www.nc2i.eu

NC2I
Nuclear Cogeneration Industrial Initiative

History of HTGR

Dominique Hittner

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

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- The new generation: modular HTGR
- Summary and conclusion

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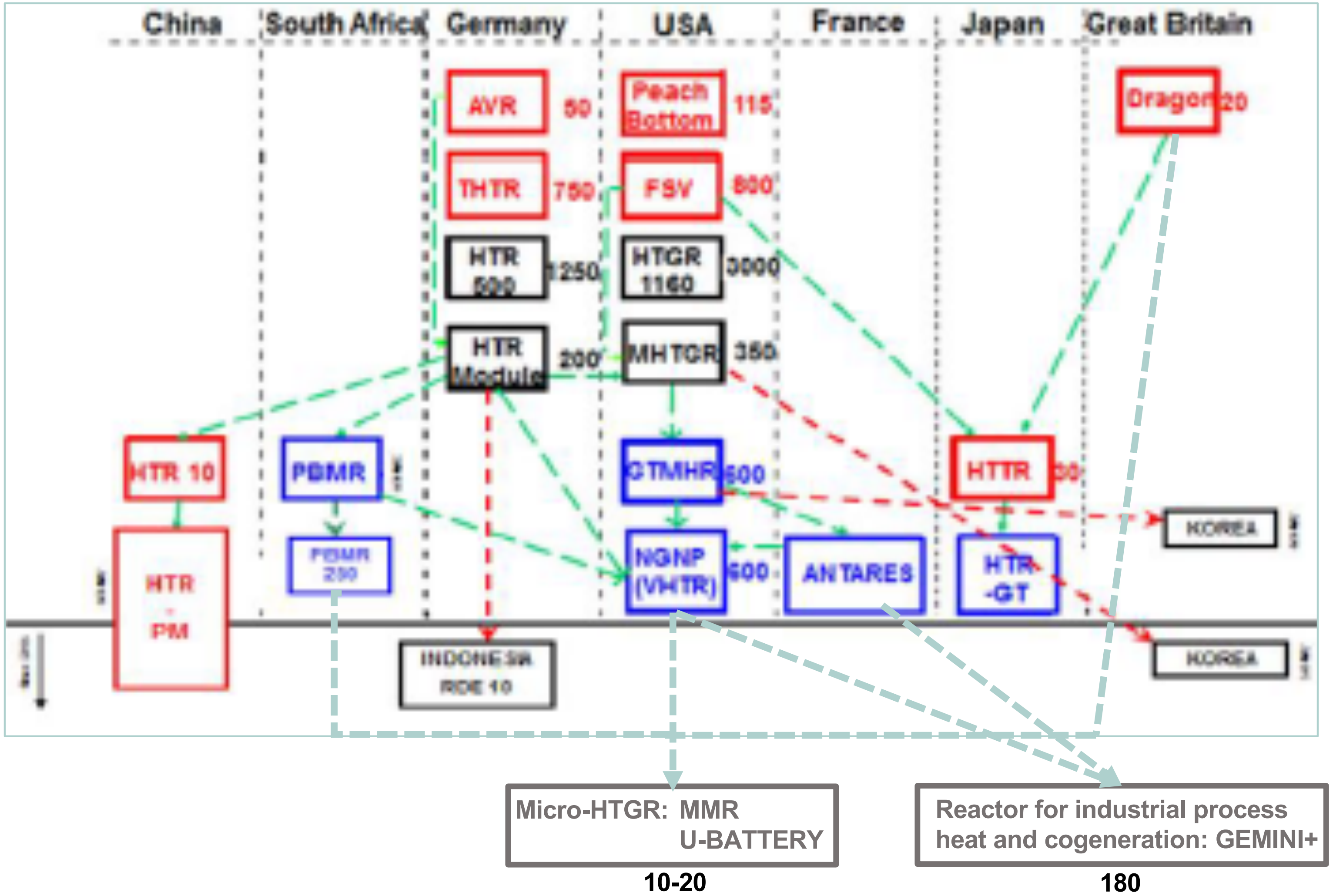
HTGR

- High Temperature
- Helium cooled
- Graphite moderated

HTGR Family Tree



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Prehistory

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“Birth of the Atomic Age“

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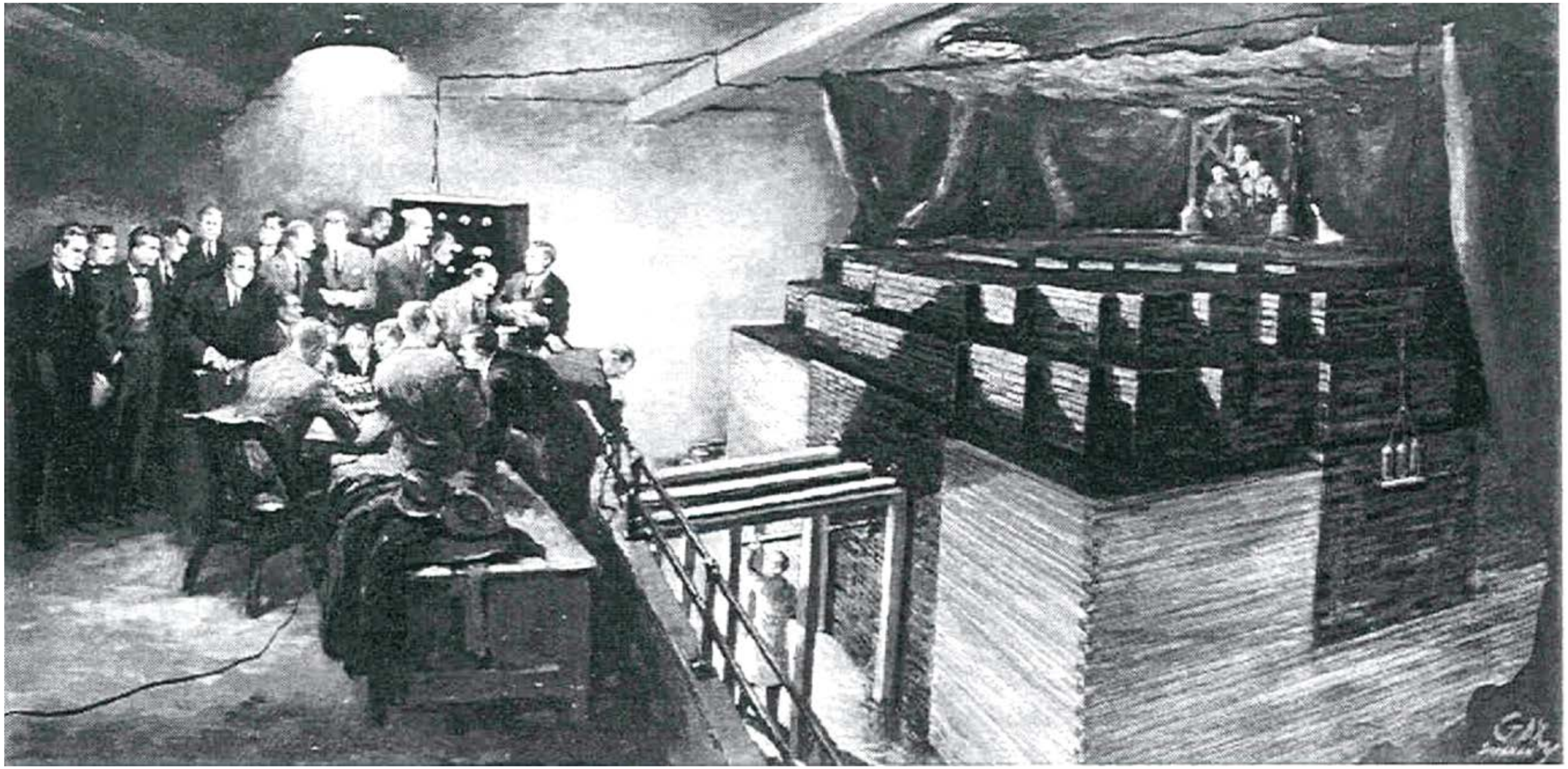

Painting by Gary Sheahan

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The Milestones of GCR History

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1942	First Self-sustained Chain Reaction (E. Fermi)
1943	3,5 MW Graphite-moderated Production Reactor (ORNL)
1947	Graphite-moderated GCR at Brookhaven
1947-90	Graphite Low-Energy Exp. Pile (UK): first Reactor in Europe
1948	36 MW_{th} British Experimental Pile Operation (BEPO)
1950	160 MW_{th} Windscale Plutonium Production Reactors
1951-53	UK studies on CO_2-cooled MAGNOX Reactors
1956-59	Commissioning of four Calder-Hall Reactors (240 MW_{el} total)
1956-68	Air-cooled 1,7 MW_{el} G-1 at Marcoule, France
1957	First Commercial GCR in France: 70 MW_{el} Chinon A1
1963	30 MW_{el} Advanced GCR (AGR) in Windscale (400°C → 600˚C)
1976	First Commercial AGR at Hinkley Point B (625 MW_{el} / 41,5 %)

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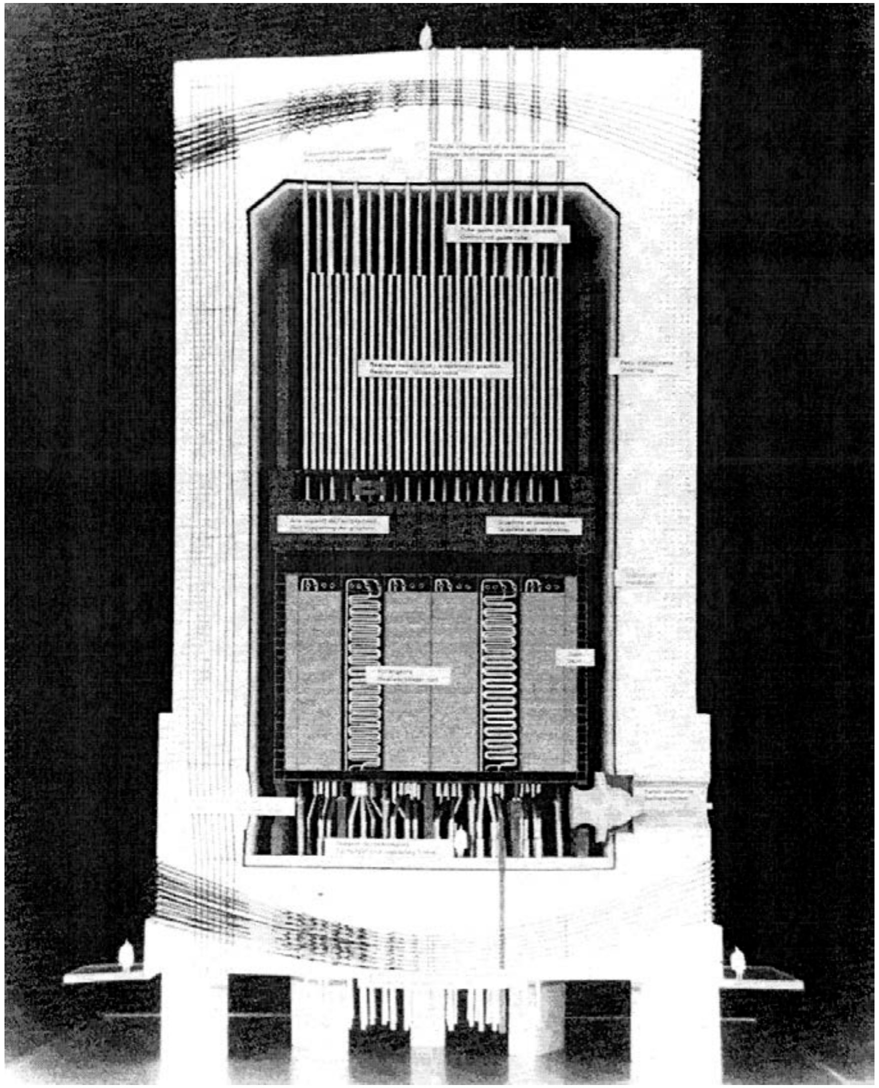
Commercial GCR

- Graphite moderated
- CO_2 closed cycle inside the concrete reactor vessel limiting temperature (corrosion)
- Steam generators inside the reactor vessel
- Conventional steam conditions (~ 540˚C)
- High thermal efficiency (> 40%)



EDF Saint Laurent reactor

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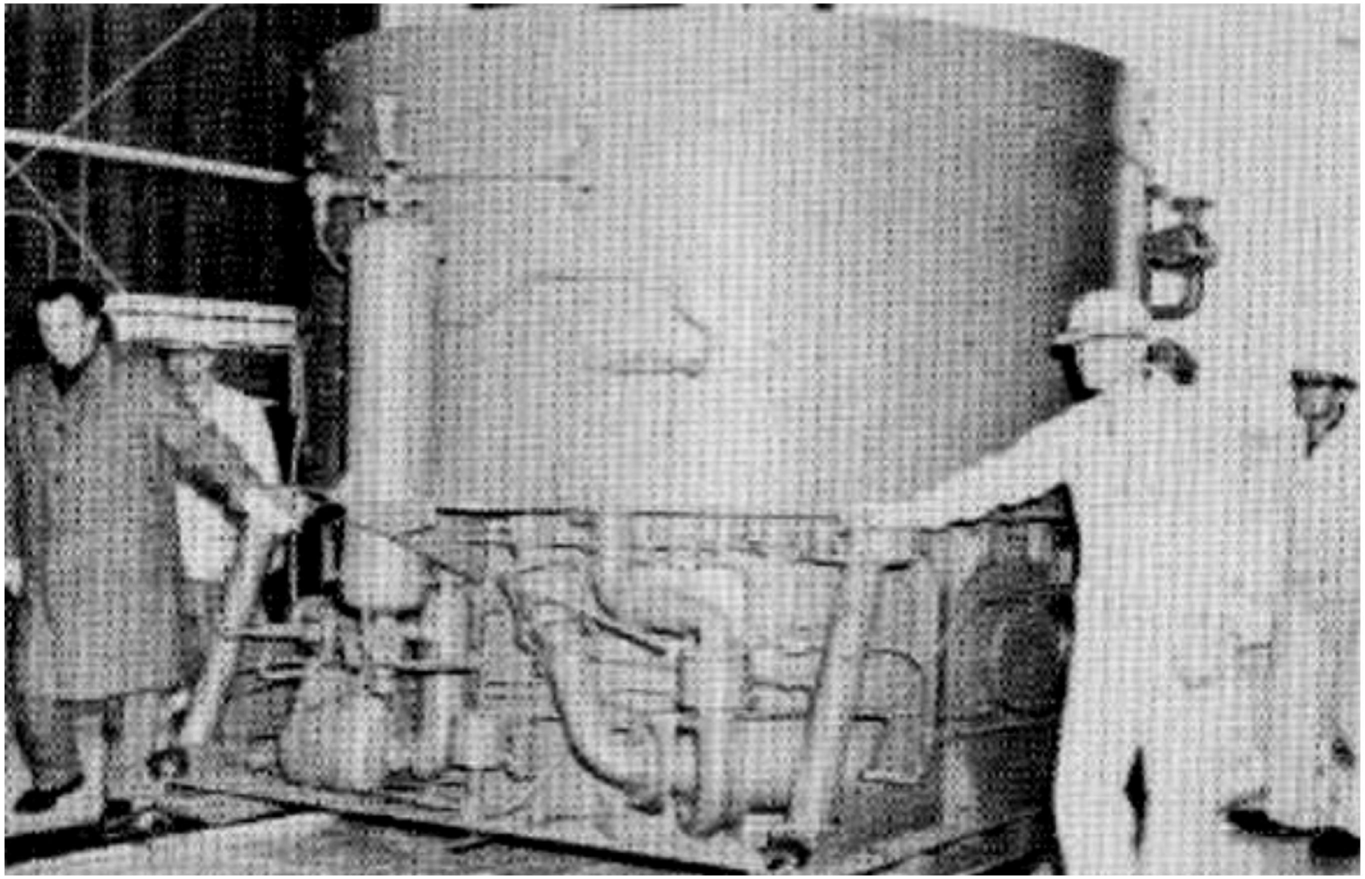
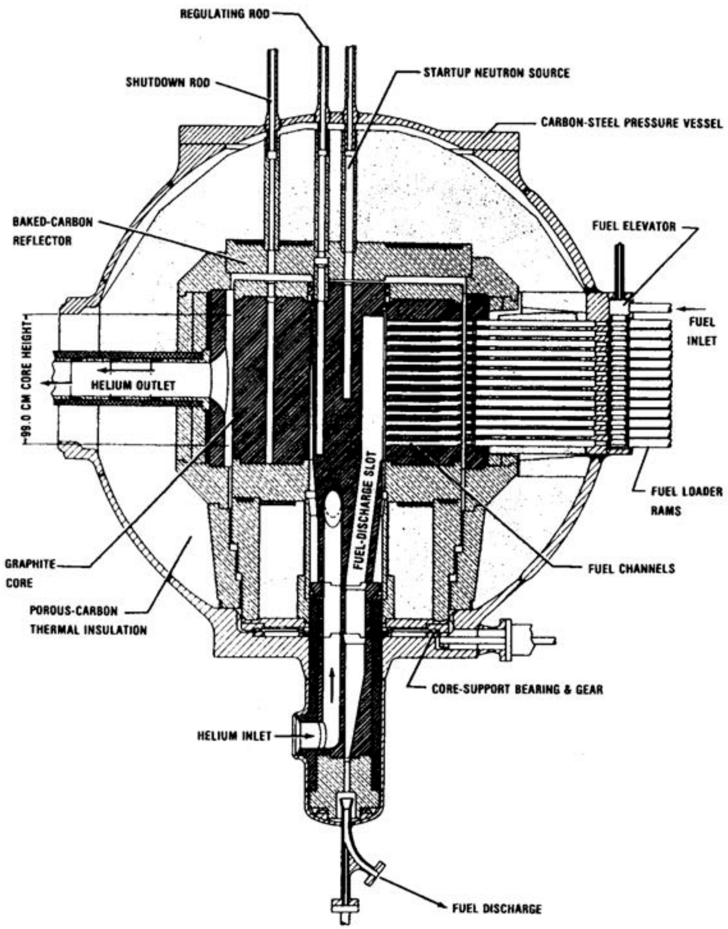
Some Exotic Reactors (1)



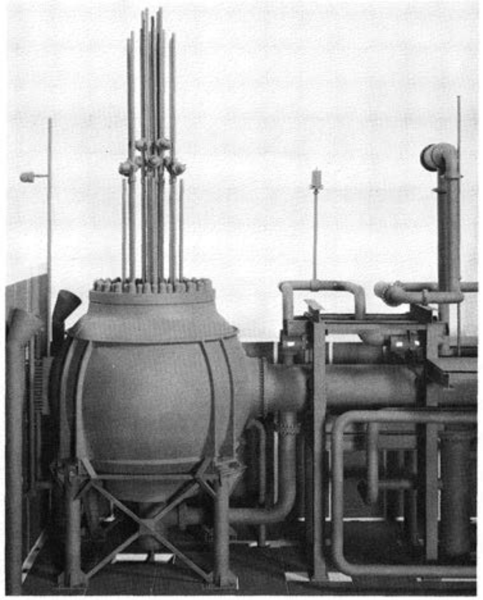
3,3 MWth Mobile Low-Power Reactor (ML1), with closed cycle gas turbine – US army, 330 kWe (1962-63)

Some Exotic Reactors (2)



Ultra-High-Temperature Reactor Experience (UHTREX) – ORNL

https://www.osti.gov/servlets/purl/4375338



Thermal Power:	**3 MW**
Helium Coolant:	**3,4 MPa**
Temperature $_{in}$:	**870° C**
Temperature $_{out}$:	**1300° C**

Extruded Fuel with TRISO C.P.

Annular Rotatable Core

On-line Refuelling

Operation: 1966-70

HTGR Birth

The Invention of HTGR Design

- Mid 1950s: Initial Studies on HTR in UK, US and Germany
- 1960s: Construction & Operation of Prototypes

Common features

- Fully Ceramic Core
- Non-Corrosive & Neutronically Inert Helium Coolant
- High Operating Temperatures
- High-Purity Graphite as Moderator and Reflector
- Slow Accident Progression (heat capacity, low power density)
- Self Stabilisation of Nuclear transients (negative temperature coefficient)

The Invention of the Coated Particle Fuel

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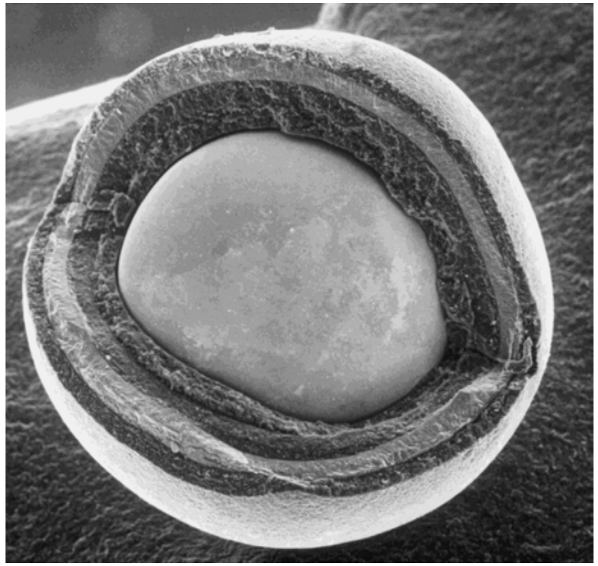

- First UO_2 or UC in ceramic clad: weak fission product (FP) retention
- Invention of Coated Particle in 1957-61 by UKAEA and Battelle
- Kernels made by precipitation from uranyl nitrate in ammonia
- Coatings via pyrolysis of hydro-carbons in fluidized-bed
- Early BISO particles contain buffer & two PyC layers
- TRISO have additional SiC diffusion barrier: FP retention till 1600°C
- Fuel elements → Compacts → Blocks → Prismatic core; Fuel elements → Pebbles → Pebble bed

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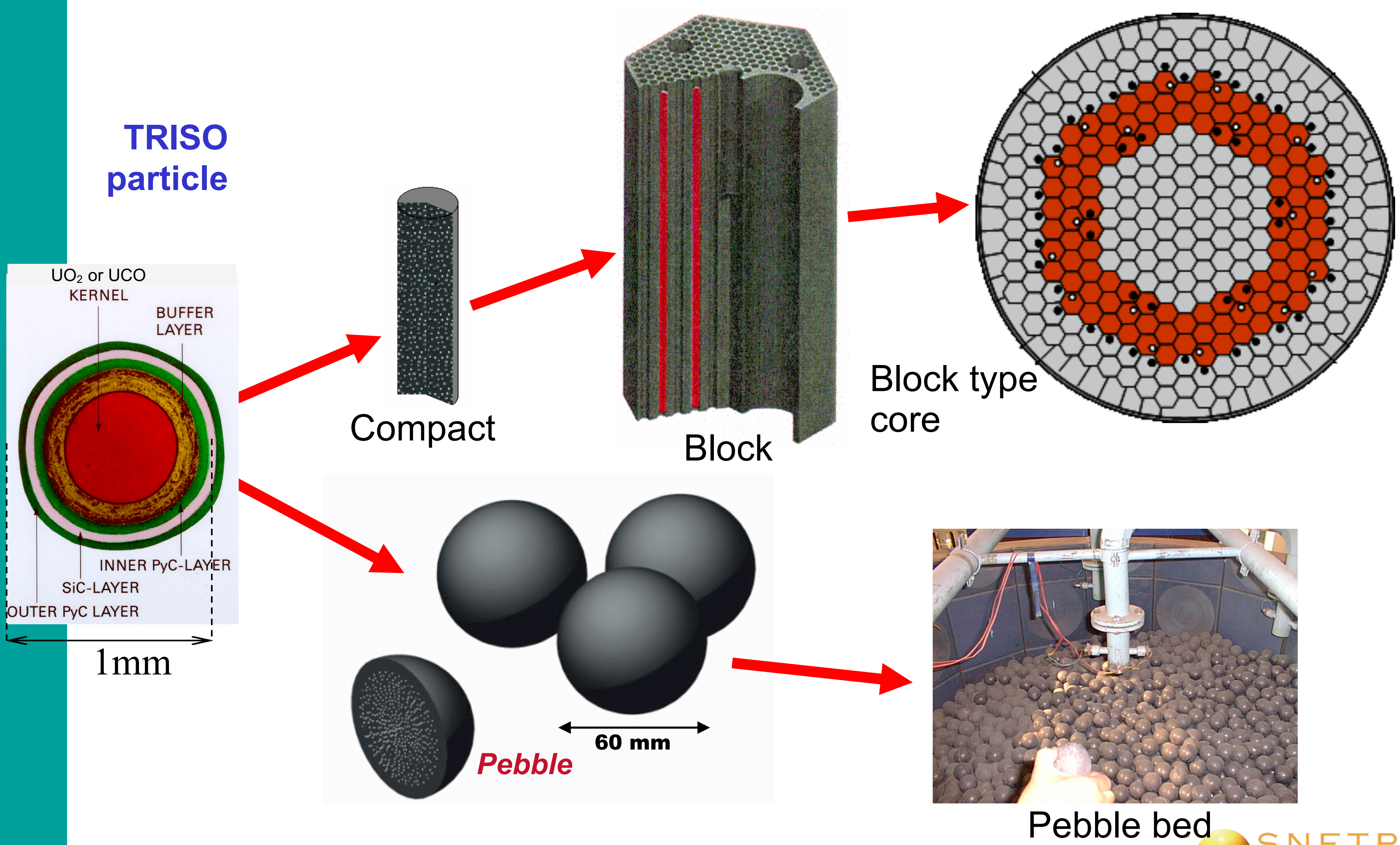
Two Types of HTGR Fuel Assemblies and Cores



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First HTGR deployment

Main Features of HTGR Reactors Being Operated

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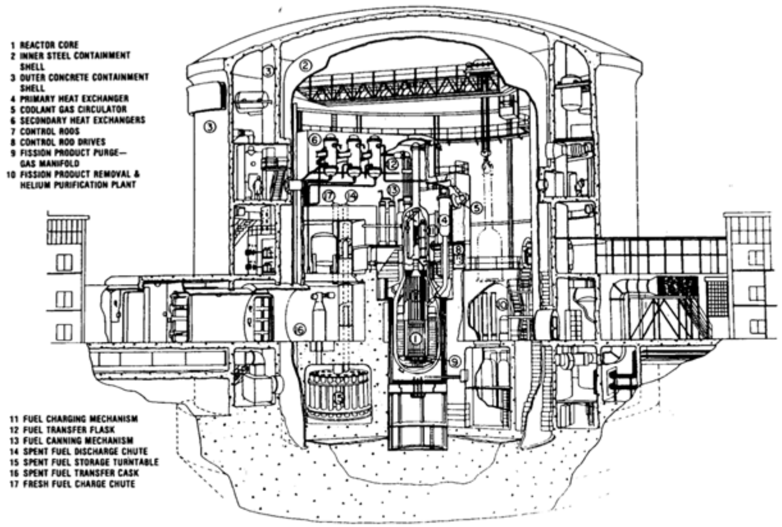
Feature	Unit	DRAGON	Peach Bottom	FSV	AVR	THTR
Power (th)	MW	20	115	842	46	750
Power (el)	MW	no conversion	40	330	15	296
P.-Density	MW/m^3	14	8.3	6.3	2.6	6
Temperature	°C Inlet	350	344	406	275	250
	°C Outlet	750	728	785	950	750
	°C Fuel		1330	1260	1350	
Pressure	bar	20.6	25	49	11	39
RPV Type		Steel	Steel	PCRV	Steel (double)	PCRV
Efficiency	%	no conversion	35	39	32.6	39
Fuel Type	design	block	fuel rods	block	pebble	pebble
c.p.-type	Layers	BISO/TRISO	BISO	TRISO	BISO/TRISO	BISO
Enrichment	HEU/LEU	HEU	HEU (Pu)	HEU & Th fertile	HEU / LEU	HEU & Th fertile
Fuel Composition		$(U/Th)C_2$ &UZrC	HEU / Th	$(U/Th)C_2$	all types	$(U/Th)O_2$
Burn-Up (max)	GWd/t		60	100	150	< 100
Core Height	m	1.6	2.29	4.75	3.0	6.0
Diameter	m	1.07	2.77	5.97	2.8	5.6
Construction	y Start	1960	1962	1968	1960	1971
Operation	y Start	1964	1966	1977	1966	1985
	y End	1976	1974	1989	1988	1989
Status		safe enclosure	safe enclosure	decommissioned	defuelled	safe enclosure

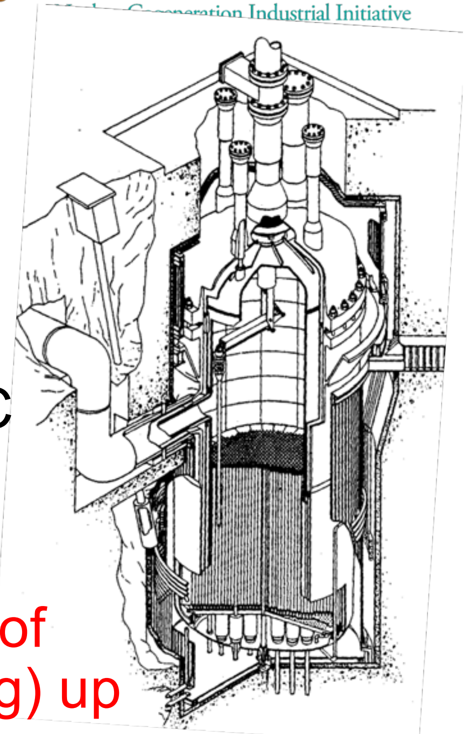
Operating experience (1)

DRAGON test reactor

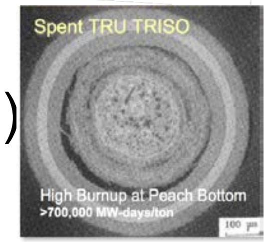


- OECD project in UK
- Good operation during 10 years, but corrosion issues
- Successful demonstration of core heat-up accident (80 days at 1800°C) $\Rightarrow$ slow fission product release up to 10^{-2}

Peach Bottom prototype, US, 40 MWe



- U/Th fuel in PyC shell, compacts in 12ft sleeves
- Successful test of Pu-burning (17 g) up to very high Bu



- Availability: 58 (Core 1) - 88% (Core 2)
- Load following demonstrated
- 90 Fuel elements cracked in Core 1, but BISO coated fuel particles exceeded expectations (Core 2)

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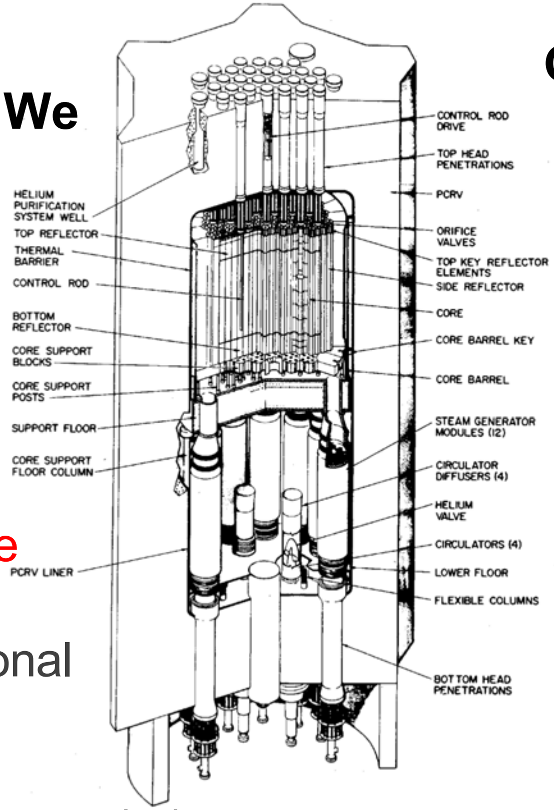
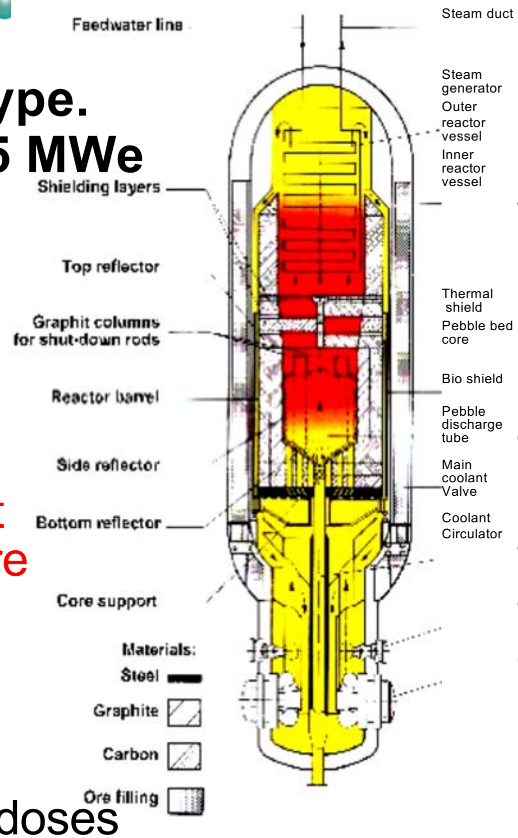
Operating experience (2)

Fort Saint Vrain prototype, 330 MWe



- Demonstrated TRISO fuel and nuclear physics of block-type core
- Very low collective dose <1 man-rem
- Forgiving operational behaviour
- Main issues
  - Water cooling pump cavitation ⇒ one year delay
  - He circulator and seals leaked bearing water ⇒ many delays
  - Reserve shutdown malfunction
  - Hot helium bypass and corrosion on control rod drives
  - Core fluctuations ⇒ 70% power
  - Core support floor liner cooling system leakage
- FSV totally decommissioned in 1997

AVR prototype. Germany, 15 MWe



- High availability over 21 years of operation to 1988
- Core outlet temperature increased 850˚C to 950˚C
- Very low personnel doses
- Mass test of HTR fuel
- High Burn-up ~ 20% fima
- Safety demonstrated via passive core cooling
- Survived water ingress accident
- Ceramic structures OK except bottom reflector cracks
- Decommissioning experience

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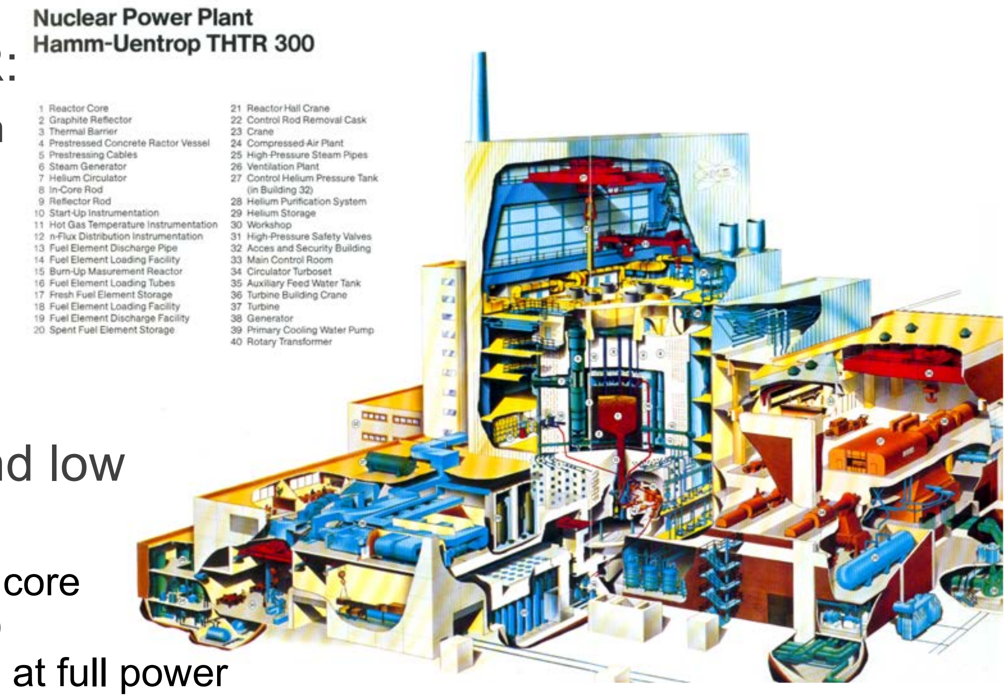
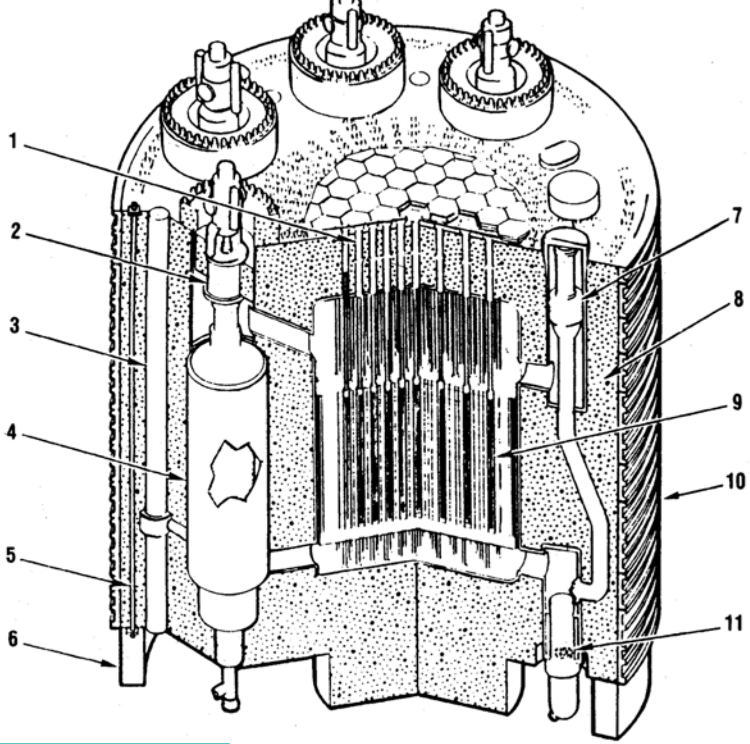
Operating experience (2)

- Commercial project although significant deviations from AVR:
  - inverse helium flow top-to-bottom
  - higher power density. 2 MW/m^3 $\Rightarrow$ 6 MW/m^3
  - 42 absorber rods directly driven into the core
  - Pre-stressed Concrete Reactor Pressure Vessel (PCRV)



- Good operational behaviour and low activity in primary circuit, but
  - cracking of pebbles due to many core rod insertions (~ 8000 of 675 000)
  - malfunction of on-load de-fuelling at full power
  - irradiation-induced failure of bolts in hot-gas duct insulation
- Fatal coincidence with Tschernobyl accident and “Transnuclear Scandal”
- Shut-down in Sept. 1989 after 16.410 h operation; availability 61,7 % in 1987
- Fuel Burn-up ~ 100 GWd/t, Reactor now in safe enclosure

Designs of Large block type HTGR in the US



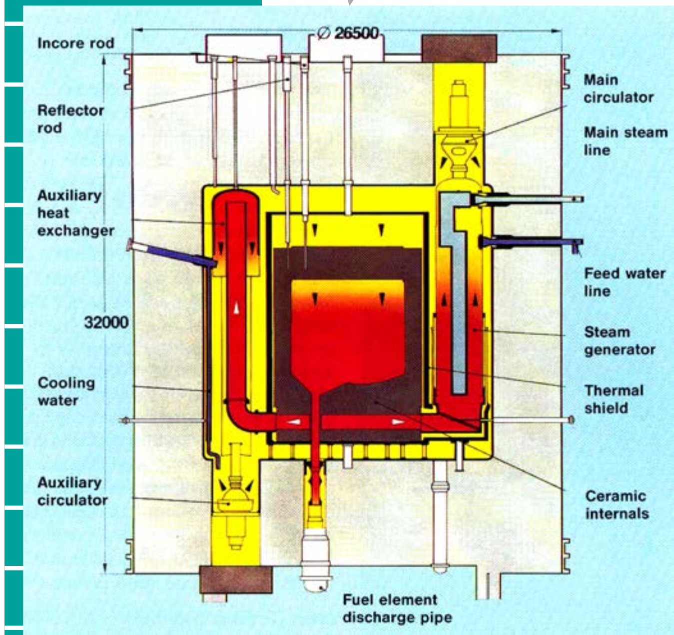
1 Control rod drive &refueling penetrations
2 Circulator
3 Feedwater access shaft
4 Steam generator
5 Liner prestressing system
6 PCRV (pod boiler)
7 Auxiliary circulator
8 PCRV
9 Core
10 Circumferential prestressing system
11 Core auxiliary heat exchanger

1160 MWe

Feature	Unit	Peach Bottom	FSV	770 MW	1160 MW	1540 MW
Power (th)	MW	115	842	2000	3000	4000
Power (el)	MW	40	330	770	1160	1540
P.-Density	MW/m 3	8.3	6.3	~ 8	8,4	~ 8
Temperature	°C Inlet	344	406	318	318	318
	°C Outlet	728	785	741	741	741
Pressure	bar	25	49	50	50	50
RPV Type		Steel	PCRV	PCRV	PCRV	PCRV
Efficiency	%	35	39	39	39	39
Fuel Type	design	fuel rods	block	block	block	block
Plant life	y	Prototype	30	40	40	40
Fuel/Colums.	Numbe r	804	1482/ 247	2744 / 343	3944 / 493	5384 / 673
Fuel Composition		HEU / Th	$(U/Th)C_2$	$(U/Th)C_2$	$(U/Th)C_2$	$(U/Th)C_2$
Core Height	m	2.29	4.75	6.34	6.34	6.34
Diameter	m	2.77	5.97	7.05	8.45	9.88

Designs of Large block type HTGR in Germany

ACRONYM	Application	Cycle	Core	Power MW	Country
HTR 1160	EL	SC	HB	700-1540 (el)	US, GB, D, F
HTR-K	EL	SC	PB-OTTO	1120 (el)	D
HHT	CHP	DC	HB & PB	1000-1240 (el)	D, US, CH
HHT-Demo	CHP	DC	PB-OTTO	670 (el)	D, CH
HTR-500	EL & CHP	SC	PB-OTTO	550 (el)	D, CH
PNP	NHP	IHX, SR	PB-OTTO	3000 (th)	D
PNP-Demo	NHP	IHX, SR	PB	500 (th)	D
HTR-Modul	CHP	SC	PB-MEDUL	200 (th)	D
HTR-100	CHP	SC	PB-MEDUL	250 (th)	D
VGR	CHP	SC	PB	140 (th) / 50 (el)	CIS
GHR-10	DH	IHX	PB-Batch	10-20 (th)	D, CH



HB: Hexagonal Block

PB: Pebble Bed

OTTO: Once-through-then-Out

MEDUL: Multiple-Recycling of pebbles

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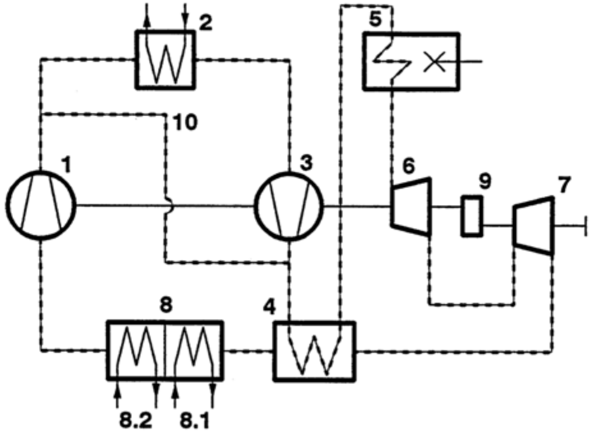
Transition to a new generation of HTGR: new features

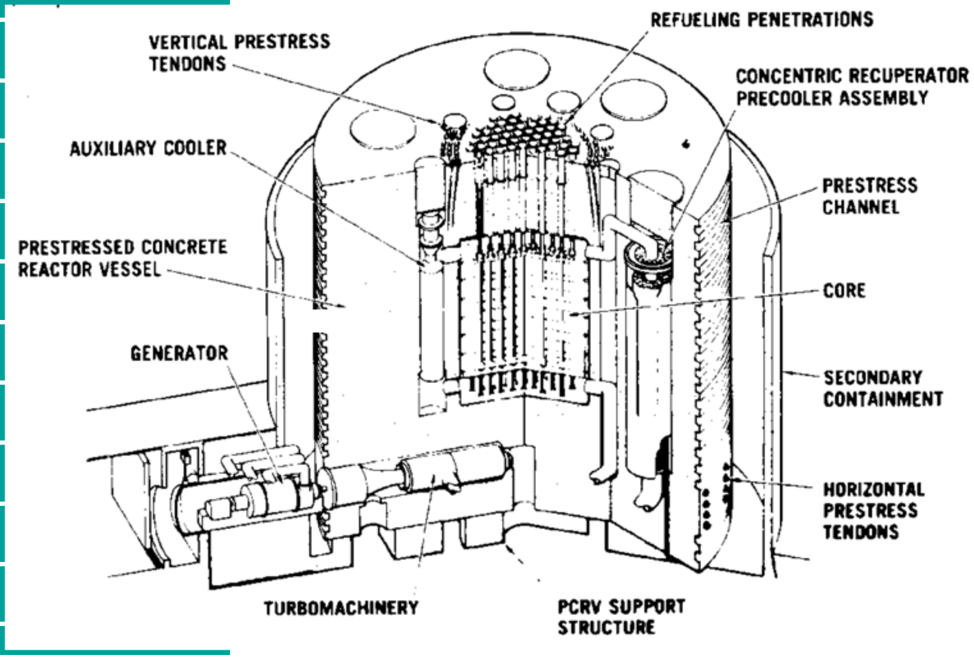
1. Direct helium cycle

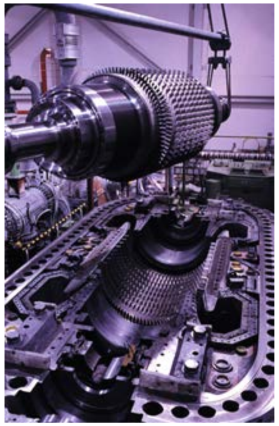


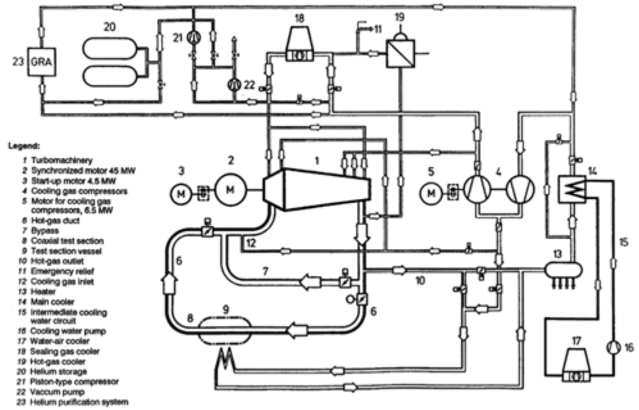
1. LP Compressor
2. Intercooler
3. HP Compressor
4. Recuperator
5. Heater
6. HP Turbine
7. LP Turbine
8. Pre-Cooler
8.1 District Heat Removal
9. Gear

EVO simulation of direct cycle plant for cogeneration of district heat and electricity

- 159,6 MW thermal
- Gas-fired heater
- 30 MWel Output
- District Heat
- 750°C / 27 bars

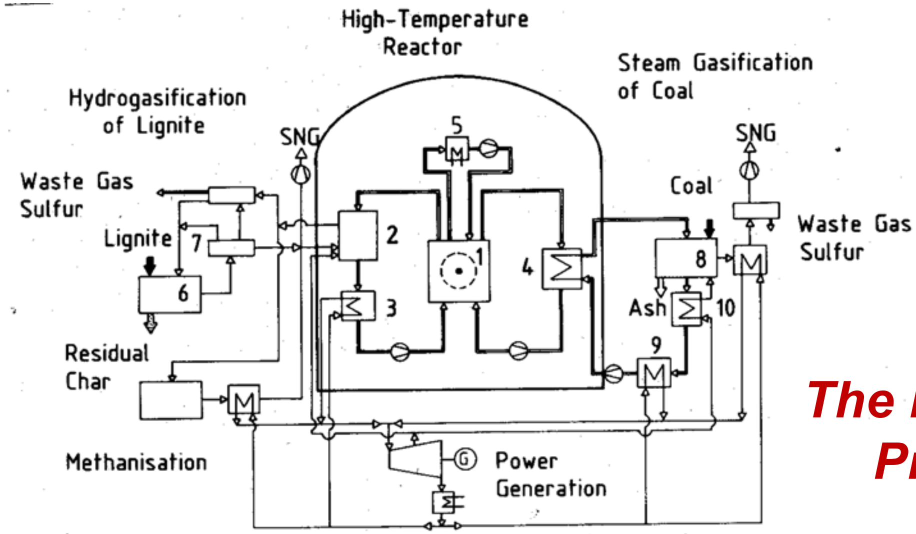






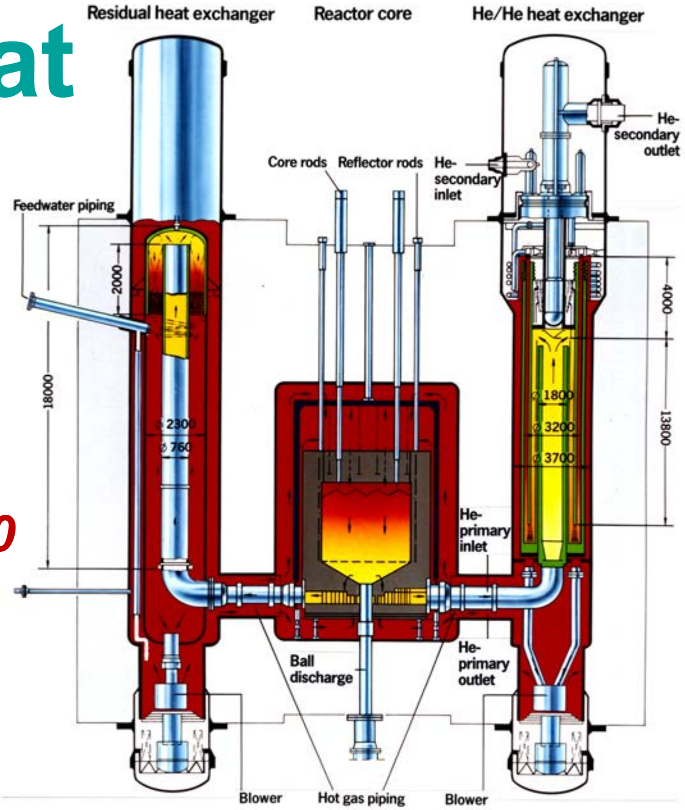
Helium High Temperature Test Facility (HHV) at FZJ

2. Application to Industrial Process Heat



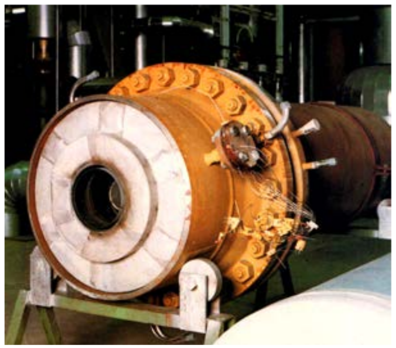
1. reactor
2. steam reformer
3. steam generator
4. intermediate heat exchanger
5. after heat removal
6. gasifier
7. gas separation
8. gasifier
9. steam generator
10. process steam superheater

The PNP-500 Project



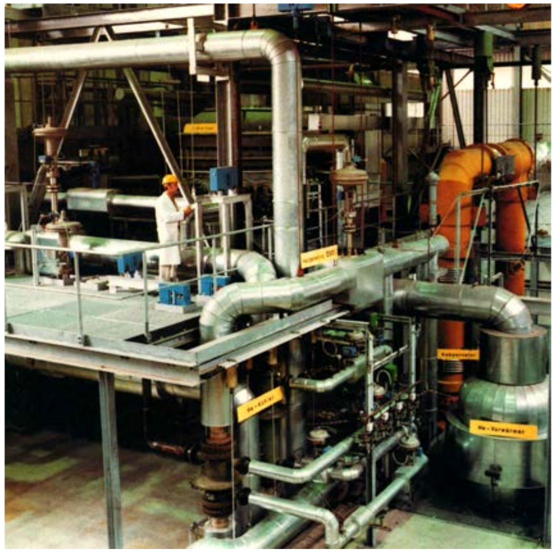
Steam Methane Reformer Bundle

IHX header



Hot gas valve

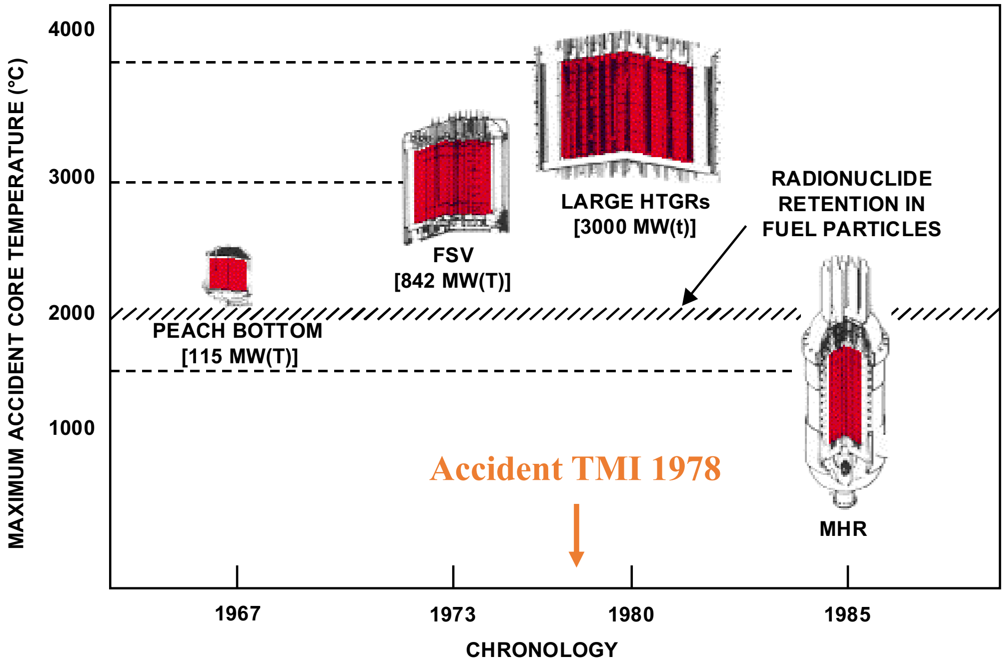
KVK Loop



The new generation: modular HTGR

A safety issue
and a new technical solution

- A problem: the maximum possible temperature of HTGR in case of severe accident increases with the power. How to keep it below the limit of integrity of the fuel?



- A solution:
  - A fuel that keeps its integrity up to high temperature: the TRISO fuel
  - A design that physically prevents the temperature to exceed the fuel integrity limit:
    - *Limited power (< ~ 250 MWth for pebble bed and 600 MWth for block type core)*
    - *A metallic vessel to release heat by radiative heat transfer*

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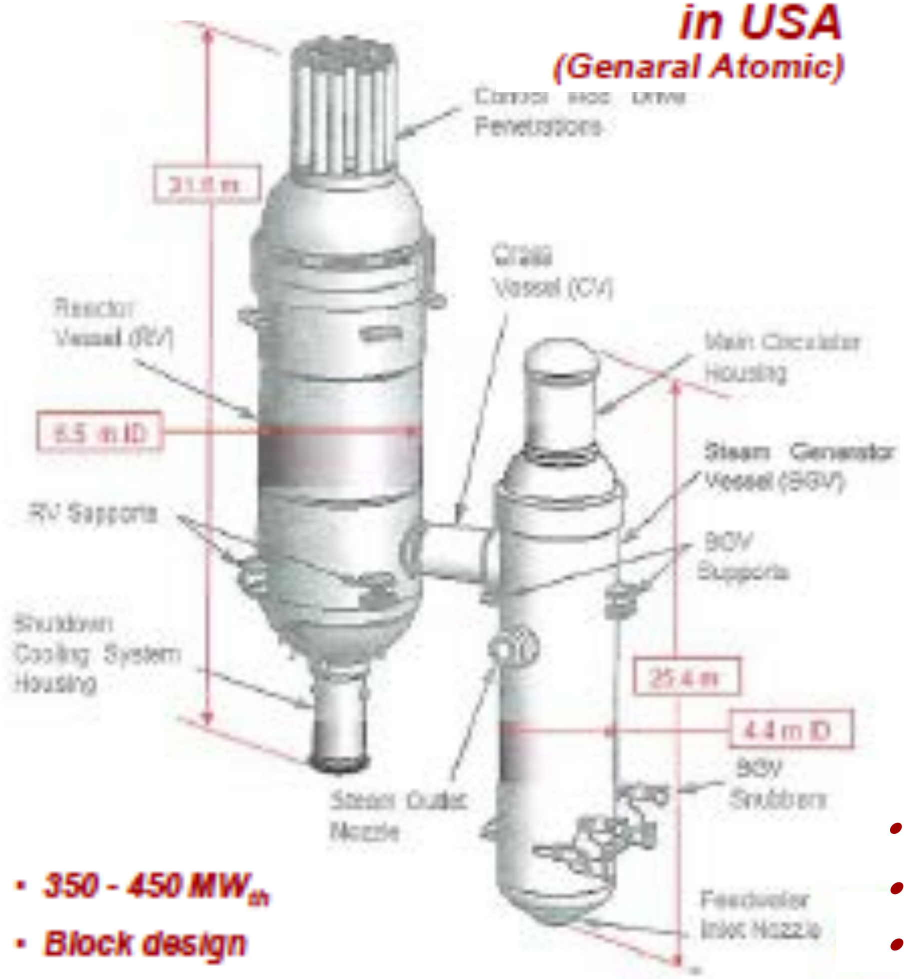
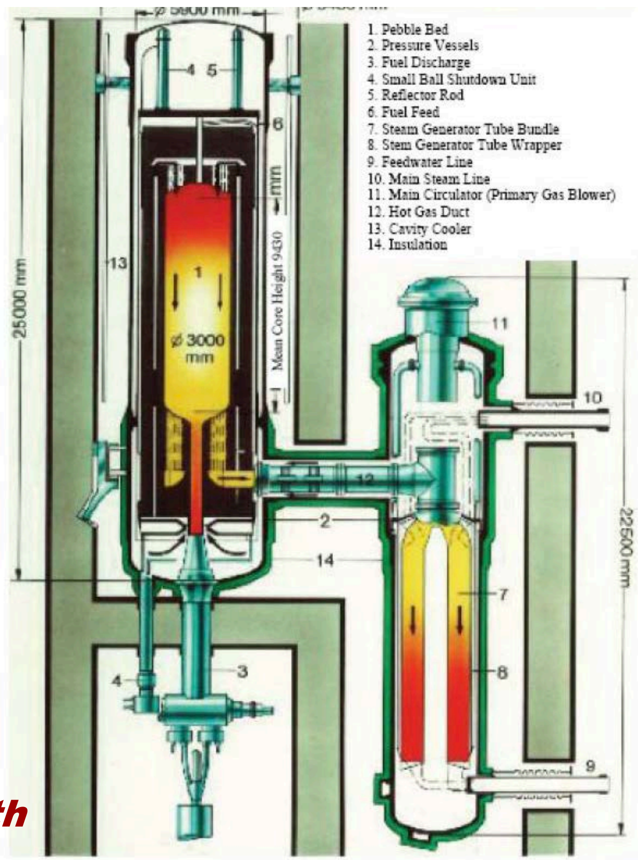
The first commercial designs in the 1980s’

MHTGR in USA
(Genaral Atomic)



- ***350 - 450 MW_{th}***
- ***Block design***
- ***Designed with steam generator***

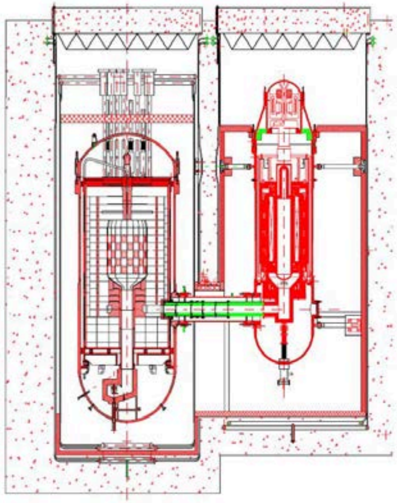
HTR-Module in Germany (Siemens / INTERATOM)

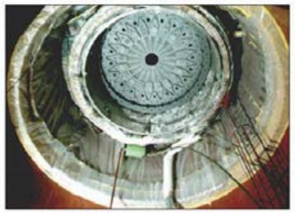


- ***200 MWth***
- ***Pebble bed design***
- ***Designed with***
  - ***steam generator***
  - ***intermediate heat exchanger***
  - ***steam reformer***

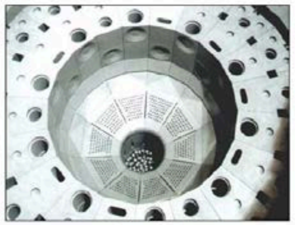
2 test reactors at the end of the 90s'

HTR-10, China
Pebble bed, 10 MWth





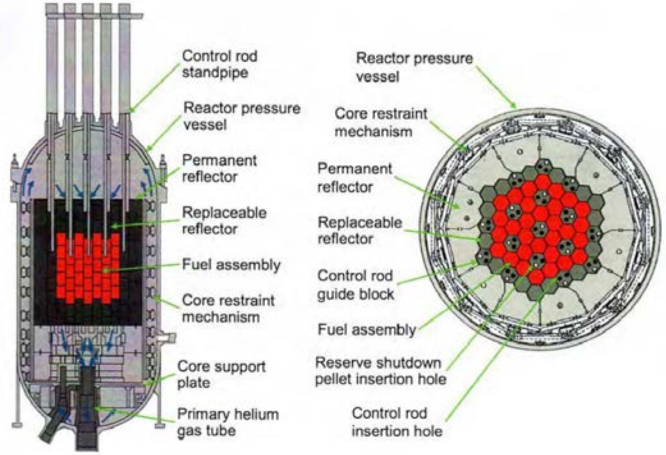
Deckenreflektor



Bodenreflektor

Still operational

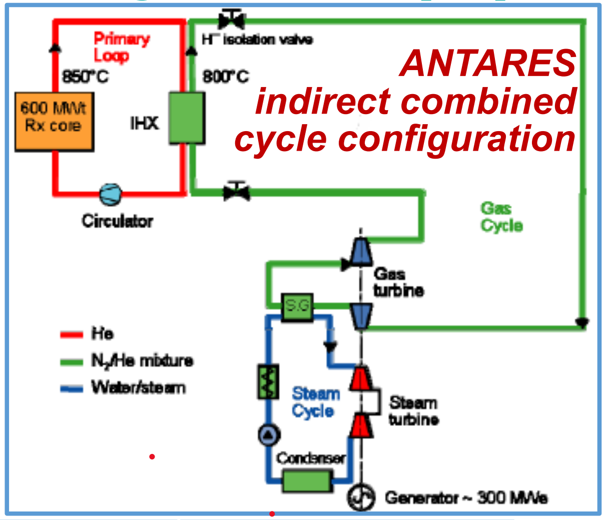
HTTR-10, Japan
Block design, 30 MWth

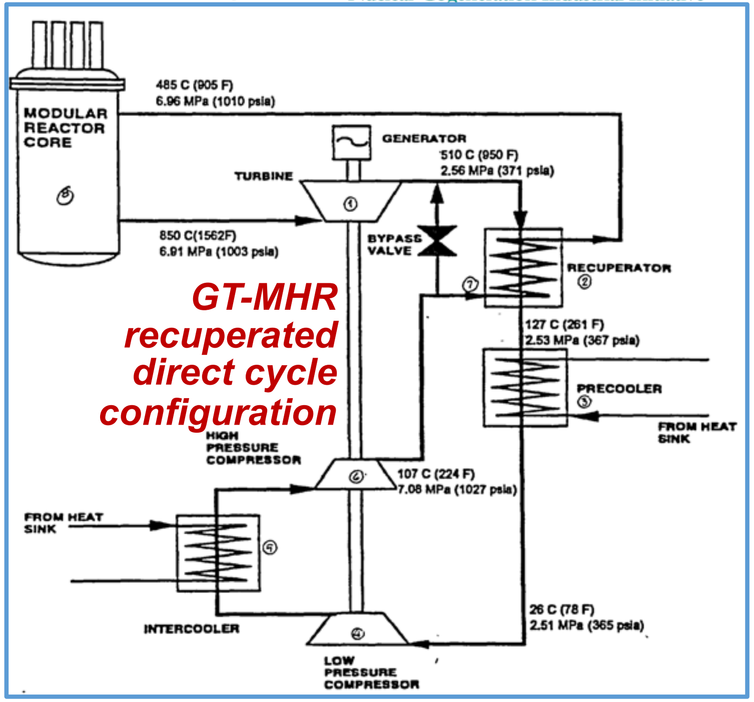


- Under regulatory review after Fukushima accident
- To be coupled with H_2 production plant

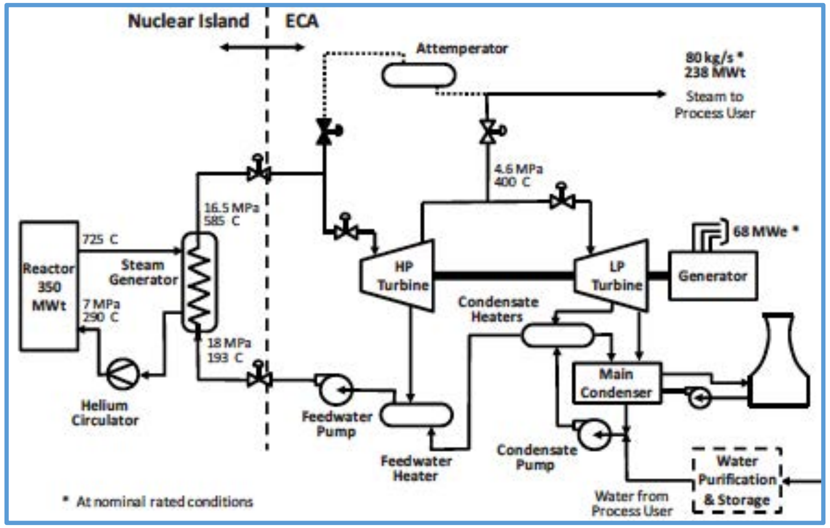
Recent projects (1)

☞ **All reactors are following modular design principles**





	Core	Thermodynamic cycle	Main applications
GT-MHR (GA + Russia)	Prismatic	Direct cycle	Power generation Burning Pu
SC-MHR (GA)	Prismatic	Steam cycle	Cogeneration of electricity & steam
PBMR (South-Africa)	Pebble bed	Direct/steam cycle	Cogeneration of electricity & steam
ANTARES (AREVA)	Prismatic	Indirect combined cycle	Cogeneration of electricity & heat
SC-HTGR (AREVA)	Prismatic	Steam cycle	Cogeneration of electricity & steam
GTHTR-300 (JAEA)	Primatic	Direct cycle	Power generation & H_2 production
HTR-PM (China)	Pebble bed	Steam cycle	Power generation



SC-MHR steam cycle configuration

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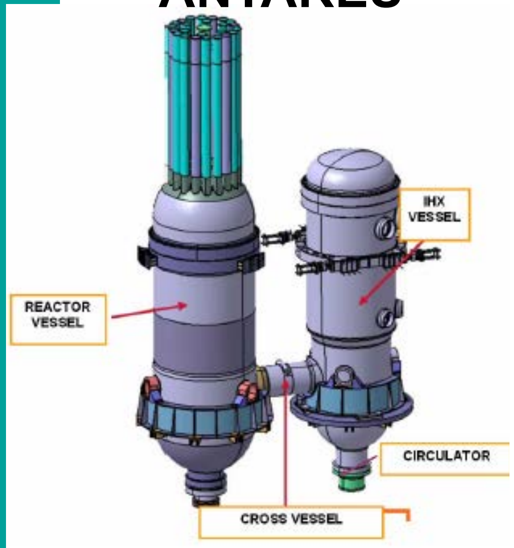
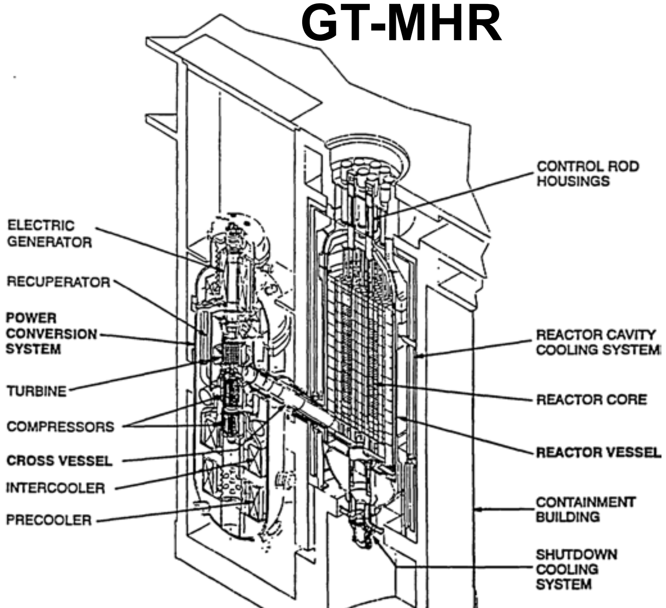
Recent projects (2)

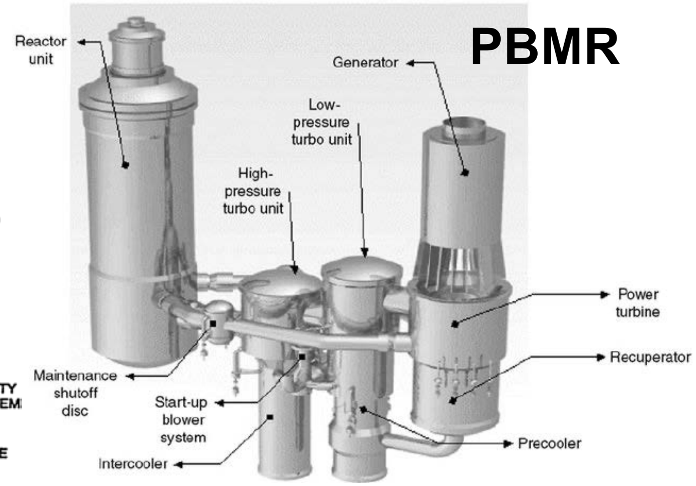
ANTARES

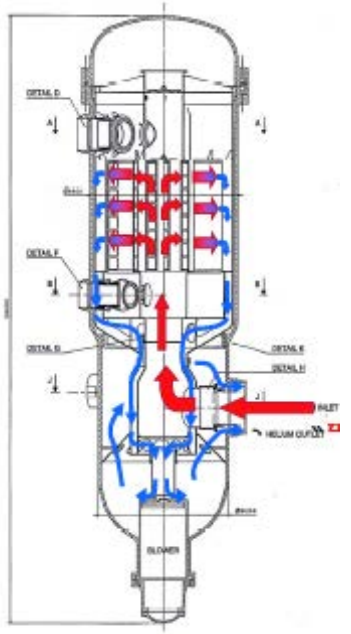


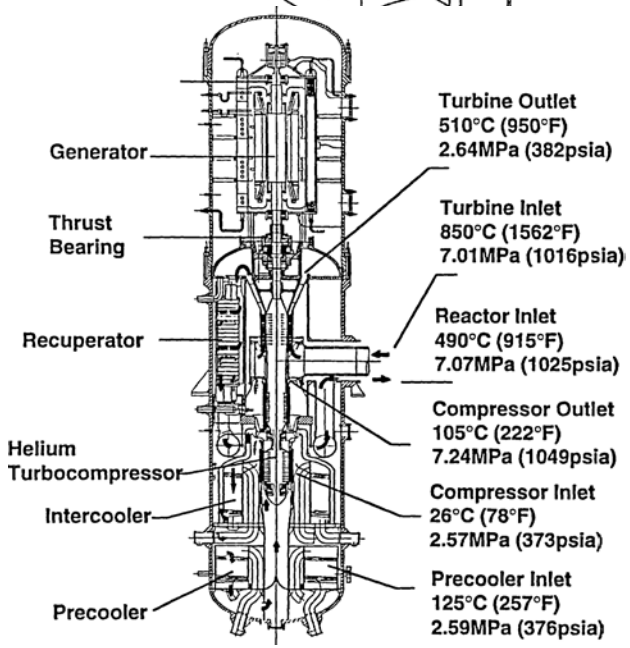
GT-MHR



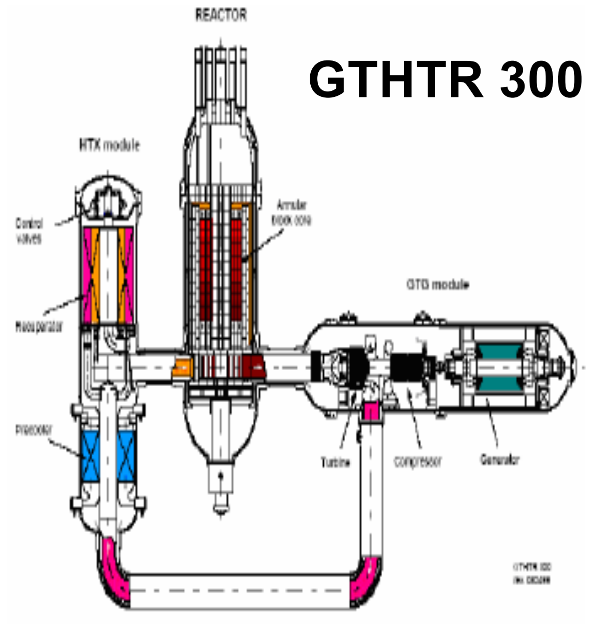
PBMR







GTHTR 300



SNETP
Sustainable Nuclear Energy Technology Platform
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The NGNP project (1)

- Energy Policy Act of 2005 established Next Generation Nuclear Plant project to build demonstration of HTGR technology by 2021
- Pre-Conceptual Designs by three vendor teams completed in 2007:
  - Westinghouse (PBMR based)
  - General Atomics (MHTGR based)
  - AREVA (SC-HTGR based)

  + Pre-licensing engagement with NRC
- Funding Opportunity Announcement (FOA) issued by the DOE in Sept. 2009 for Phase 1 NGNP conceptual design, cost and schedule estimates, and business plan preparation.

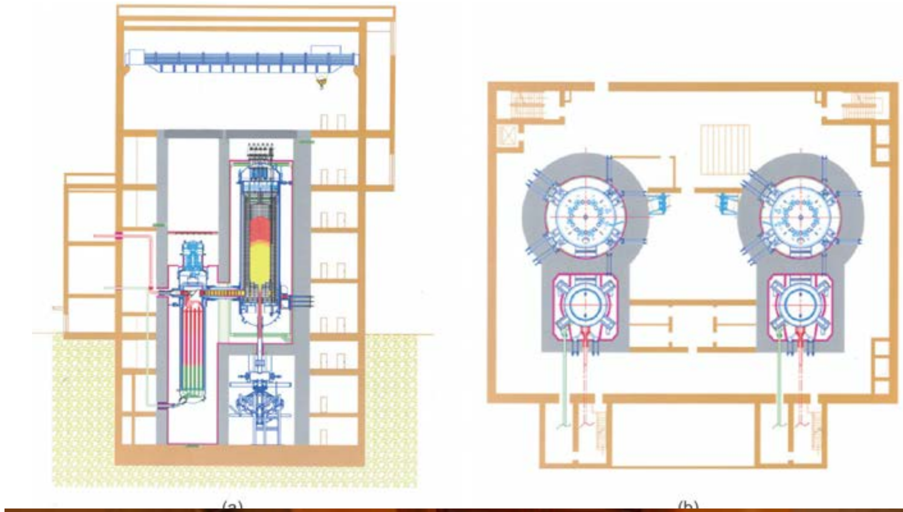
The NGNP project (2)

NC2I
Nuclear Cogeneration Industrial Initiative

- FOA awardees announced March 8, 2010: Westinghouse and GA
- Westinghouse withdrew due to the end of PBMR project
- Phase 1 finalised with a project review early 2011
- No Phase 2 launched by the DOE, NGNP activities continued through the NGNP Industry Alliance gathering vendors and end-users.
- The NGNP design programme has been supported by an important R&D programme in US National Labs:
  - Fuel qualification
  - Graphite qualification
  - Testing to support design code validation

Present project: HTR-PM

NC2I
Nuclear Cogeneration Industrial Initiative



March 2016

December 2017

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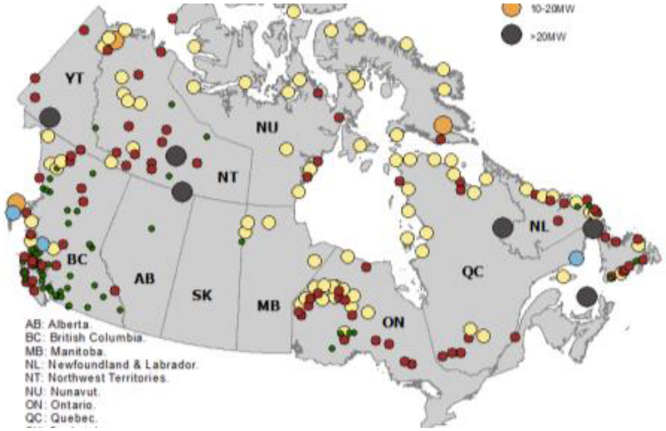
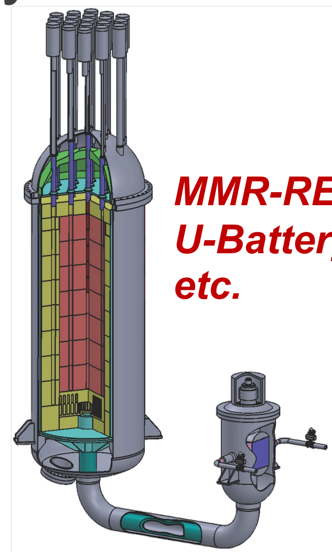
NC2I
Nuclear Cogeneration Industrial Initiative

New trends

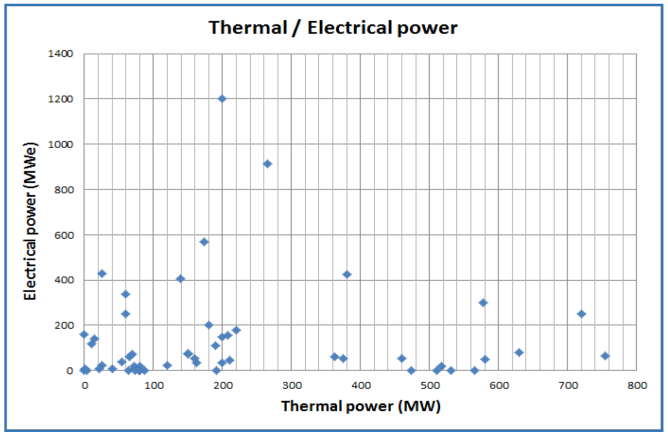
- Micro-reactors for isolated sites and military bases

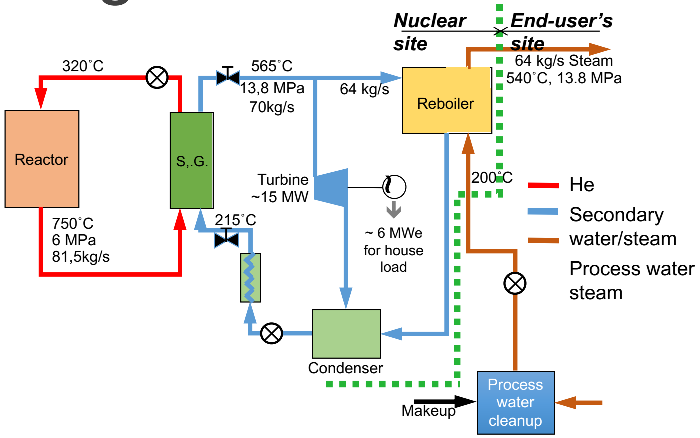




MMR-REM, U-Battery, etc.

- In Europe, emphasis on steam supply to steam networks of large industrial sites





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Summary and conclusion

Summary

3 phases of HTGR development

- **First Phase** HTGR (DRAGON, Peach Bottom, AVR) proved
  - Basic Concept and Fission Product Retention of CP Fue
  - High availability, low contamination, failure toleranc
  - Capability for high temperature operation ~ 950°
- **Second Phase** HTGR (FSV, THTR) were commercially erected and operated but suffered from prototypical and economic problems. They demonstrated the feasibility of medium-sized cores
- **Third Phase** Modular HTR recur to proven technology:
  - Inherent safety features
  - Simplified systems, series effects in construction
  - Capability for high efficiency power generation / process heat
  - Even two Test Reactors available (HTR-10, HTTR)

Conclusion

- HTGR technology has an extensive base of design, licensing and operating experience with valuable lessons learned
- Prismatic and pebble bed systems share large common base of technology, systems and components
- There is still a large potential for progress:
  - Higher operating temperature
  - Cost reduction
  - Extended market (micro-reactors for isolated sites, industrial heat)