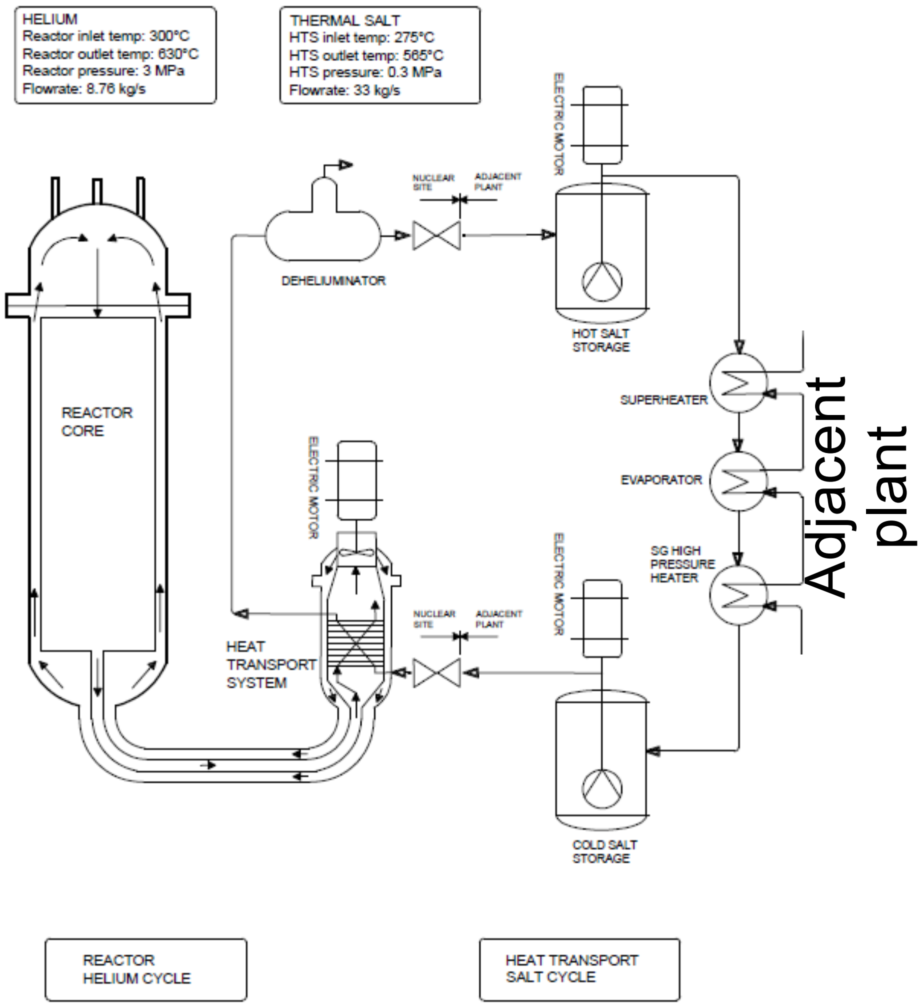
✚ Very safe innovative fuel: TRISO particles embedded in SiC matrix (Fully Ceramic Encapsulated (FCM™) fuel)

⇒Simplified design

- No refuelling
- No shutdown cooling system
- No need of redundancy of the control system
- No helium purification system
- Reduction of the number of safety classified components

A new approach for simplified micro-modular HTGR: the MMR™

- Secondary system: molten salt (current solar technology)
  - ⇒ Thermal storage: allows large load follow required off-grid, keeping the reactor at full power or only with slow transients
- Systematic use of modular construction techniques
  - ⇒ Minimises the site construction time



Canadian Nuclear Safety Commission

Canada

The Commission | Uranium | Reactors | Nuclear substances | Waste | Acts and regulations | Resources

Current pre-licensing vendor design reviews

The following table presents an overview of vendors who have applied for pre-licensing engagement with the CNSC using the vendor design review process for their new reactor designs. Vendor design review is described in guidance document GD-385, *Pre-licensing Review of a Vendor's Reactor Design*. The duration of each review is estimated based on the vendor's proposed schedule. A Phase 1 review typically takes 12–18 months and a Phase 2 review takes 24 months.

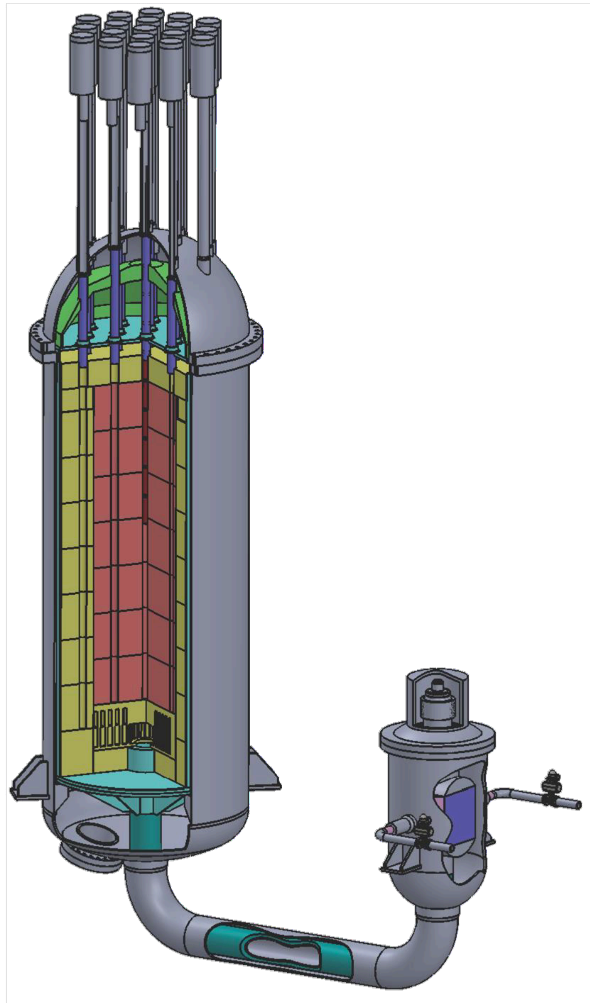
At the end of the review for each phase, an executive summary of the project report will be posted on this Web page.

Vendor	Name of design and cooling type	Approximate electrical capacity (MW electrical)	Applied for	Review start date	Status
Terrestrial Energy Inc.	IMSR Integral Molten Salt Reactor	200	Phase 1	April 2016	Phase 1 complete
			Phase 2	December 2018	Phase 2 assessment in progress
NuScale Power, LLC	NuScale Integral Pressurized Water Reactor	50	Phase 2*	April 1, 2019	Service agreement signed. Assessment pending
Ultra Safe Nuclear Corporation / Global First Power	MMR-5 and MMR-10 High Temperature Gas	5-10	Phase 1	December 2016	Phase 1 complete
			Phase 2	Pending	PHASE 2 Service Agreement in place – Project start pending
Westinghouse Electric Company, LLC	eVinci Micro Reactor Solid core and heat pipes	Various outputs up to 25 MWe	Phase 2*	Pending early 2019	Service agreement under development
LeadCold Nuclear Inc.	SEALER Molten Lead	3	Phase 1	January 2017	Phase 1 on hold at vendor's request
Advanced Reactor Concepts Ltd.	ARC-100 Liquid Sodium	100	Phase 1	Fall 2017	Assessment in progress
URENCO	U-Battery High-Temperature Gas	4	Phase 1	To be determined	Service agreement under development
Moltex Energy	Moltex Energy Stable Salt Reactor Molten Salt	300	Series Phase 1 and 2	December 2017	Phase 1 assessment in progress
SMR, LLC. (A Holtec International Company)	SMR-160 Pressurized Light Water	160	Phase 1	July 2018	Assessment in progress
StarCore Nuclear	StarCore Module High-Temperature Gas	10	Series Phase 1 and 2	To be determined	Service agreement under development

A new approach for simplified micro-modular HTGR: the MMR™

NC2I
Nuclear Cogeneration Industrial Initiative

- Towards a prototype:
  - CNL intends to provide sites for demonstration prototypes of SMRs, with a 3 steps process for qualifying vendors for getting a site
  - USNC has already gone through the first two steps



NC2I
Nuclear Cogeneration Industrial Initiative

Summary

SNETP
Sustainable Nuclear Energy Technology Platform
www.snetp.eu

Summary

- Prismatic cores require more reactivity at start of cycle than pebble bed reactors, but they allow
  - Tailored fuel management to compensate the reactivity and reduce power peaks
  - Annular cores that give additional margins for higher power, still keeping the safety approach of modular HTGR based on inherent physical properties of the reactor and use of passive system.
- Different thermodynamic cycles are possible depending on the temperature, with
  - Different thermal efficiencies (always higher than in LWR),
  - Different impacts on the safety design
  - Same application potential for prismatic and pebble bed cores
- There is still a large potential for evolution of modular HTGR