Plant engineering

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Joint IAEA-ICTP Workshop on Reactor Physics, Thermal Hydraulics and Plant Design Engineering of Small Modular Reactors (SMR4212)

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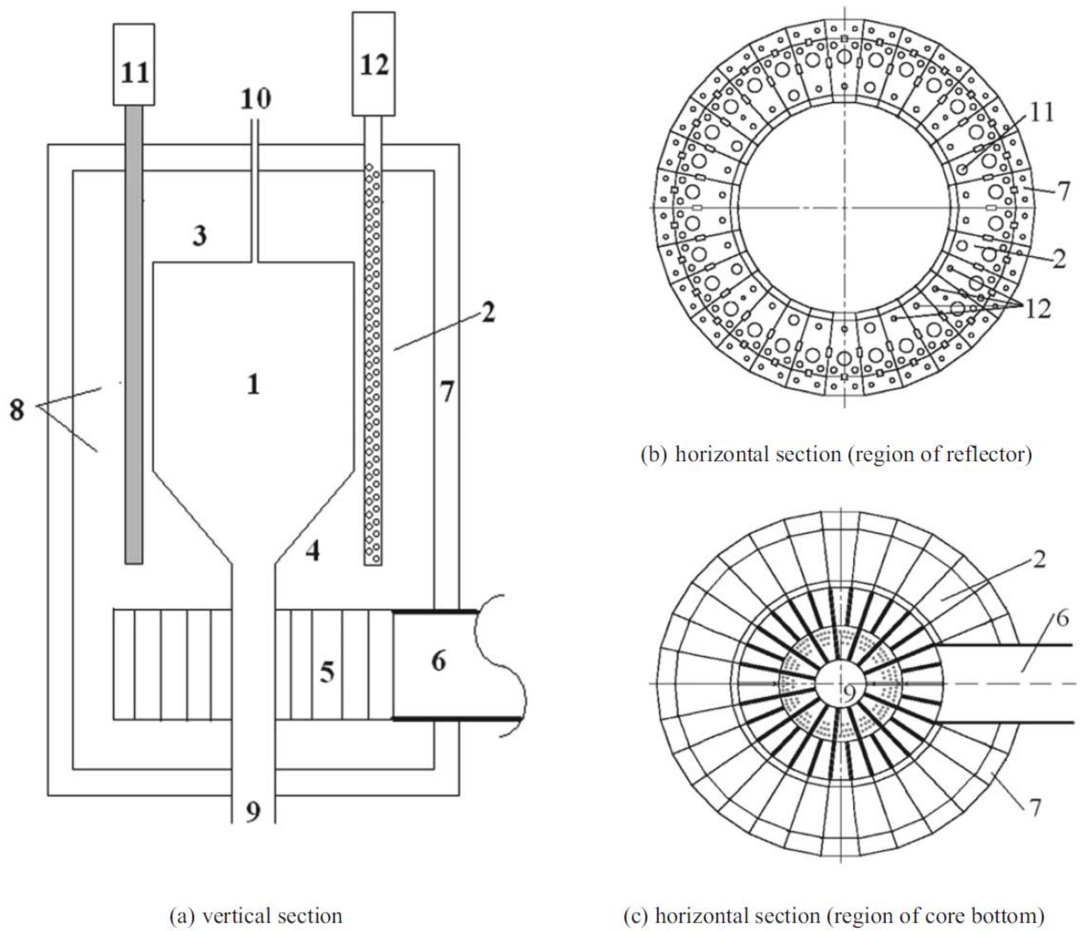
Overview

- Reactor Components
  - Internal Reactor Structures
  - Primary Enclosure
  - Shutdown and Control systems
  - Fuel Handling System
  - Measurement Installations
- Steam Generator
- Components of the Helium Cycle
- Reactor Containment Building
- Considerations as a Small Modular Reactor

Internal Reactor Structures



(1: pebble-bed core; 2: side reflector; 3: top reflector; 4: bottom reflector; 5: hot gas chamber; 6: core connection of hot gas duct; 7: thermal shield; 8: core instrumentation (neutron flux); 9: fuel element discharge tube; 10: fuel element loading tubes; 11: reflector rods with drives (first shutdown system); 12 small absorber ball systems (KLAK=second shutdown system)

Fig. 5.1 Overview on main components inside the reactor pressure vessel of a modular HTR

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Internal Reactor Structures

Data of core configuration for various HTR plants

Parameter	Unit	AVR	THTR	HTR-Module	HTR-10	HTR-PM
Thermal power	MW	46	750	200	10	250
Heating up of coolant gas	°C	220–950	250–750	250–700	250–750	250–750
Average core power density	MW/m^3	2.2	6	3	2	3.3
Fuel element cycle	–	MEDUL	MEDUL	MEDUL	MEDUL	MEDUL
Core height	m	3	5.1	9.43	2.0	11
Core diameter	m	3	5.6	3	1.8	3
Sphere discharge tubes	1	1	1	1	1	1
In-core rods	–	No	Yes	No	No	No
Coolant gas flow	–	Upward	Downward	Downward	Downward	Downward

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

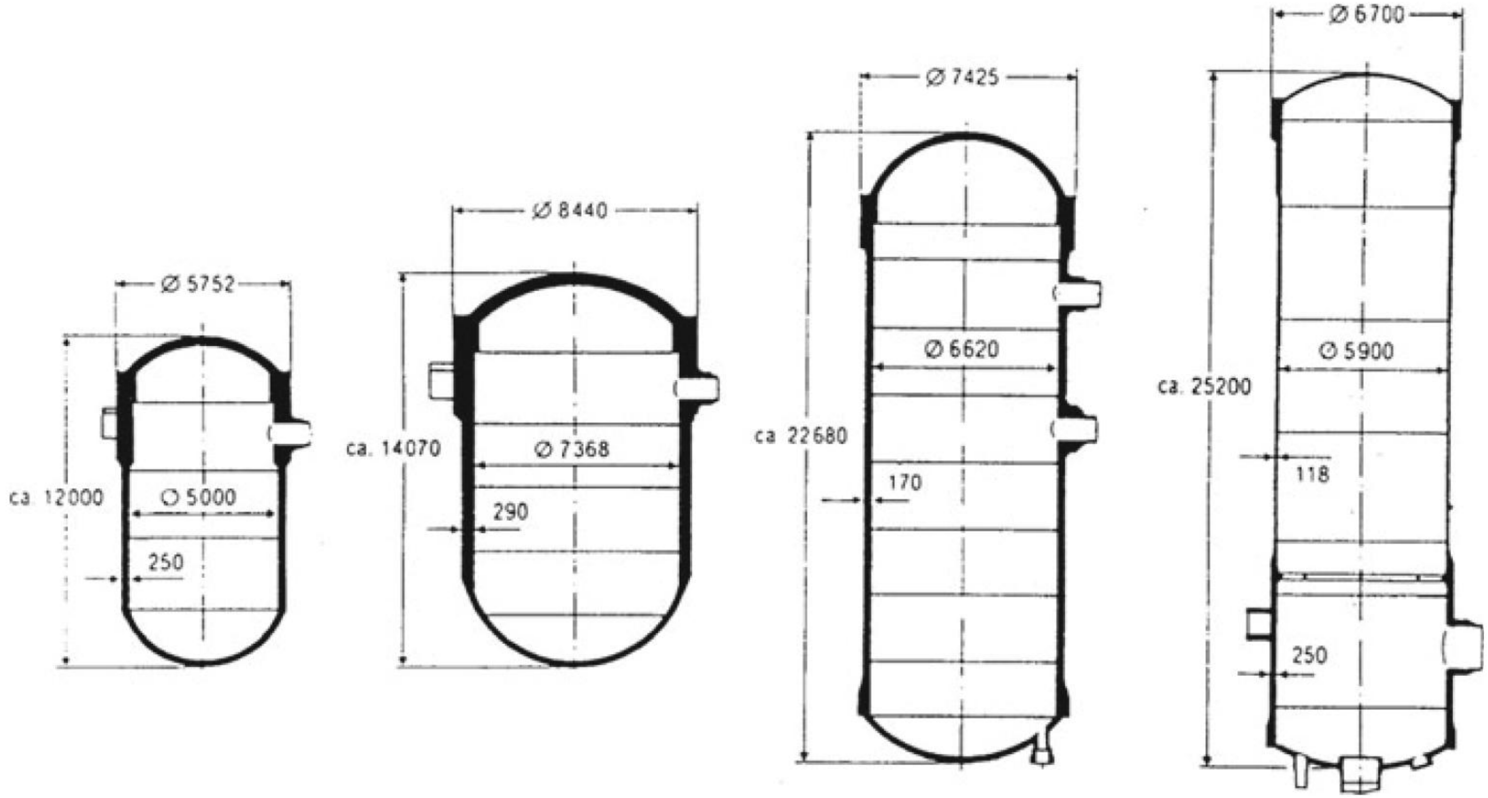
Primary Enclosure

Primary enclosure: the second barrier to retain fission products from the environment. (high safety standards, forged steel vessels)

- Reactor pressure vessel (RPV)
  - Pebble-bed core
  - Reflector (embedding two shutdown systems)
  - Thermal shield
  - Core instrumentation
  - Fuel element discharge/loading tubes
- Steam generator vessel (SGV)
  - Steam generator
  - Helium circulator
- Connecting vessel (CV)
  - Contains hot gas duct between the reactor and the steam generator

Primary Enclosure

Comparison of reactor pressure vessels for different reactors



(a) pressurized water reactor (1300MW$_{el}$) (b) heavy water reactor (Atucha II) (c) boiling water reactor (1300MW$_{el}$) (d) HTR-Module (200MW$_{th}$)

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Internal Reactor Structures

Data of the reactor pressure vessel

Parameter	HTR-PM	HTR-module	PWR	BWR
Inner diameter (m)	5.7	5.9	5	6.6
Clear height (m)	24.7	24.8	11.6	22.3
Operational pressure (MPa)	7	6	16	7
Design-basis pressure (MPa)	8	7	17.25	8.73
Design-basis temperature (°)	350	350	350	300
Thickness of cylindrical wall (mm)	131	118	250	170
Weight (t)	~670	830	500	780
Material	SA508-3/SA533-B	20 MnMoNi 55	22 MnMoCr 37 20 MnMoNi 55	22 MnMoCr 37
Inner corrosion protection	–	–	Necessary	–
Fast neutron dose (n/cm^2)	$<10^{18}$	$<10^{18}$	$<10^{19}$	$<10^{19}$

- Large similarities between the pressure vessels of modular HTR and of large boiling water reactors
- Lower pressures and fast neutron doses

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Shutdown and Control systems

- Two independent shutdown systems

Aspects of shutdown systems of HTR

System	Function	Single effects	Large HTR (THTR)	HTR-Module 200 MW
First shutdown system	Fast shutdown; control of power	Accidents; temperature equalization; control processes (temperature reduction)	Reflector rods	Reflector rods
Second shutdown system	Longtime cold shutdown; trimming processes	Temperature reduction (cold); xenon decay; protactinium decay; subcriticality; accidents	In-core rods	Special small absorber elements in reflector[a]

[a]KLAK system: small boron absorber balls in borings in side reflector

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Shutdown and Control systems

- Strong negative temperature coefficient

Reactivity: the deviation of an effective multiplication factor from unity.

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

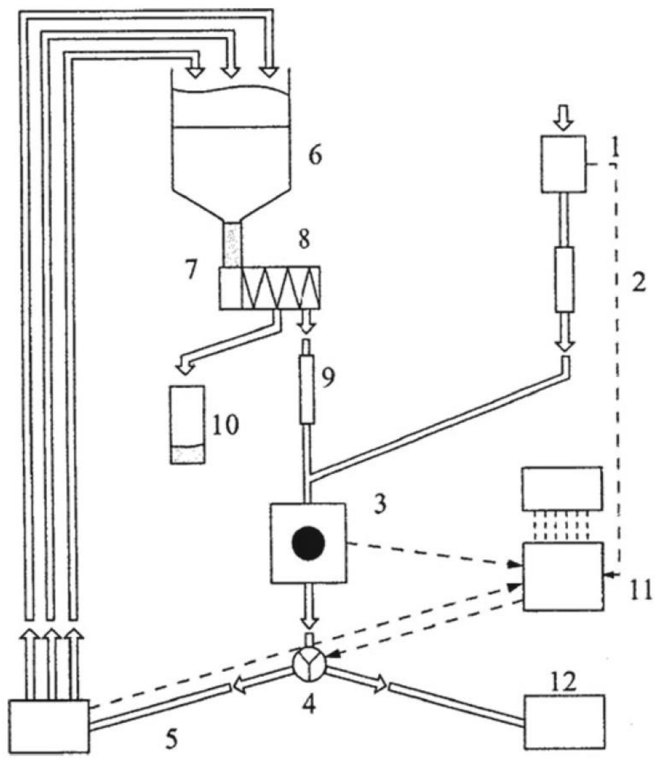
Temperature coefficients

Reactor	Value $\Gamma \cdot 10^{-5}$/K	Temperature (K)	remark
THTR	-8.2	319	measured
THTR	-8.4	480	measured
THTR	-7.6	470	calculated
THTR	-4	1200	calculated
HTR-Model	-5	900	calculated

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Fuel Handling System

Fuel handling system of THTR (MEDUL concept)



(a) principle

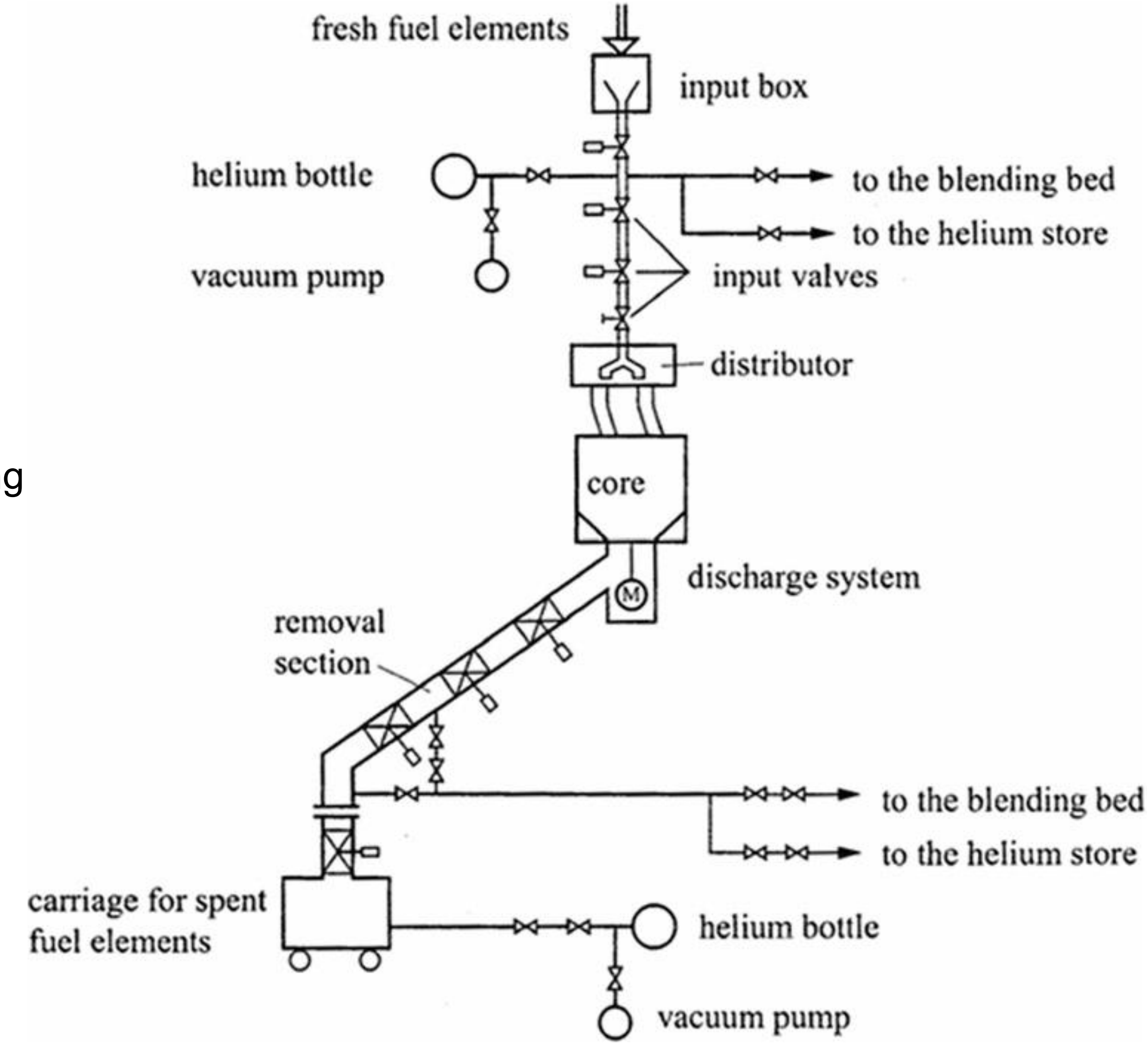
Parameter	dimension	value
Thermal power	MW	750
Number of fuel elements in core	-	675000
Heavy metal content in element	g/FE	11
Average burnup	MWd/t	100000
Number of fresh fuel element per day	1/day	680
Fuel elements recycling rate	1/day	4080
Average residence time in core	year	2.5
Number of spent fuel element per day	1/day	680

(b) data of system

1: loading system for fresh fuel elements, 2: buffer storage, 3: burnup measurement reactor, 4: switching system, 5: pneumatic elevation system, 6: core, 7: fuel element discharge system, 8: scrap singulizer and separator. 9: intermediate storage, 10: storage vessel for damaged spheres, 11: process control, 12: storage vessel for spent fuel elements

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Fuel Handling System



Principle of the fuel handling system in case of OTTO cycle for HTR plants

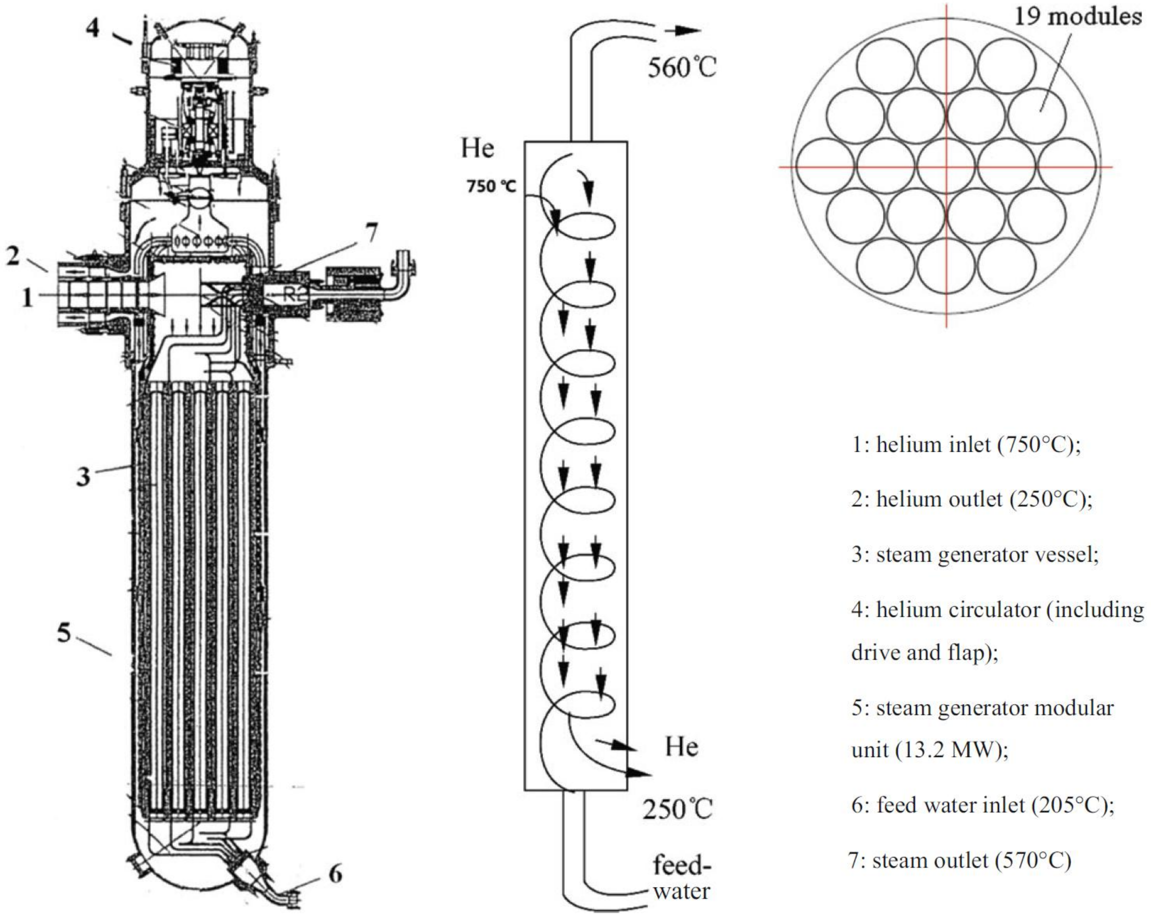
Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Measurement Installations

- Measurement of Neutron Flux
  - Thermal neutrons
  - Six channel groups, distributed over the whole region
- Measurements of the Thermo-Hydraulic Parameters of the Core
  - Temperatures and pressures in the helium circuit
  - Blind graphite balls containing material probes: maximal temperature during operation

Steam Generator

Steam generator of the HTR-PM



(a) vertical section of steam generator arrangement [77]

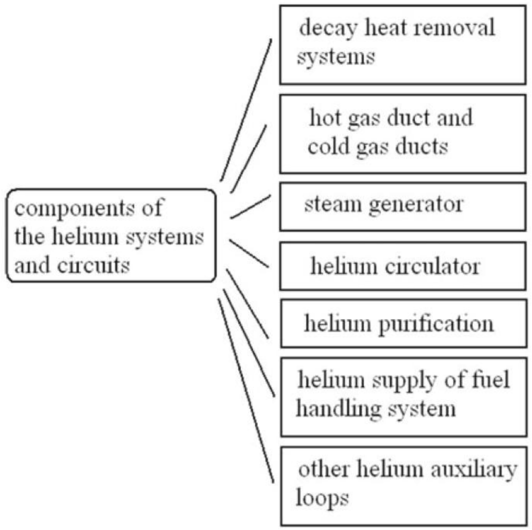
(b) module-Unit (13.2 MW)

(c) arrangement of modular units in steam generator

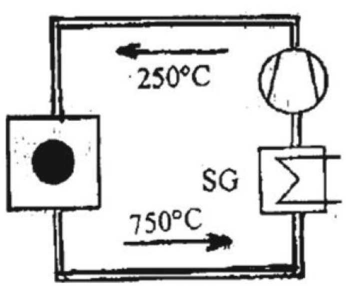
Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Components of the Helium Cycle

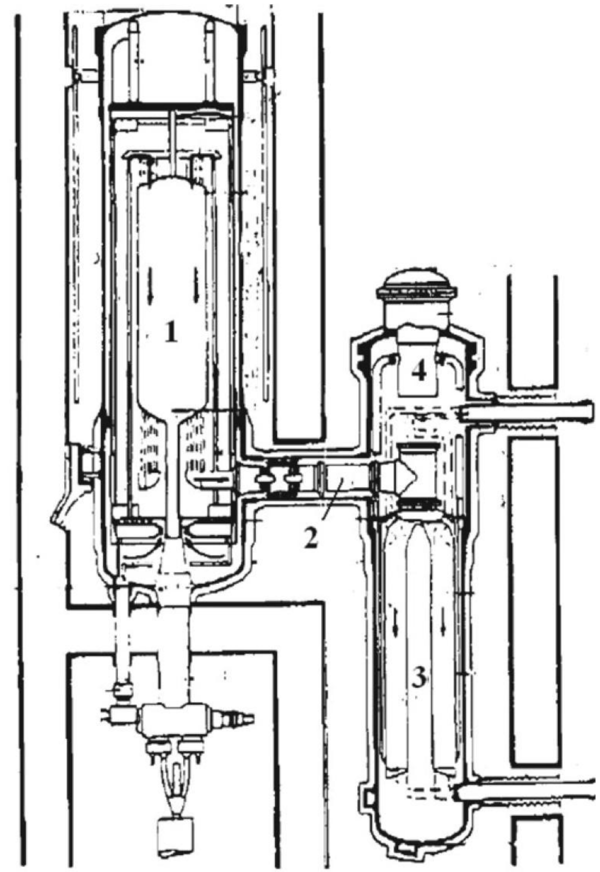
Components and circuit of the helium cycle



(a) components and circuits of helium cycle



(b) flow sheet of the helium cycle



1: reactor, 2: coaxial hot gas duct; 3: steam generator; 4: helium circulator

(c) arrangement of components of HTR-MODULE

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Components of the Helium Cycle

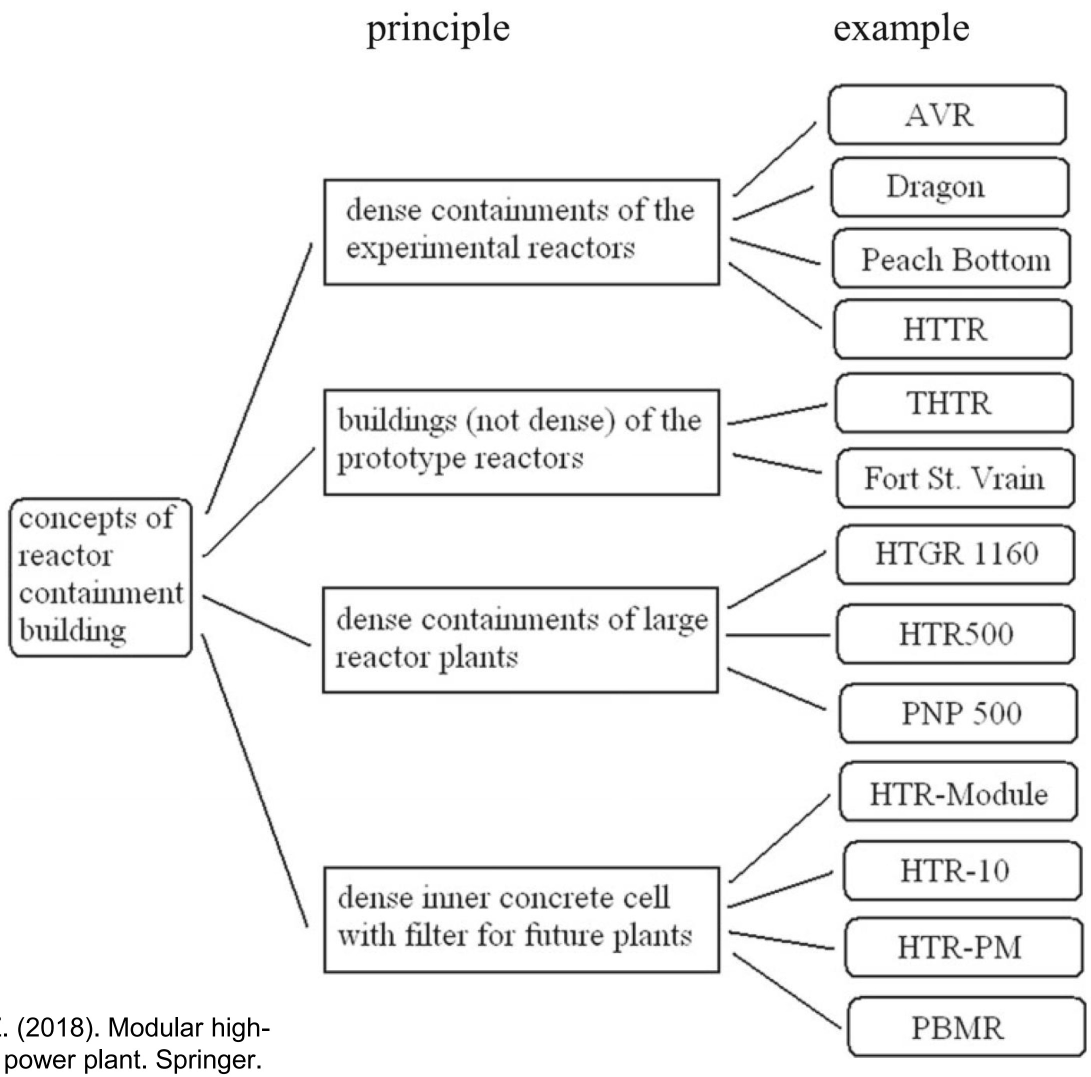
Data of helium cycles of helium-cooled nuclear reactors

	Thermal power (MW)	Helium inlet temperature (°C)	Helium outlet temperature (°C)	Helium pressure (MPa)	Helium mass flow rate (kg/s)	Application, use of heat
Reactors						
UHTREX	3	870	1300	3.5	1.25	Test facility
AVR	46	275	950	1.1	13	Steam cycle
THTR	750	250	750	4.0	288	Steam cycle
Dragon	20	350	750	2.0	9.6	Water cooling
Peach Bottom	115	344	770	2.4	52.8	Steam cycle
FSV	842	400	770	5.0	438	Steam cycle
HTR-10	10	250	750	3.0	4.3	Steam cycle
HTTR	30	385	850	4.0	12	Steam cycle
HTR-PM	250	250	750	7.0	96.2	Steam cycle
PBMR	400	500	900	9.0	192.5	Brayton cycle

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Reactor Containment Building

Concepts of reactor containments or containment buildings for HTR plants



Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Reactor Containment Building

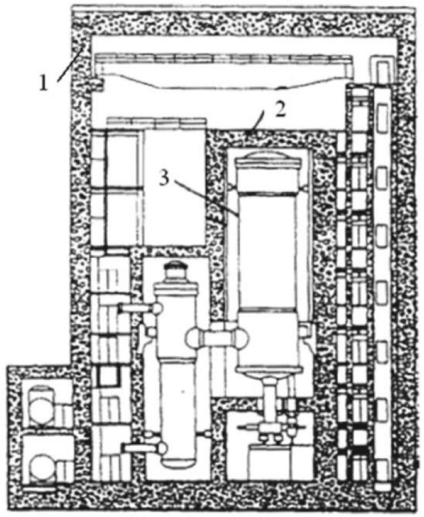
Concepts of reactor buildings and containments in HTR plants

Generation	Plant	Characteristics	Density	Protection against impact	Additional remarks
(1) Experimental reactors	AVR	steel RPV (double), steel containment	Yes	1 m concrete	46 MW Germany
	Dragon	steel RPV, steel containment	Yes	1 m concrete	20 MW Great Britain
	Peach Bottom	steel RPV, steel containment	Yes	1 m concrete	110 MW USA
(2) Prototype reactors	THTR 300	PCRV, reactor hall	No	Given by PCRV	750 MW Germany
	Fort St. Vrain	PCRV, reactor hall	No	Given by PCRV	870 MW USA
(2+) First commercial concepts	HTGR 1160	PCRV, concrete containment	Yes	2 m concrete + PCRV	3000 MW USA
	HTR 500	PCRV, concrete containment	Yes	2 m concrete + PCRV	1250 MW Germany
(3) Modular HTR systems	HTR-Module	Steel RPV, concrete building	No	2 m concrete + inner cell	200 MW Germany
	HTTR	Steel RPV, concrete building	No	2 m concrete + inner cell	30 MW Japan
	HTR 10	Steel RPV, concrete building	No	2 m concrete + inner cell	10 MW China
(4) Next future plants	PBMR	Steel RPV, concrete building + filter	Partly (inner cell)	2 m concrete + inner cell	200 MW South Africa
	HTR-PM	Steel RPV, concrete building	Partly (inner cell)	2 m concrete + inner cell	250 MW China

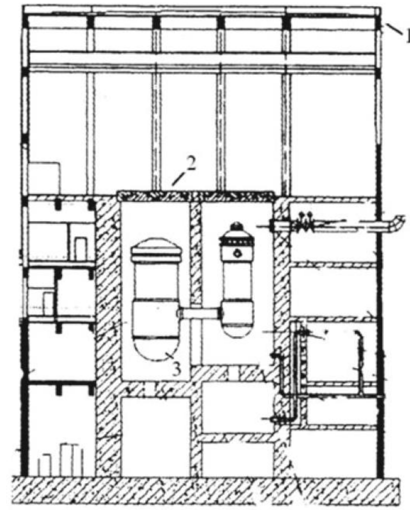
Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Reactor Containment Building

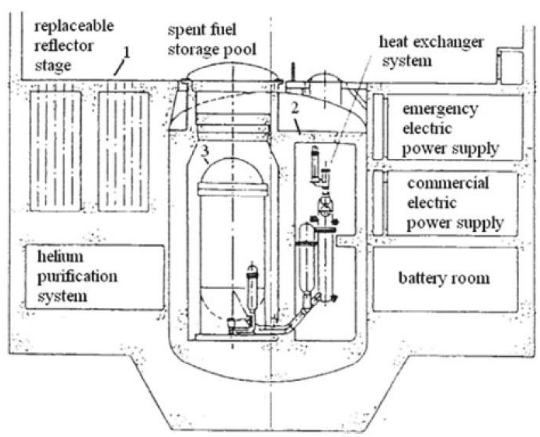
Concepts of reactor containment building of modular HTR



(a) HTR-Module [26]



(b) HTR-10 [27]



(c) HTTR [28] 1: containment; 2: inner concrete cell; 3: reactor pressure vessel

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Considerations as a Small Modular Reactor

- Multidisciplinary integration: reactor physics, thermal fluid dynamics, fuel & materials, mechanical & structural engineering, chemical & radiological systems, electrical & instrumentation engineering, and safety & systems engineering.
- Key objectives:
  - Compactness: maximize off-site build, fit more systems within one transportable module
  - Simplicity: core design, piping and pumps, logistics flow
  - Maintainability: reduce human interaction, less need for intervention
- Challenges
  - High temperature / pressure
  - High irradiation
  - High integration of passive systems

Considerations as a Small Modular Reactor

Plant Layout Principles

- Defense-in-Depth Safety
- Modular Scalability
  - Standardized units (plug-and-play)
  - Integrated reactor-turbine modules
  - Hot-swappable interfaces (unified utility connections)
- Compact Integration
- Security Zoning
  - Multi-layer access
  - Buffer zone
- Emergency Preparedness
- Regulatory Harmonization
  - IAEA/ISO alignment
  - Pre-licensing coordination

Considerations as a Small Modular Reactor

Modular Deployment Strategy

- Core Elements
  - Standardized Design: unified interfaces
  - Harmonized Design: IAEA - Nuclear Harmonization and Standardization Initiative (NHSI)
  - Factory Prefabrication: most components built off-site
  - Scalable Clusters: 50-300MW(e) increments
- Key Actions
  - Supply chain: globalized suppliers
  - Regulatory Sync: multinational licensing, short approval time
  - Funding models: gov-backed loans, power purchase agreements