International Workshop on Advances in Design of Generation-IV Small and Medium Sized of Modular Reactors (SMRs)

HTR development in China

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Outline

- ***1 Technical features HTGR***
- ***2 Status of HTR-PM project***
- ***3 Licensing experience of HTR-PM***
- ***4 New HTR plants in China***

1 Technical features HTGR

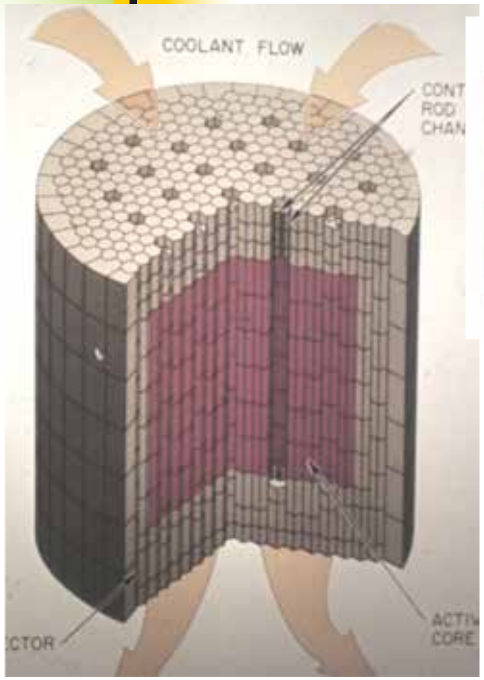
- ***1.1 Definition of HTGR***
- ***1.2 Features of HTGR***
- ***1.3 Overview of HTGR projects***

1.1 Definition of HTGR

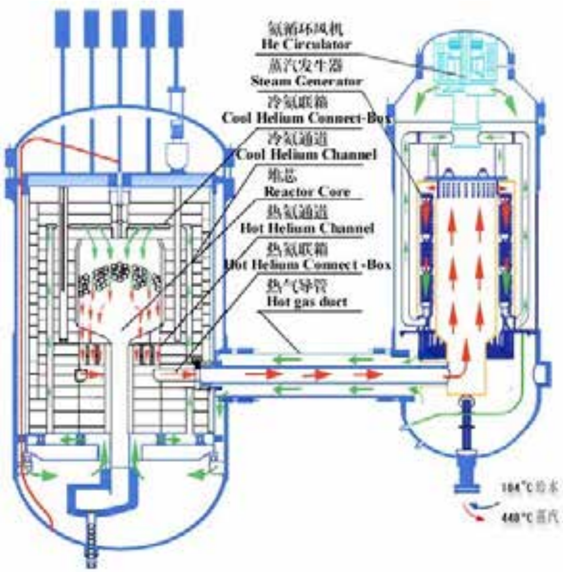
- ***HTR / HTGR***
  - ***High temperature gas cooled reactor***
  - ***HTGR more likely referred to prismatic (popular in USA)***
  - ***HTR more likely referred to pebble bed (popular in Germany)***
  - ***In many cases, HTR and HTGR are equivalent***
- ***Simple idea, excellent performance***
  - ***High efficiency, safety, more application area***

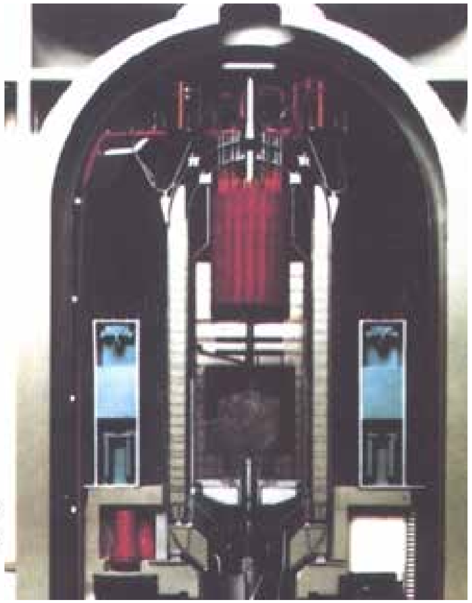
Prismatic & pebble bed HTR

Coal stoves

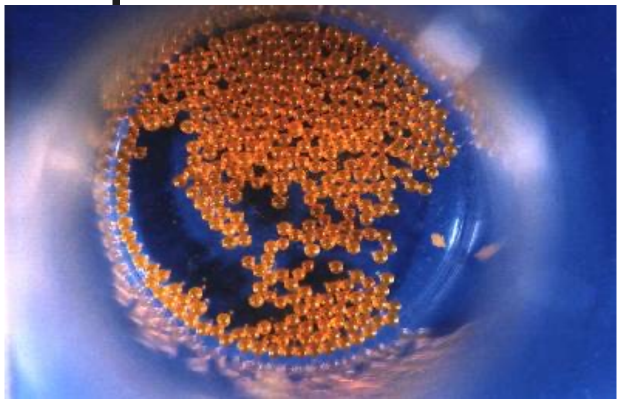


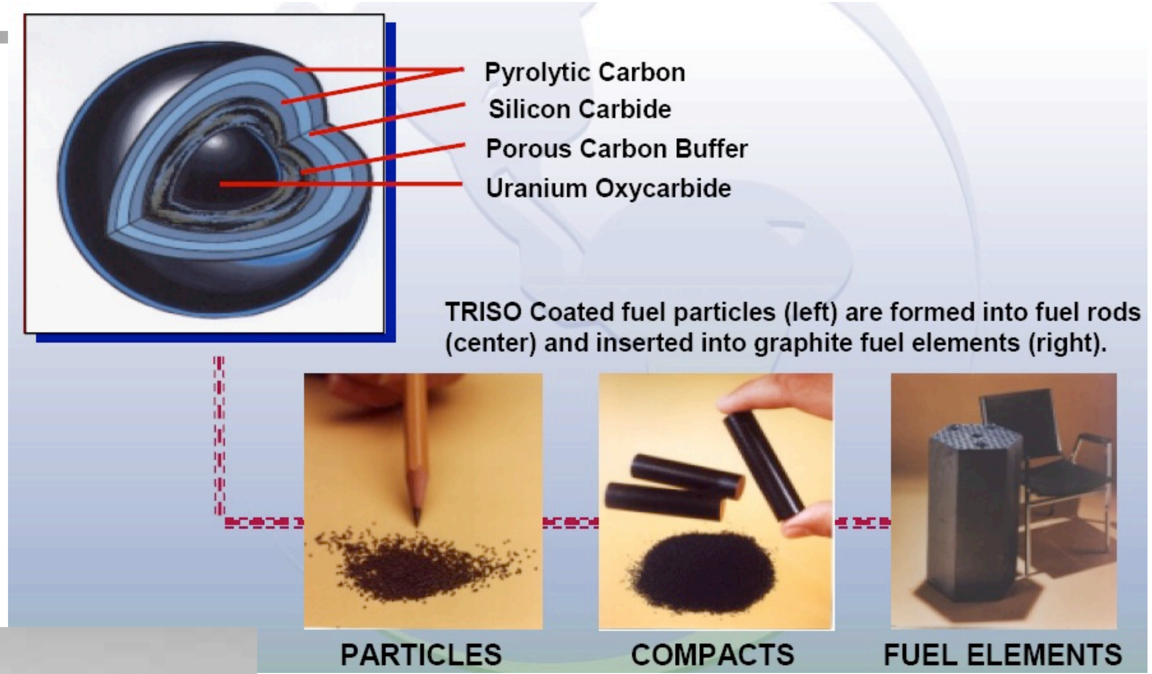
Simple idea

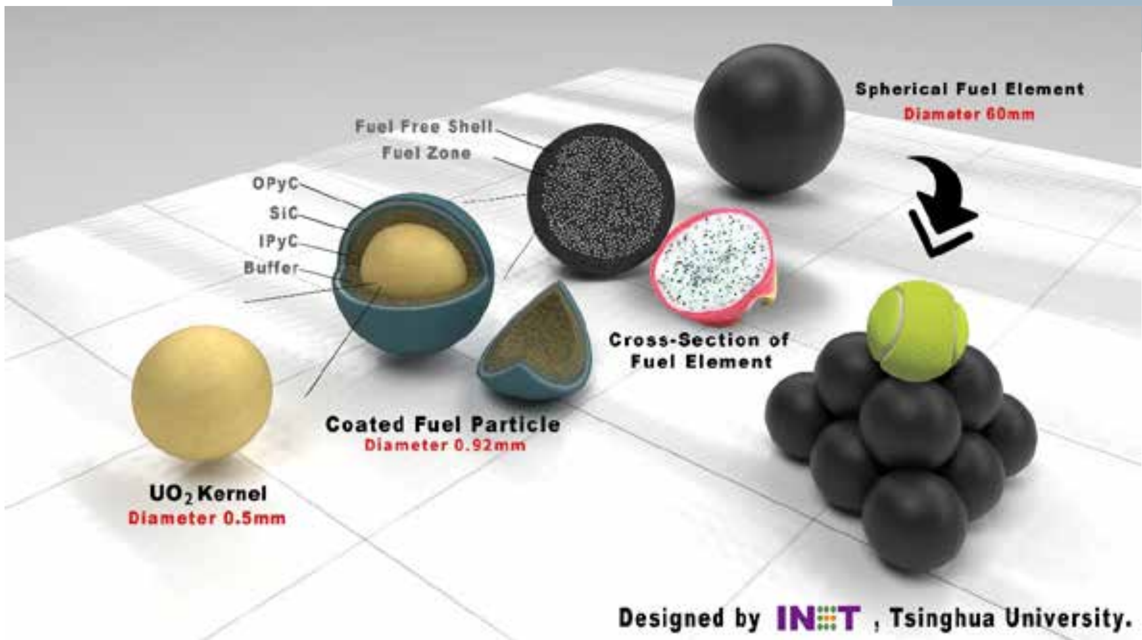


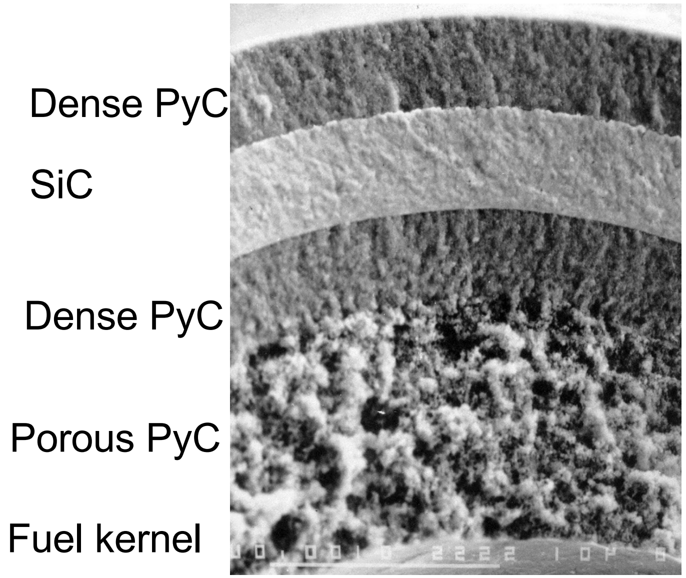


Same TRISO coated particle fuel
Same inherent safety features









Different name for HTR project

- ***Different stages, different name, increased performance, similar technology***
  - ***Technical mature: High temperature gas cooled reactor (HTGR，HTR)***
    - ***Helium coolant, coated particle fuel, in 1960s***
  - ***Technical Improvement: Modular HTGR***
    - ***Small size, modular, inherent safety, 1980s***
  - ***New trend: Very high temperature reactor (VHTR)***
    - ***Named by Gen IV International Forum, 21st century***
    - ***Mature modular HTGR belongs to VHTR, GIF Technical Roadmap Update, 2014***

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1.2 Features of HTGR

- ***Features, compared with LWR:***
  - ***Coolant: Helium***
  - ***Moderator: Graphite***
  - ***Core structure: graphite/ceramic***
    - ***Can withstand high temperature***
  - ***Fuel: TRISO coated particle***
  - ***Outlet temperature: very high, 700-1000℃***
  - ***Possible application: electricity generation, process heat (co-generation), hydrogen production***
  - ***Safety feature: inherent safety***

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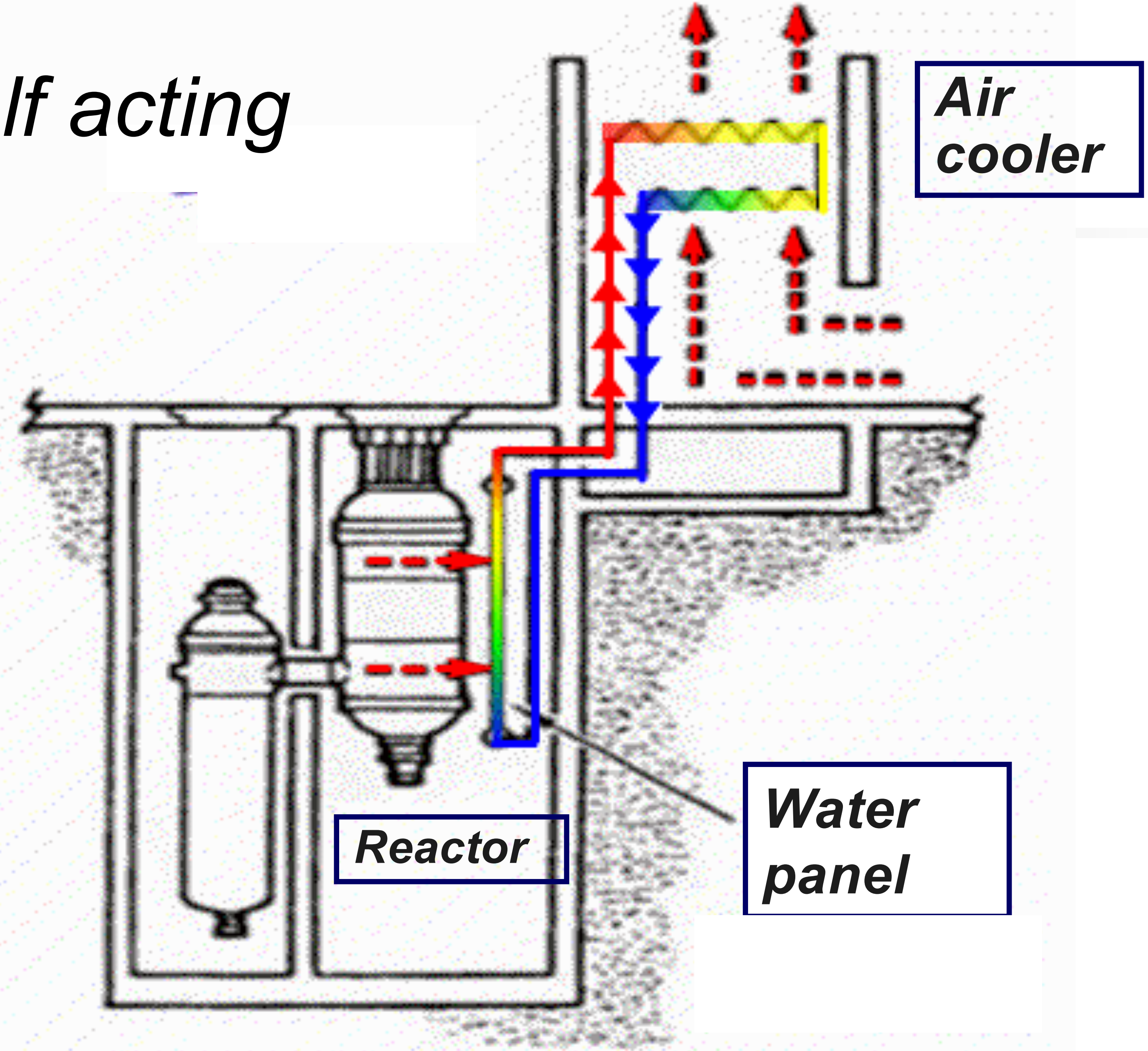
1.2 Features of HTGR

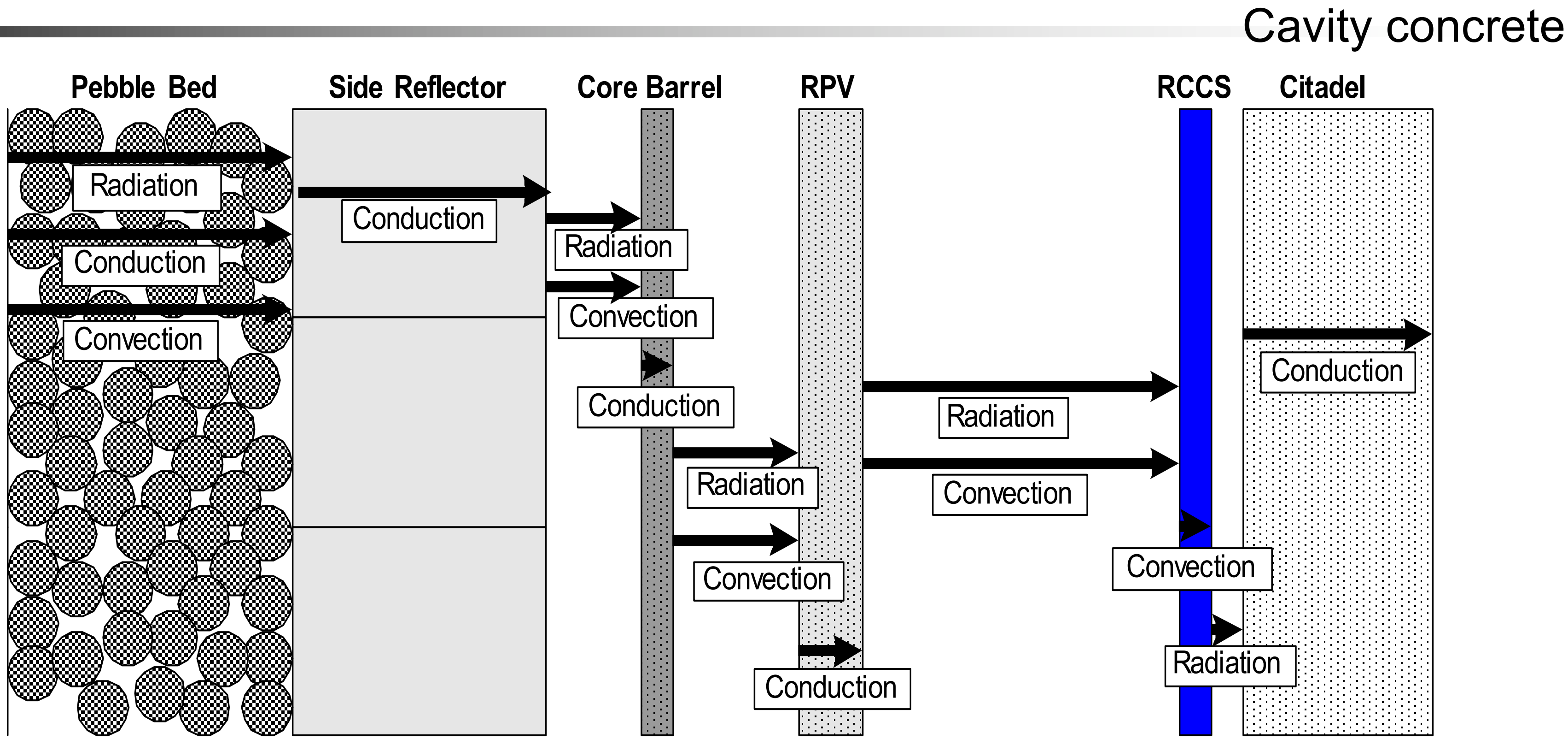
- *Inherent safety*
  - *Melt free core*
  - *Self dispersed/removed decay heat*
    - *No emergency core cooling is required*
  - *Long grace time/slow transient*
    - *Several days*
  - *Robust fuel to retain FP in all conditions*
    - *With dedicated core design to limit the max fuel temperature*
    - *Not sensible for loss of coolant*
    - *Not sensible for air and steam*
      - *Slow corrosion of air and steam with graphite*

Self acting



Decay heat removal

Decay heat transfer path based on temperature gradient

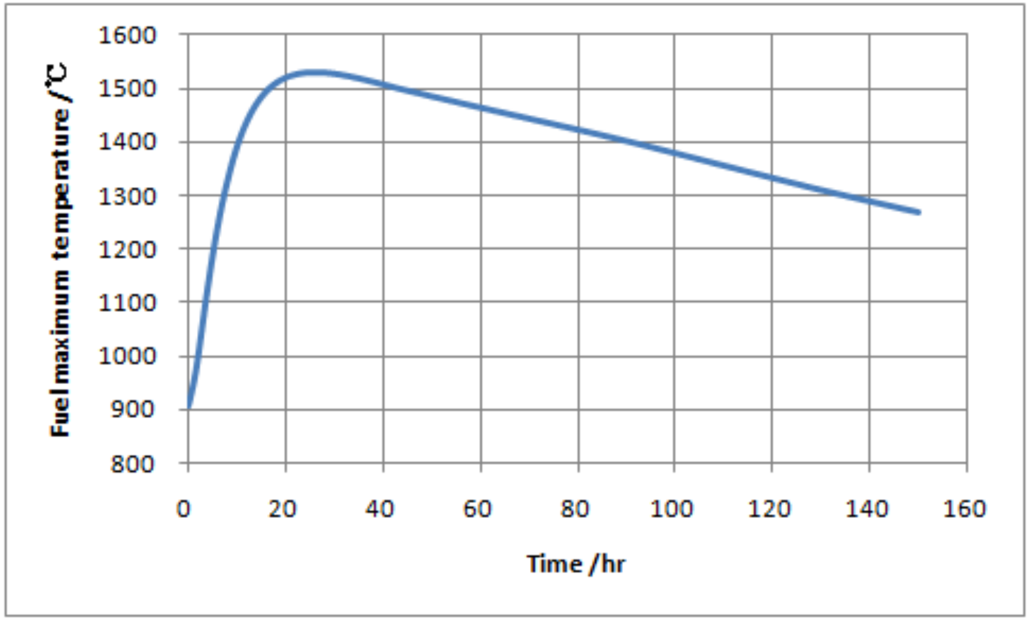


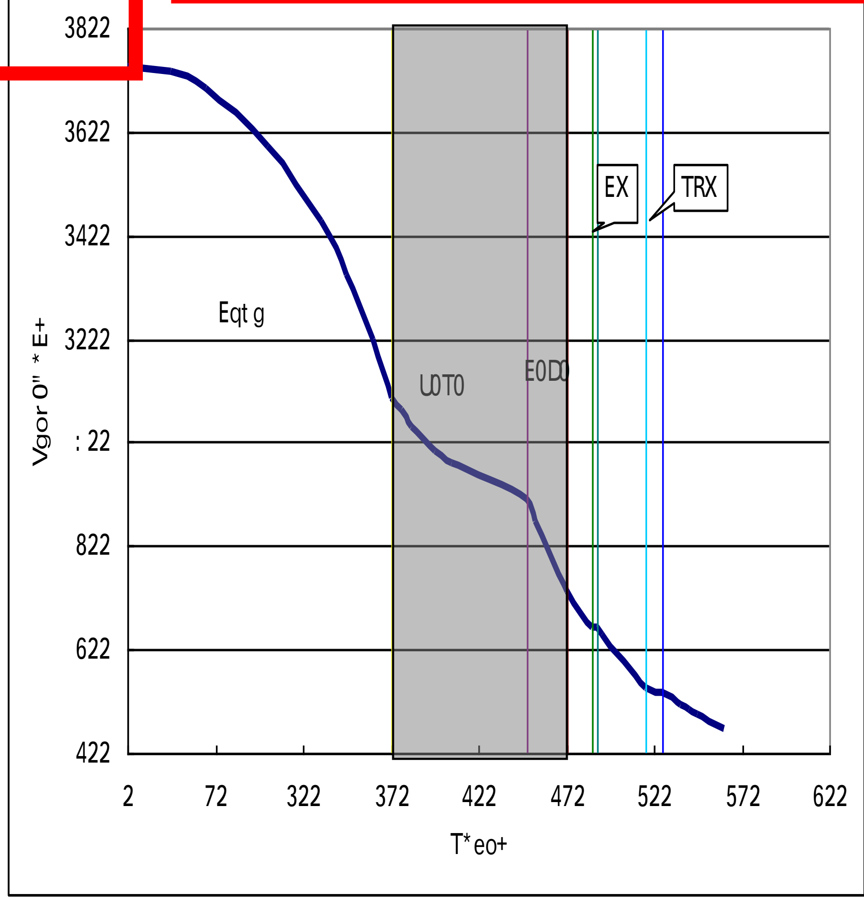
- *Inherent* ***post-shutdown decay heat removal is achievable through conduction, natural convection and radiation heat transfer. Design choices include core geometry, low power density and high thermal capacity of the core structures.***

Temperature for DLOFC accident

Even for total loss of coolant, no action, after long time, temperature less than limit, high temperature just in small area, small time interval

Total Loss of coolant can never be assumed in other reactors.



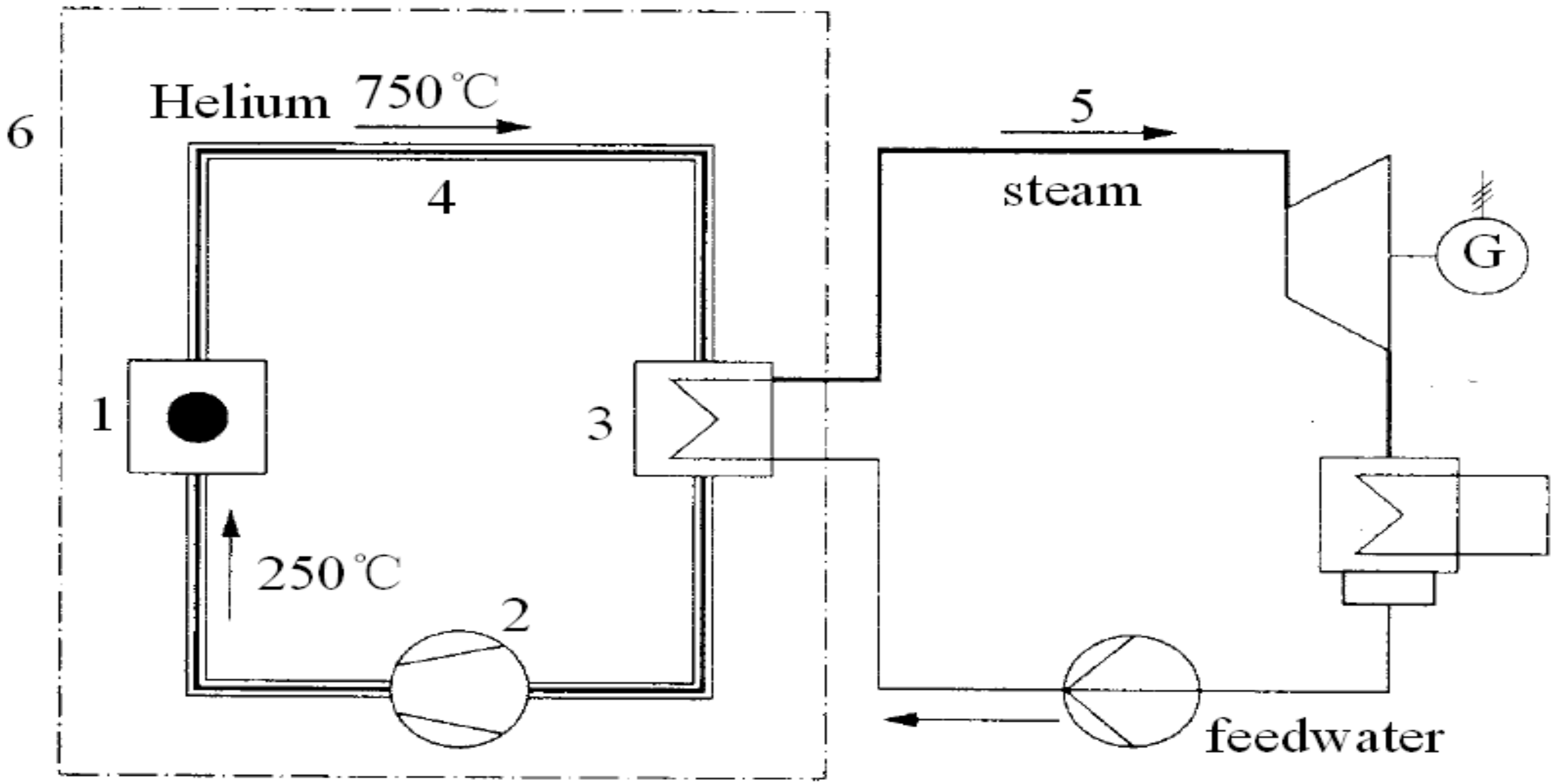


1.2 Features of HTGR

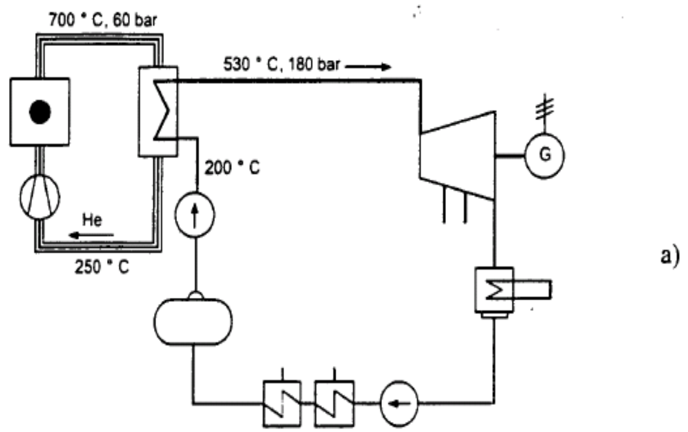
- ***HTGR Specific systems***
  - ***Helium system***
    - ***Sealing and lubrication***
    - ***Special blower***
  - ***Once-through steam generator/gas turbine/IHX with process heat***
    - ***Special manufacture and high temperature metal***
    - ***Flexible primary/secondary circuits***
  - ***Fuel handling system***
    - ***Different for prismatic and pebble***
  - ***Confinement/Vented Low Pressure Containment***
    - ***No leak-tight requirement***

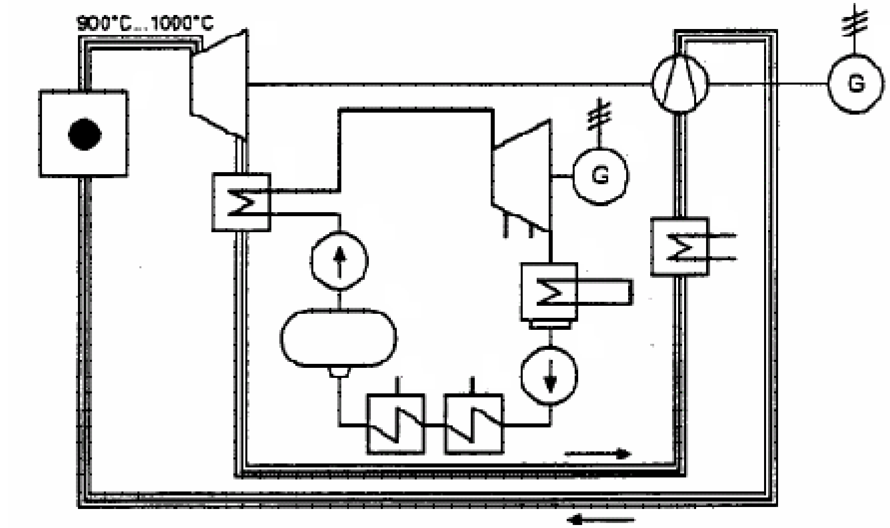
1.2 Features of HTGR

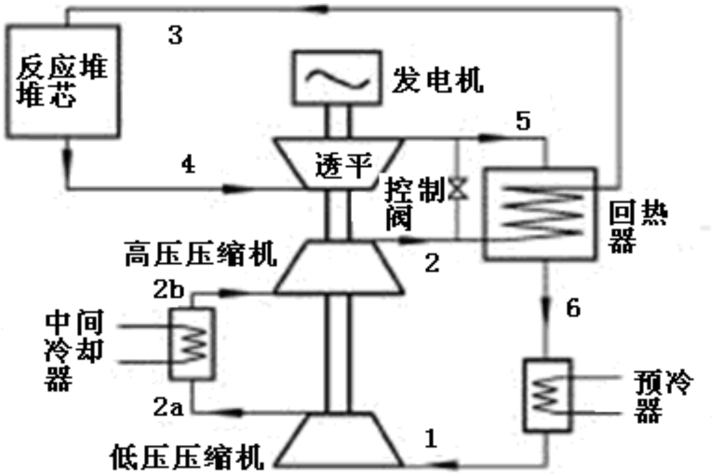
- ***Typical configuration for HTGR plant (steam cycle, Rankine Cycle)***

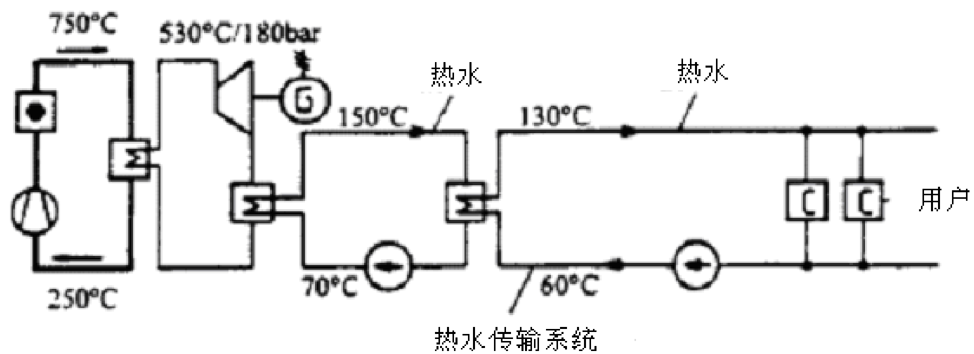


All applications: steam turbine, gas turbine, process heat, co-generation







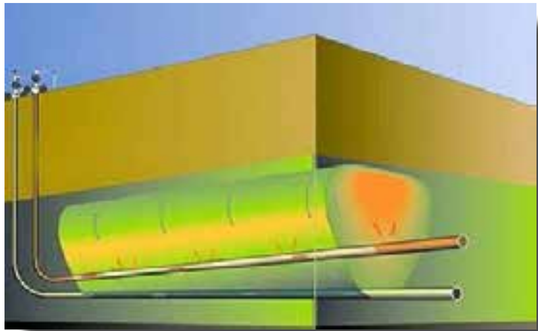


Process heat applications and co-generation

- *(Petro)Chemical*
- *Coal-to-Liquids*
- *Hydrogen production*
- *Seawater desalination*
- *…*

Hydrogen Production

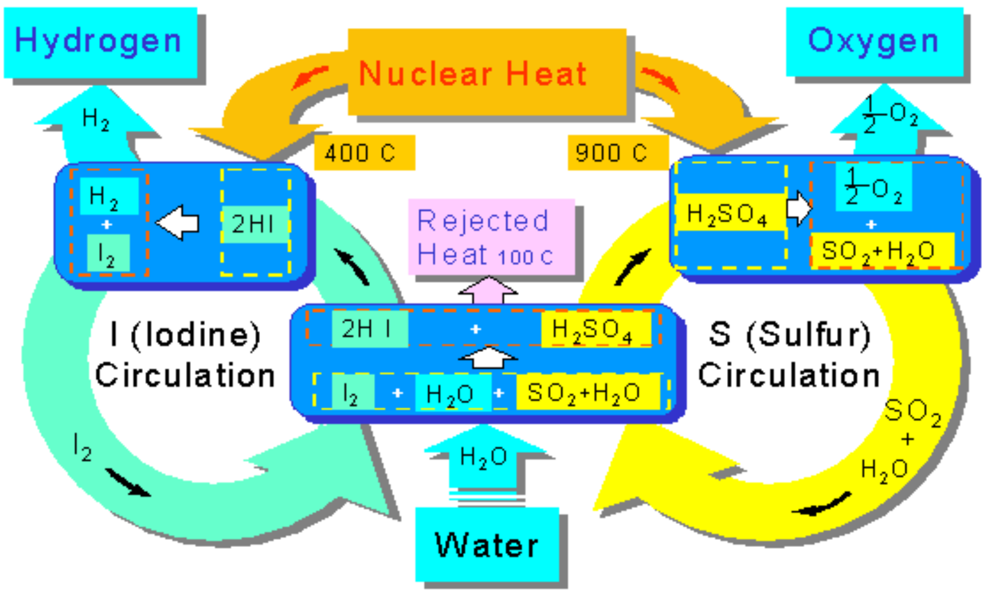
Petrochemical, ammonia, fertilizer Production

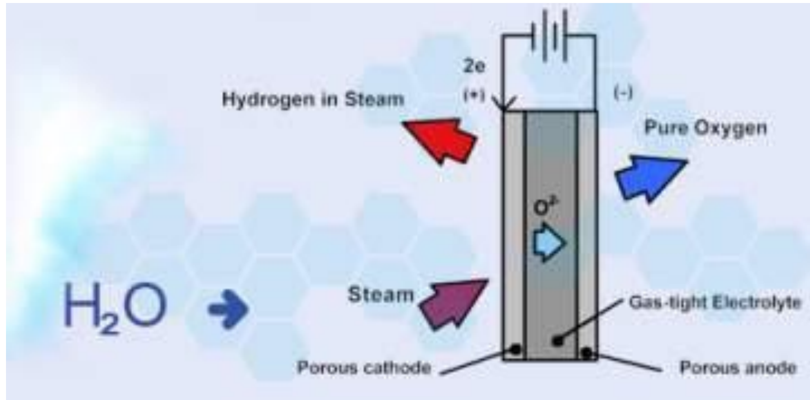


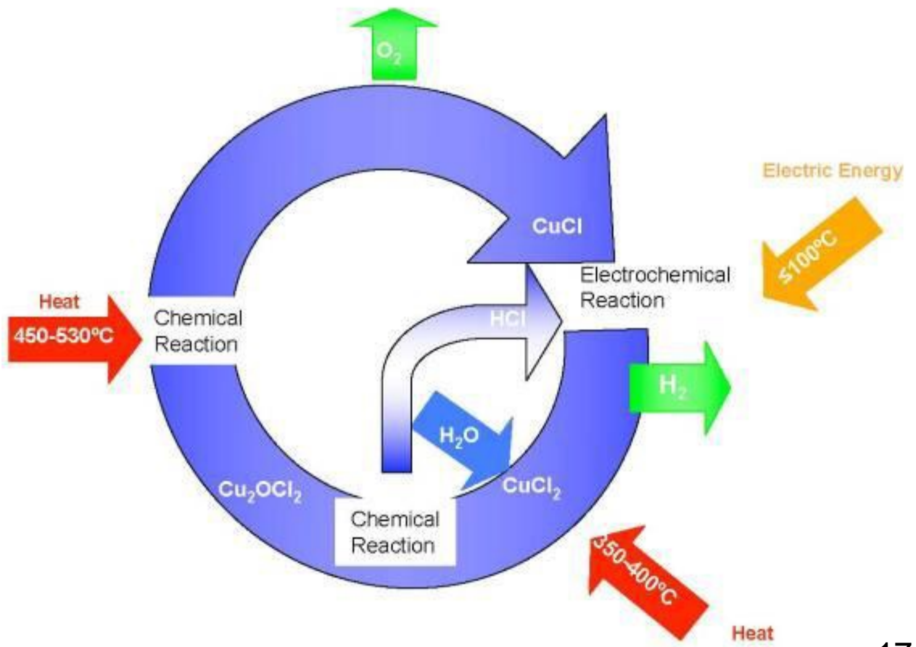
Hydrocarbon recovery

Coal-to-Liquids

Hydrogen production: S-I, HTSE, Cu-Cl







1.3 Overview of HTGR projects

- ***HTGRs operated***
- ***HTGRs designed***
- ***Current HTGR projects***

HTGRs operated

- ***Dragon** (UK)*
- ***Peach Bottom II** (USA)*
- ***AVR:** Arbeitsgemeinschaft Versuchsreaktor (Germany)*
- ***THTR:** Thorium Hochtemperaturreaktor (Germany)*
- ***FSV:** Fort St. Vrain (USA)*

- ***HTTR:** High temperature engineering test reactor (Japan)*
- ***HTR-10:** 10MW high temperature test reactor (China)*

- ***HTR-PM:** High temperature reactor—pebble-bed module (China)*

HTGRs Designed

- **HTR-MODUL: 200MWt, Pebble bed, Germany**
  - **HTR-100, HTR-500, PR-500, PNP, …**
- **MHTGR: 350MWt, 450MWt, Prismatic, US**
  - **HTGR-1160, NGNP, …**
- **GT-MHR: 600MWt, Prismatic, gas-turbine, US-Russia**
- **PBMR: 302MWt, 400MWt, Pebble bed, gas turbine, South Africa**
- **GTHTR300: 600MWt, Prismatic, Gas turbine, Japan**
- **ANTARES: 625MWt, Prismatic, Areva US**
- **Xe-100, 200MWt, pebble bed, X-energy, US**

- **HTR-PM: 250MWt*2, Pebble bed, China**
  - **HTR-PM600: 250MWt*6, Pebble bed, China**
  - **HTR-PM600S: 250MWt*6, pebble bed, steam supply, China**
  - **HTR-PM1000: 250MWt*10, Pebble bed, China**

Current HTGR projects

Project Name	Type	Thermal Power(MW)	Country	Phase
HTR-PM	Pebble bed	250*2	China	Operation
HTR-10	Pebble bed	10	China	Operation
HTTR	Prismatic	30	Japan	Operation
HTR-PM600	Pebble bed	250*6	China	Design
Xe-100	Pebble bed	200	US	Design
SC-HTGR	Prismatic	625	US	Design
GT-MHR	Prismatic	600	Russia/US	Design
MHR-T	Prismatic	600	Russia	Design
MHR-100	Prismatic	215	Russia	Design
GTHTR-300	Prismatic	600	Japan	Design
NHDD	Pebble bed	200	Korea	Design
RDE	Pebble bed	10	Indonesia	Design
U-Battery	Prismatic	10	UK	Design
EUHTER	Prismatic	165	Poland	Design
MMR(USNC)	Prismatic	15	US	Design
BANR(BWXT)	Prismatic	50	US	Design

2 Status of HTR-PM project

- ***HTR-PM: High temperature gas cooled reactor--pebble bed module***

- ***HTR-PM demonstration plant***
  - ***Supported by the Chinese National Key Science and Technology Project (1 of 16 projects)***
    - ***Government support the R&D***
    - ***Commercial operation***
    - ***Technology demonstrated for future commercial HTR plant***
  - ***Located in Shidao Bay, Shangdong Province***

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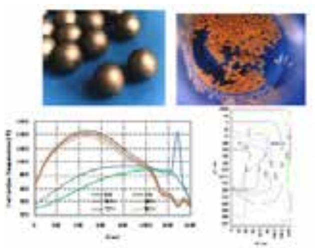
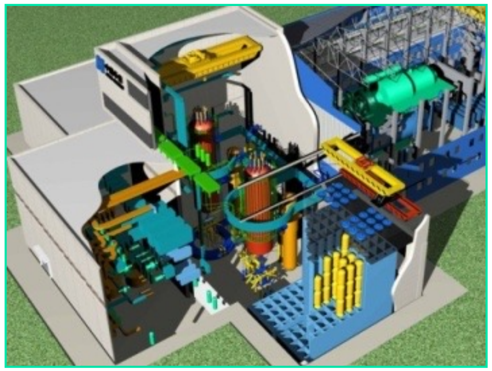
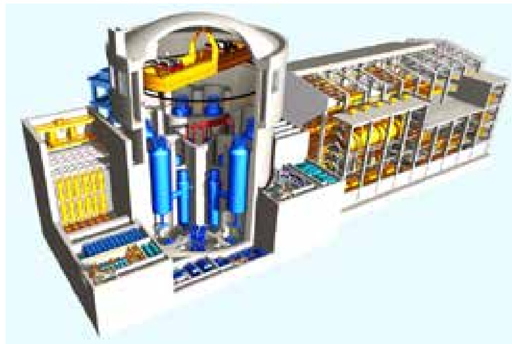
Overview of China HTR program

- China chose pebble bed HTR
- Research was started in 1970s
- Benifited from international cooperation







Fundamental R&D	Test reactor	Demonstration plant	Commercial plant
1970s	1986-, HTR-10	2001-, HTR-PM	2014~, HTR-PM600

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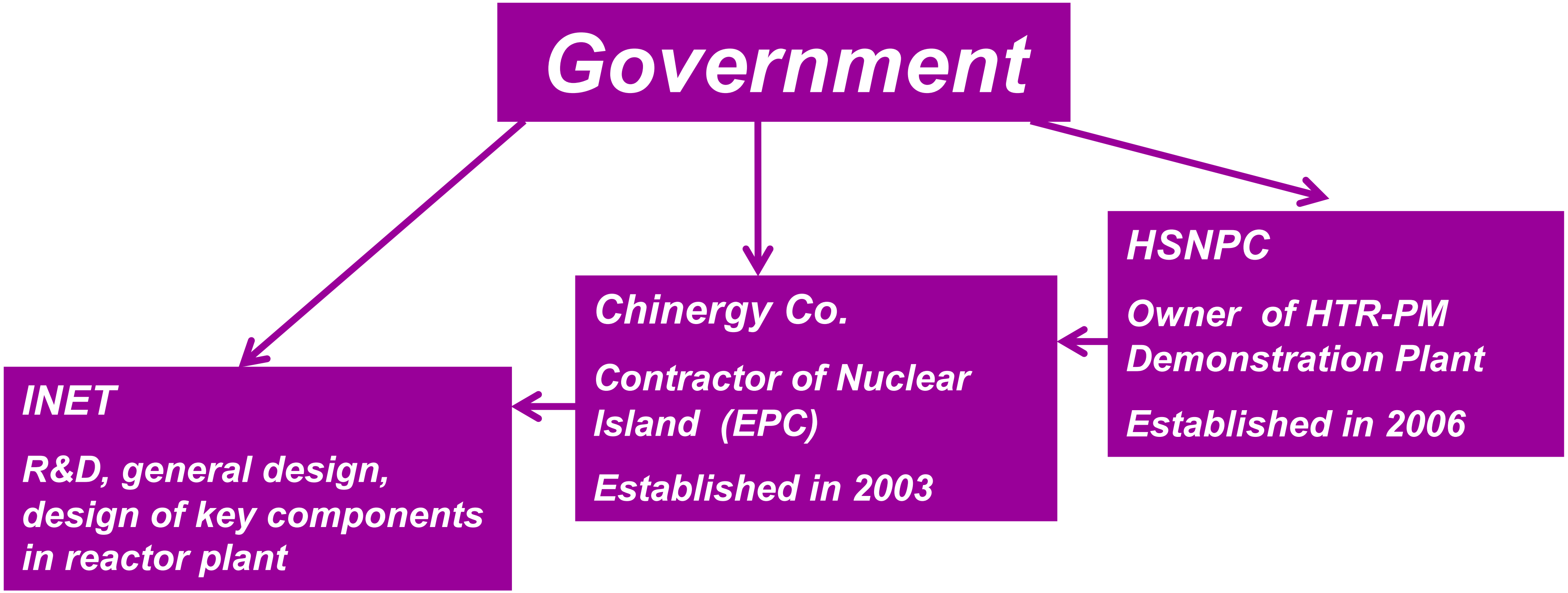
2 Status of HTR-PM project

- ***Mission of HTR in China***
  - ***Supplement to PWRs***
    - ***for power generation, especially to replace coal-fired power plant in popular region***
  - ***Co-generation***
    - ***of steam and electricity,***
    - ***& Hydrogen production in future***
  - ***Technology Innovation***
    - ***Supported as one of National Key Science and Technology Projects***
    - ***Establishment of whole supply chain***

HTR-PM development team

- *As one of national key S&T projects, including research, design, licensing, manufacturing, construction, fuel fabrication, operation, …, with many partners*



HTR-PM demonstration plant in Shidao Bay, Shandong

The overview of the HTR-PM site

HTR-PM Preparation

- 2003: finished pre-concept design and decided to use steam turbine
- 2004: signed industry investment agreement
- 2006.01: became a key government R&D project
- 2006.09: decided to use 2×250 MWt reactors with a 200 MWe turbine
- 2008.02: government approved the HTR-PM project
- 2008.10: issued procurement contracts of the lead components
- 2008.4-2009.9: PSAR review
- 2012.12: government issued construction permit and we poured the first concrete

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Main milestone for construction

2012.12.9: FCD

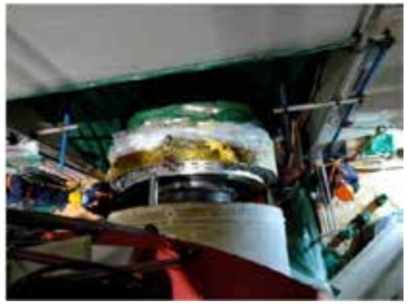
2015.6.24: 2# module for big component

2016.3.20: 2# RPV
2016.9.14: 1# RPV

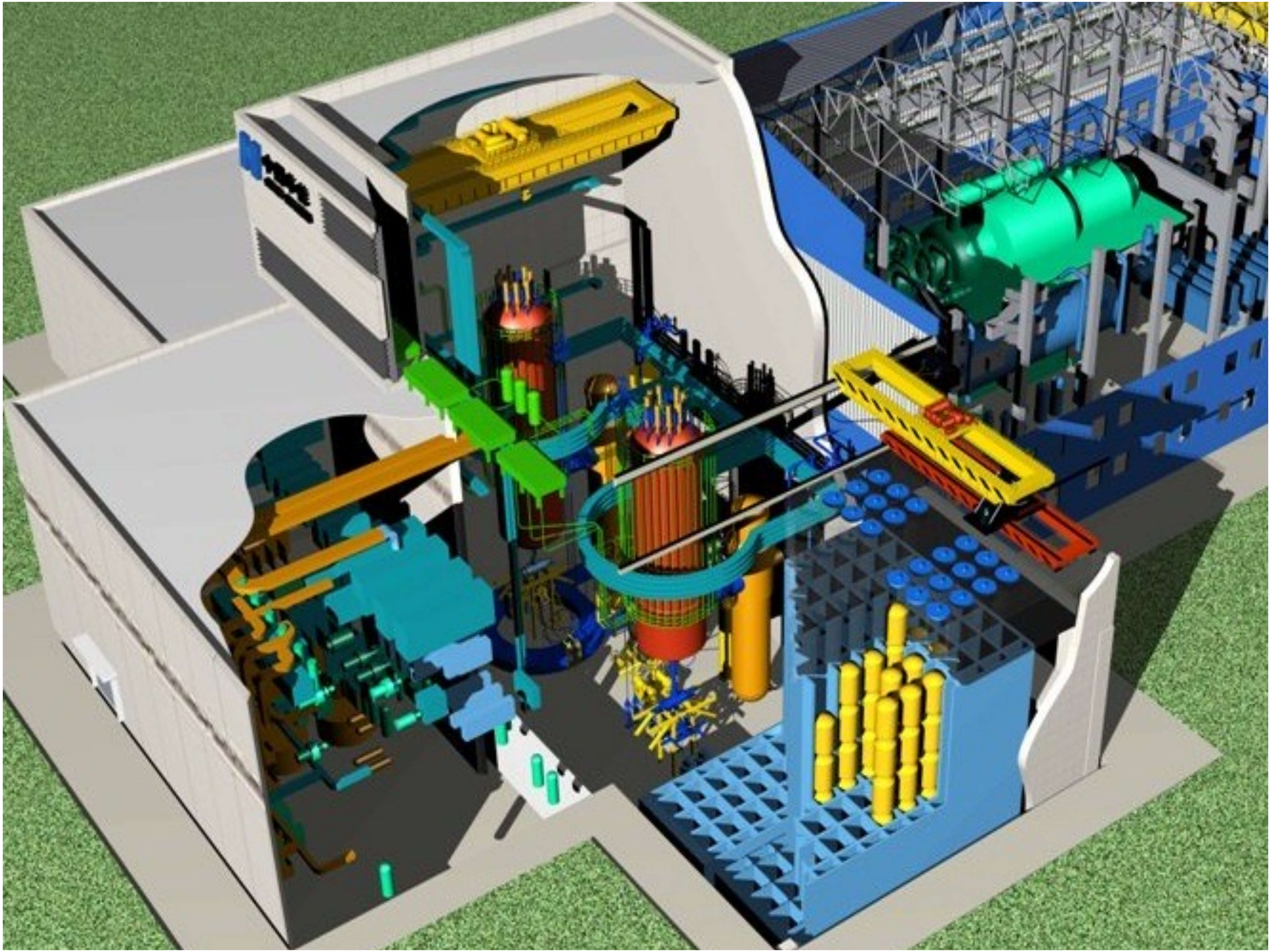
2017.6.8: 2# Core internal

2018.3.30: 2# head of RPV

2019.1.27: 2# SG

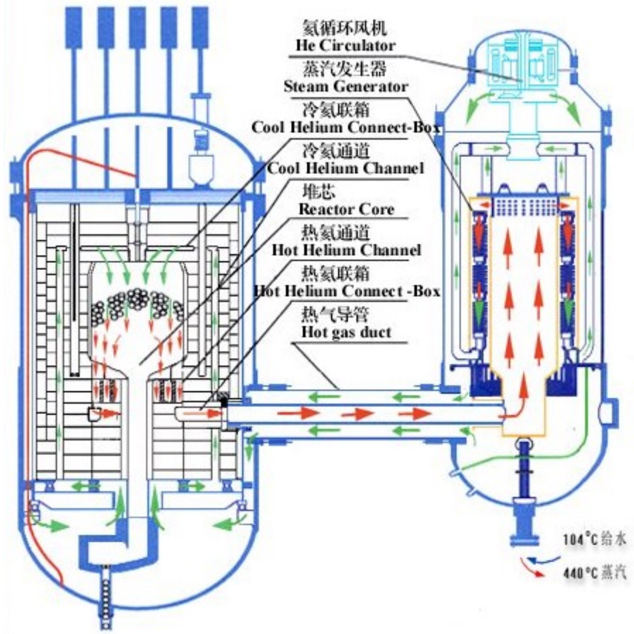


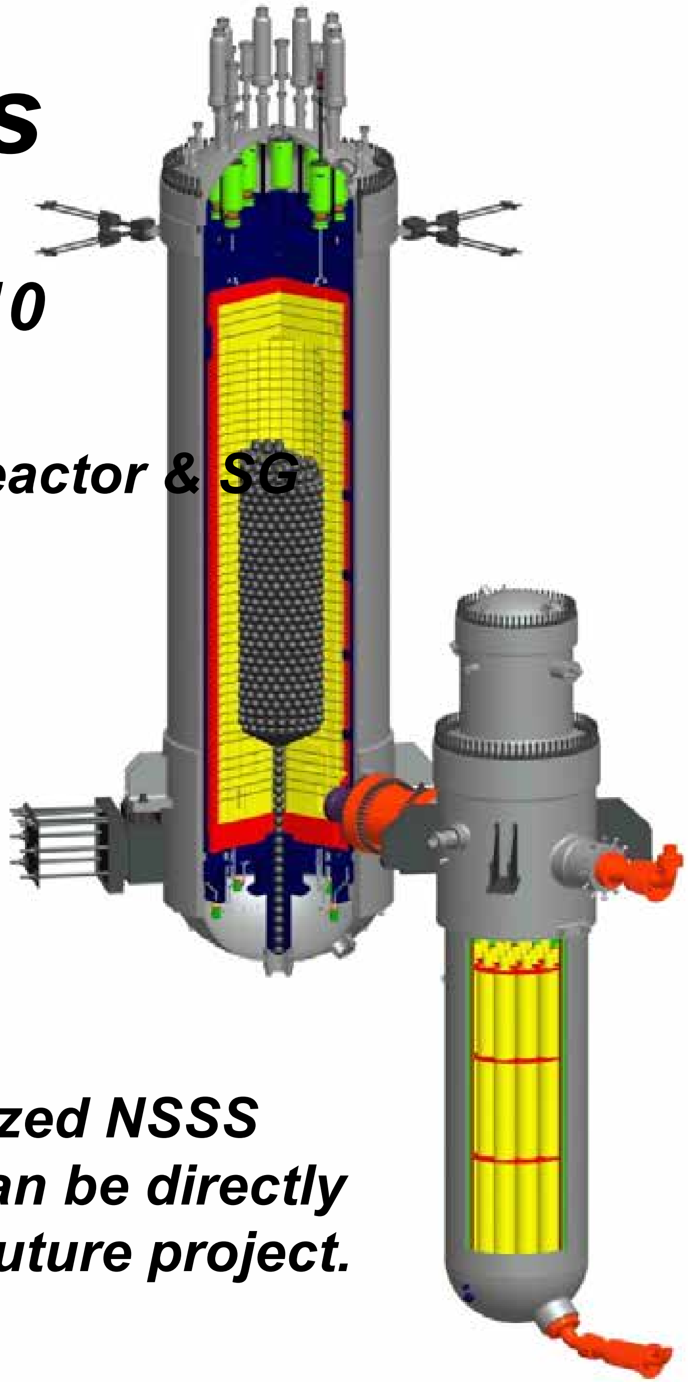
2020.3.18: Fix 2# RPV, SGPV, HDPV



HTR-PM progress

- *Technology based on HTR-10*
  - *Single zone core*
  - *Side by side arrangement of reactor & SG*
  - *Super heat steam*
  - *Modular desgin*

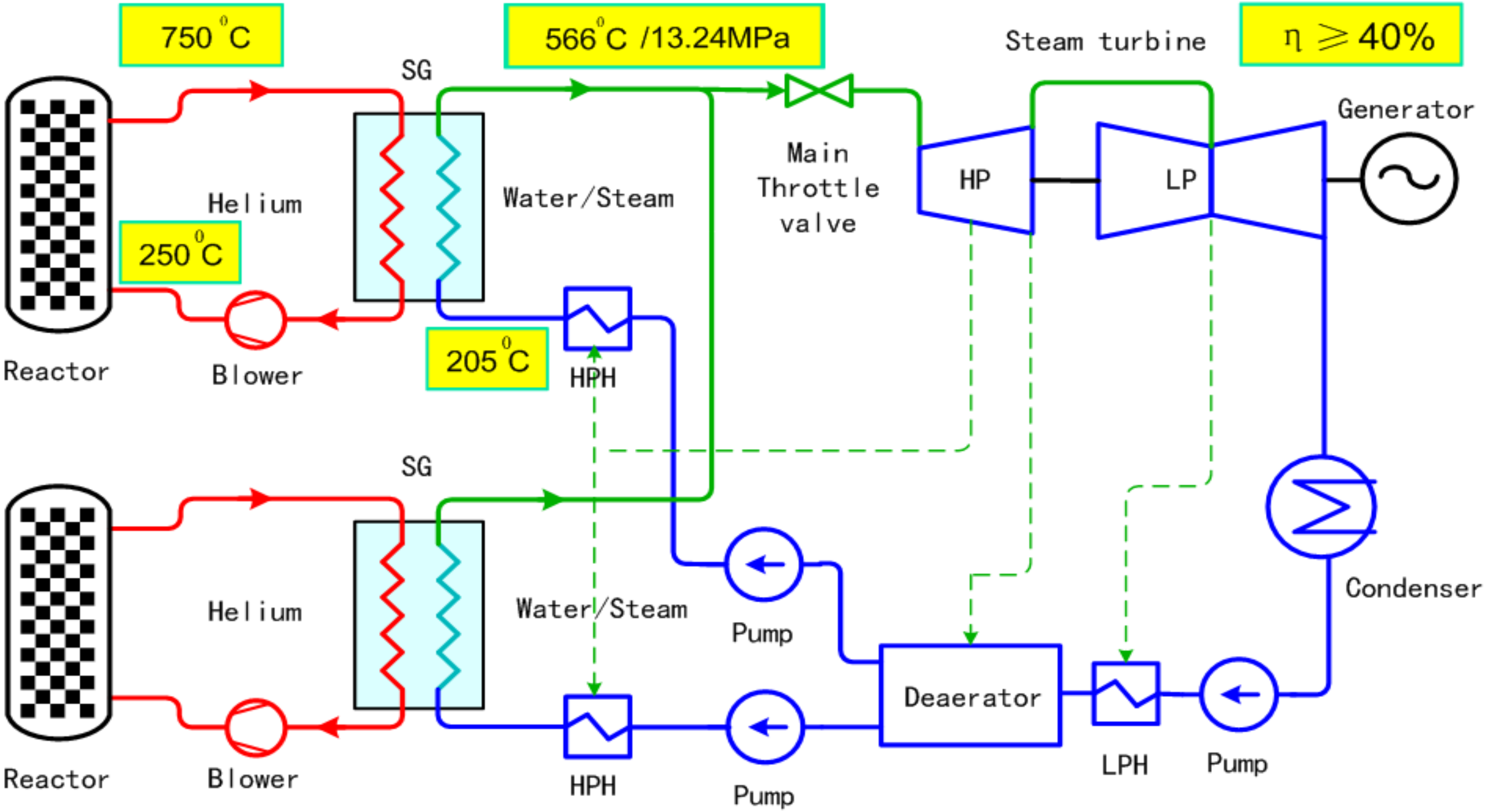




- *Standardized NSSS module can be directly used for future project.*

HTR-PM progress

- *2 NSSS modules connected with 1 turbine in HTR-PM*
  - *6 modules will be connected with 1 turbine in HTR-PM600*



HTR-PM Design Parameters

Plant electrical power, MWe	211
Core thermal power, MW	250
Number of NSSS Modules	2
Core diameter, m	3
Core height, m	11
Primary helium pressure, MPa	7
Core outlet temperature, °C	750
Core inlet temperature, °C	250
Fuel enrichment, %	8.5
Steam pressure, MPa	13.25
Steam temperature, °C	565/535

2 Status of HTR-PM project

- ***Main achievements***
  - ***Standard NSSS module with full scale test and operation demonstration***
  - ***Experience & development team covering design, manufacturing, licensing, construction & installation, commissioning test, operation, …***
  - ***Licensing framework***
  - ***Test facilities for future development***
  - ***Whole supply chain***
  - ***Fuel fabrication capability***
  - ***Operation experience feedback for future plants***
  - ***…***

Test Facilities for HTR-PM Project

ETF-HT	Engineering Test Facility- Helium Technology	10MWt test power, 7.0MPa, 250-750℃, helium	Heat source to verify steam generator
ETF-SG	Engineering Test Facility- Steam generator	10MWt test power, 13.25MPa, 205-570℃, water	Secondary loop and third loop to verify steam generator
ETF-HC	Engineering Test Facility- Helium Circulator	4.5MWe, 7.0MPa, 250℃, helium	Full scale verification of helium circulator
ETH-FHS	Engineering Test Facility- Fuel Handling System	7.0Mpa, 100-250 ℃, helium, two chain	Full scale verification of fuel handling system
TH-FHS	Test Facility- Fuel Handling System	Full geometry size, air, 0.1MPa	Verification of the fuel movement in the FHS system
ETF-CRDM	Engineering Test Facility- Control Rods Driving Mechanism	1MPa, 100-250℃, helium	Full scale verification of Control Rods Driving Mechanism
ETF-SAS	Engineering Test Facility- Small Absorber Sphere System	7.0MPa, 100-250℃, helium	Full scale verification of small absorber sphere system
ETF-SFS	Engineering Test Facility- Spent Fuel System	Full geometry size, air, 0.1 MPa	Full scale verification of major components of spent fuel storage system
TF-SFCD	Test Facility- Spent Fuel Canister Drop	Full geometry size, Full height (30m), Full weight (17t)	Full scale drop verification of spent fuel canister
ETF-HPS	Engineering Test Facility- Helium Purification System	7.0MPa,25-250℃,helium Purification flow rate: 40kg/h	Verification of purification efficiency (greater than 95% and system resistance less than 200kPa).
TF-PBEC	Test Facility- Pebble Bed Equivalent Conductivity	1600℃, helium/vacuum	Measurement of pebble bed equivalent conductivity
TF-PBF3D	Test Facility- Pebble Bed Flow 3D	0.1 MPa, room temperature, air	Three-dimensional simulation test for pebble bed flow (1:5 scale)
TF-HGM	Test Facility- Hot Gas Mixing	atm,20-150℃, air	Reduced scale (1:2.5) verification of hot gas mixing at reactor core outlet
ETF-DCS	Engineering Test Facility- Distributed Control System	Reactor power control system, fuel cycle control system, VDU-based Man-Machine Interface	verification of DCS architecture and major control Systems
ETF-RPS	Engineering Test Facility- Reactor Protection System	Prototype of Reactor Protect System with 4 channels	Full scale verification of Reactor Protect System
ETF-MCR	Engineering Test Facility- Main Control Room	1:1MCR control consoles, mimic panels, layouts and inner environments	Full scale verification of Man-Machine Interface

2 Status of HTR-PM project

- ***HTR-PM Supply chain:***
  - ***Plant Owner (in China): China HUANENG Corp.， China National Nuclear Corp.(CNNC) ， China General Nuclear Power Corp.(CGNPC)***
  - ***Main Components Suppliers:***
    - ***Shanghai Electric: RPV, Metallic Reactor Internals, CRDMs, SASs, Steam Turbine, Helium Circulators***
    - ***Harbin Electric: Steam Generator, Generator***
    - ***Toyo Tanso: Graphite***
    - ***CGNPC: RPS, DCS, Simulator***
  - ***Fuel supplier: CNNC with INET***
  - ***Nuclear island EPC Contractor: CHINERGY***
  - ***R&D, NSSS and main NI system Engineering: INET***
  - ***Other components: companies inside and outside China***

2 Status of HTR-PM project

- ***Main progress(commissioning test):***
  - ***2021.08.21: first fuel loading***
  - ***2021.09.12: first criticality of the 1# reactor***
  - ***2021.11.01: first criticality of the 2# reactor***
  - ***2021.12.20: first connection to the grid with partial power (15MWe)***
  - ***2022.10.20, 2022.12.7, 2022.12.9: reached 200MWt***
  - ***2023.8.13, 9.1, 9.15: transient test***
    - ***Lost of off-site power supply, turbine trip, load ejection,***
    - ***Trip 1# or 2# NSSS module, or bypass steam***
  - ***2023.9.26 12:30-9.30 16:30, 100hr continuous operation***
  - ***2023.12.6: Commercial operation***

2 Status of HTR-PM project

- ***Main results from commissioning test:***
  - ***All types of test are finished***
  - ***All systems operate stably***
  - ***Coordination control system works fine***
    - ***Reactor power quickly follows the helium flowrate***
  - ***Trip of reactor without cooling has no challenge, as expected***
  - ***Trip of reactor can simulate ATWS, because drop of control is very slow***
  - ***Continuous operation of reactor after trip of turbine can is demonstrated***

Recent photo of HTR-PM

Recent photo of HTR-PM

2 Status of HTR-PM project

- Experience from HTR-PM
  - Commercial operation demonstrated the technology maturity
  - Many technical problems are solved
  - First of a kind (FOAK) are not easy
    - Key components: RPV, SG, core internals, helium circulator, fuel handling system
    - Whole plant is also FOAK
  - Experience feedback for future projects is important
  - Safety performance is demonstrated
    - Availability and maintenance consideration need continuously improvement

3 Licensing experience for HTR-PM

- ***3.1 Requirement/standards system for HTR***
- ***3.2 Special requirement for HTR-PM***
- ***3.3 Main concerns during Licensing of HTR-PM***

3.1 Requirement/standards system for HTR

- ***No specific requirement/standards system developed for HTR yet, in China, & worldwide***
- ***General requirement/standards system developed from LWR are used for design/licensing of HTR***
- ***Some special requirement/standards for HTR are developed***
  - ***More and more will be developed***
  - ***NNSA lead this activities***

3.1 Requirement/standards system for HTR

- *No essential change to current requirement are made, especially for industrial norms/standards*
  - *core melt free is recognized, but is not reflected to requirement of component design*
  - *safety classification may optimized in future, to balance the cost and safety*
- *Some technical adaption is made, taking into account of*
  - *helium, high temperature, pebble bed, TRISO coated particle fuel, once through SG, ...*
  - *Vented low pressure containment*
  - *...*

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3.1 Requirement/standards system for HTR

- ***Requirement structure of IAEA***
  - ***IAEA provide reference requirement structure***

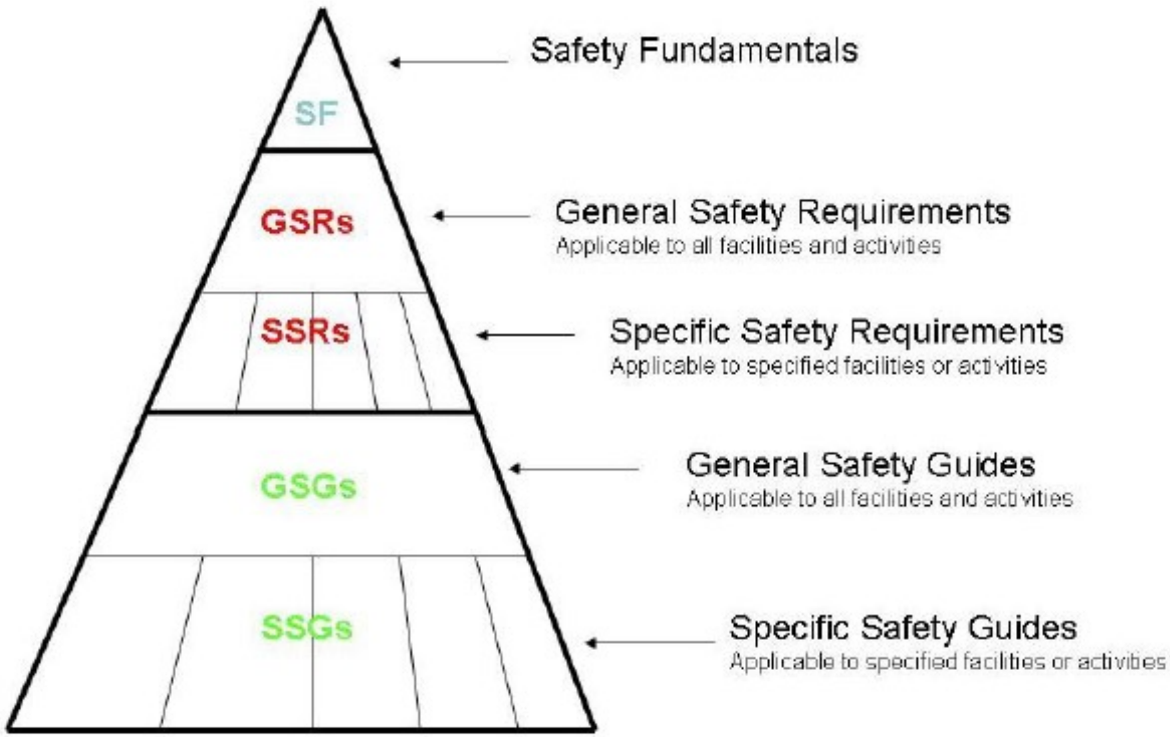

Fig. 1: Safety Standards Categories

3.1 Requirement/standards system for HTR

- *Chinese standard system*
  - *Laws*
  - *Department requirement*
    - *HAF, learn from IAEA GSR/SSR*
  - *Guides*
    - *HAD, learn from IAEA GSG/SSG*
  - *Standards/codes*
    - *GB, NB, EJ, …*
  - *Technical document*
    - *IAEA TECDOC, NUREG,…*

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3.1 Requirement/standards system for HTR

- ***Chinese standard system***
  - ***China adopts ISO,IEC,IAEA, …***
    - ***IAEA SSR 2/1 is adopted by NNSA***
  - ***Some projects also directly use ASME, RCC,.. for system/components***
    - ***Most of them are transferred to national or industrial standards: GB (National Standards), NB (Energy Industry Standard)***

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3.2 Special requirement for HTR-PM

- ***HTR-PM consideration***
  - ***HTR-PM is designed and licensed according to requirement of commercial NPP***
  - ***HTR-10 is also designed and licensed according to requirement of commercial NPP***
    - ***Try to support later on commercial HTGR at very beginning***
  - ***Regulatory and INET jointly developed some specific requirement for HTR***
    - ***Specific design criteria, for HTR-10 and HTR-PM***
    - ***Policy announcement, for HTR-PM***

3.2 Special requirement for HTR-PM

- ***Standards adopted in HTR-PM***
  - ***GB，NB，EJ,***
    - ***Most equivalent to ASME/IEC/IEEE***
  - ***KTA***
    - ***Helium property (KTA3102)***
    - ***Pebble bed property(KTA3102)***
    - ***Graphite structure (KTA3232)***
  - ***ASME***
    - ***For mechanical part***

3.2 Special requirement for HTR-PM

- ***SSR 2/1(safety for design) consideration***
    - *China NNSA adopt SSR 2/1 as HAF102 (HAF: nuclear safety requirement)*
  - *HTR version of SSR 2/1 is developed in IAEA (CRP), Chinese HTR version HAF102 is also developed in China, but both are not formally released*
  - *Most items are applicable for HTR*
  - *Some minor changes are made*
    - *Containment, fuel, ECCS*
    - *Similar plant state, including Design Extension Condition, but without core melt*
  - *Some changes for HTR version of Chinese equivalent safety guides (HAD) are also proposed, but no essential changes are proposed*

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3.2 Special requirement for HTR-PM

- ***Develop safety design criteria guided by licensing authorities in 2003***
  - ***Try to develop specific version of requirement for Modular HTGR, jointly by designers and licensing experts, from 2003 t0 2004***
  - ***Draft was finished in 2004***
    - ***Based on experiences from HTR-10***
    - ***Based on concept design for commercial HTGR***
  - ***Not published/released, but this draft document increased the agreement between Designer & licensing authorities***

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3.2 Special requirement for HTR-PM

- ***TOC of the draft requirement:***
  - ***1 Introduction***
    - ***1.1 Safety features of Modular HTGR***
      - ***1.1.1 Safety features of Modular HTGR***
      - ***1.1.2 Fundamentals of Modular HTGR***
    - ***1.2 Safety goals of Modular HTGR***
    - ***1.3 Defense in Depth concept***
    - ***1.4 Accident management***
    - ***1.5 Requirement for emergency planning***

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3.2 Special requirement for HTR-PM

- *TOC of the draft requirement:*
  - *2 System design requirement for HTGR*
    - *2.1 reactor core and associated features*
      - *2.1.1 General Design*
      - *2.1.2 Fuel element*
      - *2.1.3 Reactor core control*
      - *2.1.4 reactor shutdown*

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3.2 Special requirement for HTR-PM

- ***TOC of the draft requirement:***
  - ***2 System design requirement for HTGR***
    - ***2.2 reactor coolant system***
      - ***2.2.1 Design of reactor coolant system***
      - ***2.2.2 In-service inspection on boundary of primary coolant system***
      - ***2.2.3 Inventory of coolant***
      - ***2.2.4 Purification of coolant***
      - ***2.2.5 Removal of decay heat from the core***
      - ***2.2.6 Ultimate sink of decay heat***

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3.2 Special requirement for HTR-PM

- ***TOC of the draft requirement:***
  - ***2 System design requirement for HTGR***
    - ***2.3 Containment***
      - ***2.3.1 Function***
      - ***2.3.2 Design philosophy and possible configuration***
      - ***2.3.3 Performance requirement***

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3.2 Special requirement for HTR-PM

- TOC of the draft requirement:
  - 2 System design requirement for HTGR
    - 2.4 Instrumentation and Control system
    - 2.5 Emergency control center
    - 2.6 Emergency power supply
    - 2.7 Waste treatment and control system
    - 2.8 Fuel handling and storage system
    - 2.9 Radiation protection

3.2 Special requirement for HTR-PM

- ***TOC of the draft requirement:***
  - ***Appendix 1: postulated Initiating events***
  - ***Appendix 2: Redundancy, diversity and independence, inherent safety***

3.2 Special requirement for HTR-PM

- ***Develop design criteria for HTR-PM***
  - ***Jointly with INET and NNSA, 2004-2007***
  - ***Based on experience of draft version of safety requirement***
  - ***Along the progress of HTR-PM design***
  - ***Address the function requirement / design requirement / standards used for key systems and components, much more detailed than safety requirement***

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3.2 Special requirement for HTR-PM

- ***Design criteria (40 chapters)***
  - ***1 Operation and accident conditions***
  - ***2 Safety class of structures, systems and components***
  - ***3 Accept criteria for accident analysis***
  - ***4 Accident analysis method related to environment***
  - ***5 Design principles and requirement for radiation protection***
  - ***6 Design criteria for radioactive solid waste treatment system***
  - ***7 Design criteria for air purification system of nuclear grade***
  - ***8 Design criteria for radioactive liquid waste treatment system***
  - ***9 Neutronics design criteria***
  - ***10 Thermo-hydraulics design criteria***

3.2 Special requirement for HTR-PM

- ***Design criteria (40 chapters)***
  - ***11 General design criteria for reactor structure***
  - ***12 Design criteria for ceramics core internals***
  - ***13 Design criteria for metal core internals***
  - ***14 Design criteria for pressure vessels***
  - ***15 Design criteria for hot gas duct***
  - ***16 Design criteria for the supporting of main components in reactor coolant system***
  - ***17 Design criteria for steam generator***
  - ***18 Design criteria for nuclear fuel***
  - ***19 Design criteria for fuel handling system***
  - ***20 Design criteria for fuel storage and transportation system***

3.2 Special requirement for HTR-PM

- ***Design criteria (40 chapters)***
  - ***21 Design criteria for helium coolant system***
  - ***22 Design criteria for helium purification and supporting system***
  - ***23 Design criteria for decay heat removal system***
  - ***24 Design criteria for confinement***
  - ***25 Design criteria for main helium circulator***
  - ***26 Design criteria for control rod system***
  - ***27 Design criteria for small absorber ball system***
  - ***28 protection criteria for the hypothetic pipe break accident***
  - ***29 Design criteria for the pressure control and relief system for primary circuit***
  - ***30 Design criteria for the reactor protection system***

3.2 Special requirement for HTR-PM

- ***Design criteria (40 chapters)***
  - ***31 Design criteria for the instrumentation and control system***
  - ***32 Design criteria for the process instrumentation***
  - ***33 Design criteria for the control room***
  - ***34 Design criteria for backup shutdown point***
  - ***35 Design criteria for the emergency electricity supply system***
  - ***36 Design criteria for the cable layout and isolation***
  - ***37 Design criteria for layout of nuclear steam supply system***
  - ***38 Design criteria for the installation, commissioning, operation and maintenance requirement***
  - ***39 Design criteria for the decommission***
  - ***40 Design criteria for radiation shielding***

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3.2 Special requirement for HTR-PM

- ***Policy announcement for HTR-PM licensing in 2008***
  - ***1 Forewords***
  - ***2 Safety objectives (goals)***
  - ***3 Defense in depth***
  - ***4 General design criteria***
  - ***5 Containment: VLPC***
  - ***6 Accident source term: mechanism based***
  - ***7 Emergency plan: Technically not needed***
  - ***8 Application of PSA: to support design***
  - ***9 V&V for safety analysis software***

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3.2 Special requirement for HTR-PM

- *Topics for Policy announcement for HTR-PM licensing*
  - *Inherent safety philosophy*
  - *Long and smooth time envelop*
  - *Good performance of fuel*
  - *Limited release*
  - *Probabilistic safety goal: 50mSv, 10^{-6} /reactor year*
  - *VLPC*
  - *BDBA as PSA*

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3.2 Special requirement for HTR-PM

- ***Main considerations: based on current licensing framework***
  - ***Framework based on IAEA safety standard series (LWR oriented)***
  - ***SAR structure based on SRP from NRC***
  - ***Standards based on international experience (ASME, IEEE, IEC, …)***
  - ***Specialties for Modular HTGR, accepted in safety requirement, design criteria, specified in policy announcement***

3.2 Special requirement for HTR-PM

- ***Main considerations: Recognized features of Modular HTR***
  - ***1) Good negative feedback; Larger margin for fuel temperature between operation and limit, self shutdown because of temperature increase, or keep in very low power level;***

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3.2 Special requirement for HTR-PM

- ***Main considerations: Recognized features of Modular HTR***
  - ***2) Slow transient because of low power density, large heat capacity of core internals, TRISO fuel for high temperature. Proper core geometry for self removal of decay heat;***

3.2 Special requirement for HTR-PM

- ***Main considerations: Recognized features of Modular HTR***
  - ***3) For conventional LWR, containment acted as the final barrier to limit the accident consequence and to retain the radioactive material, on the contrary, modular HTGR rely on the high reliable TRISO fuel to retain the radioactive material. VLPC act as DiD or ALARA.***
    - ***Sub-atmosphere ventilation in normal operation***
    - ***Direct release is permitted for helium pipe break accident***
    - ***Ventilation with filter for long term depressurized accident, for ALARA***

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3.3 Main concerns during Licensing of HTR-PM

- ***Before licensing***
  - ***Jointly develop draft safety requirement, design criteria***
  - ***Formally release a policy announcement***
- ***During licensing***
  - ***Detailed assessment PSAR/FSAR***
  - ***Propose some changes to design***
- ***After licensing***
  - ***CP conditions: experiments required, V&V***

3.3 Main concerns during Licensing of HTR-PM

- ***Main topics in FSAR review***
  - ***Uncertainty for everything***
    - ***Or conservation for everything***
  - ***Experimental data for code V&V***
  - ***Roles of PSA***
  - ***Management of BDBA***
  - ***Controlled state***
  - ***Multiple NSSS modules***
  - ***…***

4 New HTR plants in China

- ***Strategy for new plants***
- ***Demands for process heat***
- ***Concept of HTR-PM600***
- ***Concept for HTR-PM600S***

Strategy for new HTR plant

- ***HTR-PM belongs to SMR***
  - ***250MWt/100MWe per module***
  - ***2 NSSS modules + 1 turbine as 1 units***
- ***HTR-PM demonstrated***
  - ***The safety features of modular HTR***
  - ***Technical feasibility for multiple NSSS modules***
  - ***The supply chain of modular HTR***
    - ***The main components***
    - ***The fuel fabrication***
    - ***The licensing experience***
    - ***The experienced development team***
    - ***…***

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Strategy for new HTR plant

- ***Batch construction of HTR-PM is possible***
- ***How to improve HTR-PM?***
  - ***Provide versatile applications***
    - ***Electricity, steam, hydrogen, or co-generation***
  - ***Reduce the cost***
    - ***Larger plant, but with more NSSS modules***
  - ***Reduce risk***
    - ***Standardized components/NSSS modules***
    - ***Modular construction***
  - ***Flexible***
    - ***Different number of NSSS modules in 1 units***
    - ***China need larger plant: more modules***
    - ***Other countries may need small plant: less modules***

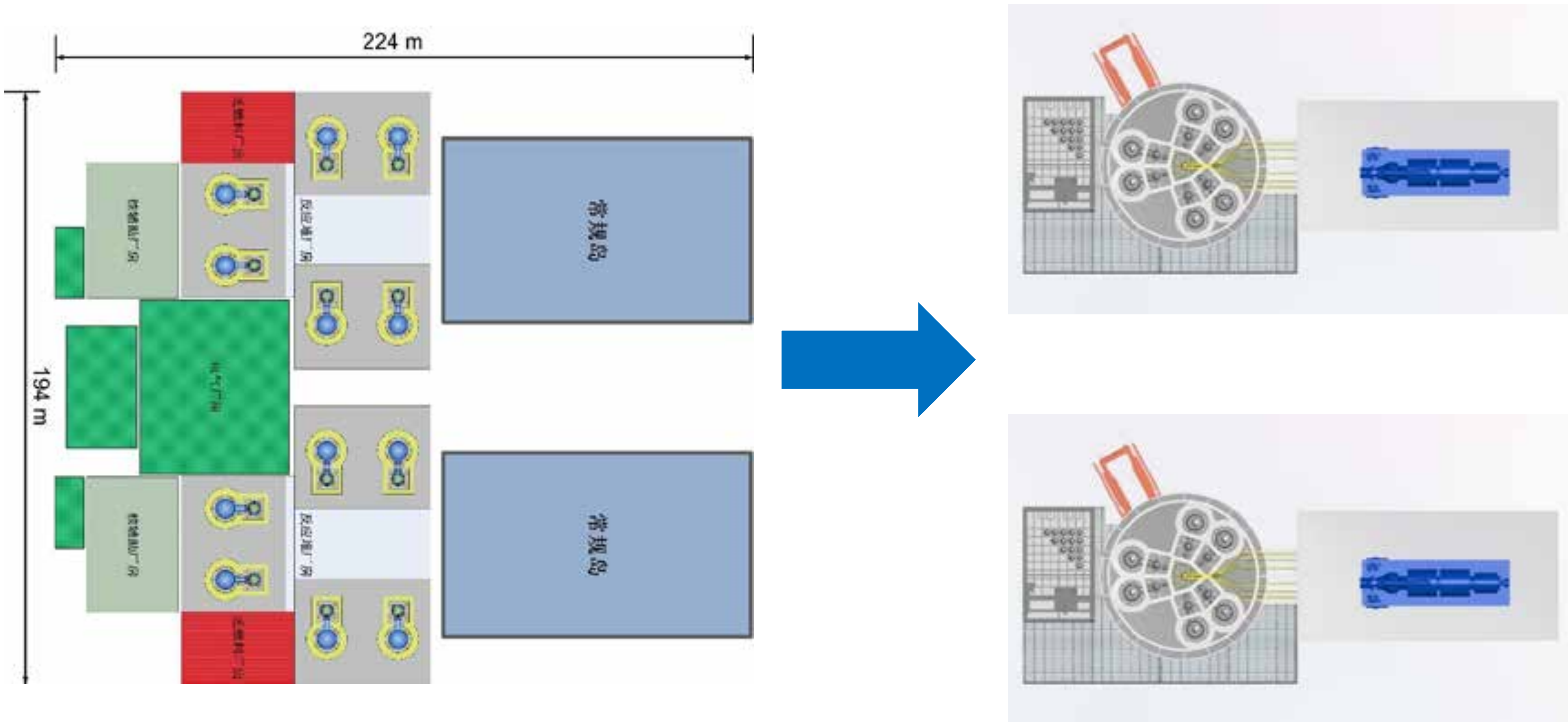
Strategy for new HTR plant

- ***HTR-PM600 is one of solutions***
  - ***6 NSSS modules connect to 1 steam turbine, comparing with 2 modules in HTR-PM, with***
    - ***the same safety features,***
    - ***the same major components,***
    - ***the same primary circuit parameters,***
  - ***With the same site footnote and building volume comparing with the same size PWRs.***
  - ***With the interface of steam extraction capability for co-generation***
  - ***With lower construction cost***
  - ***Still maintain the advantages of SMR***

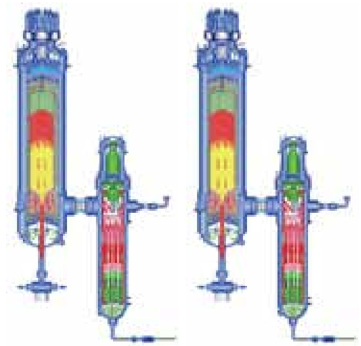
Concept for HTR-PM600

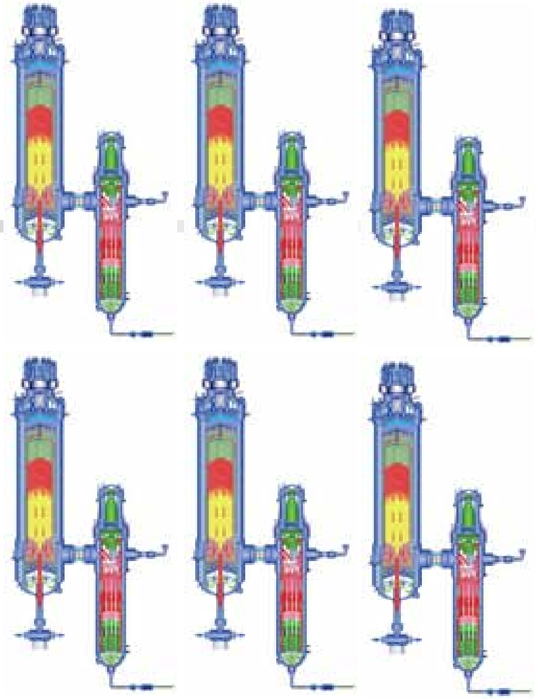
Evolution of HTR-PM600 layout:

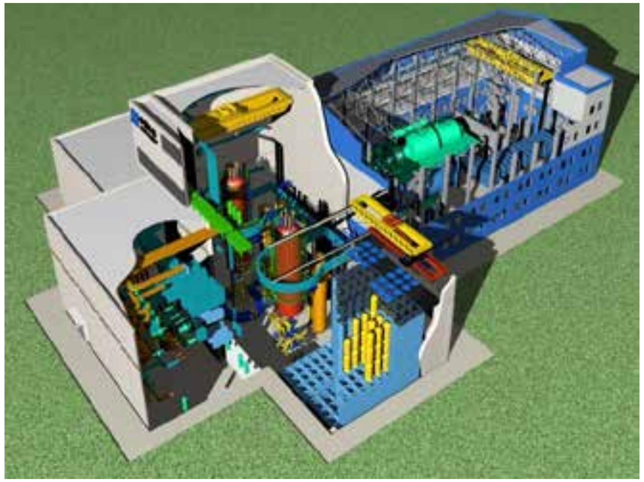
The volume of seismic qualified building was reduced 50%, the same as PWR

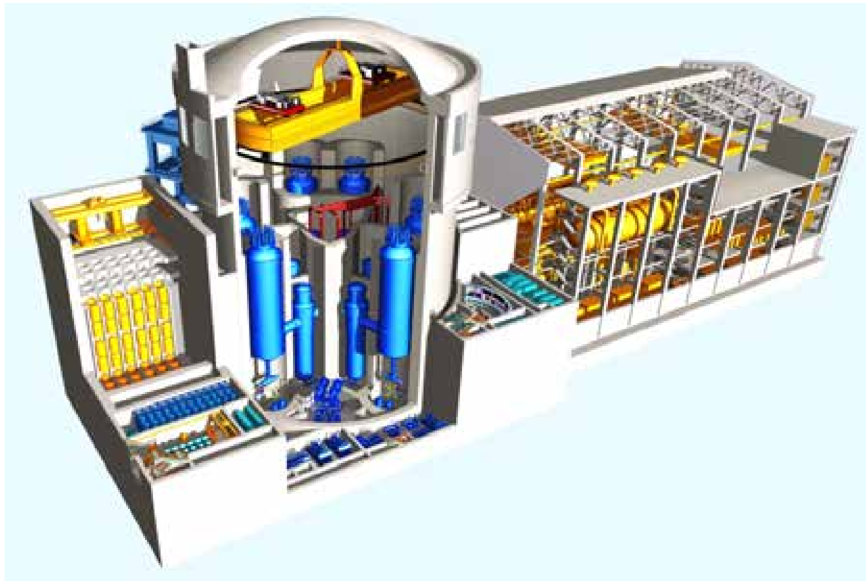


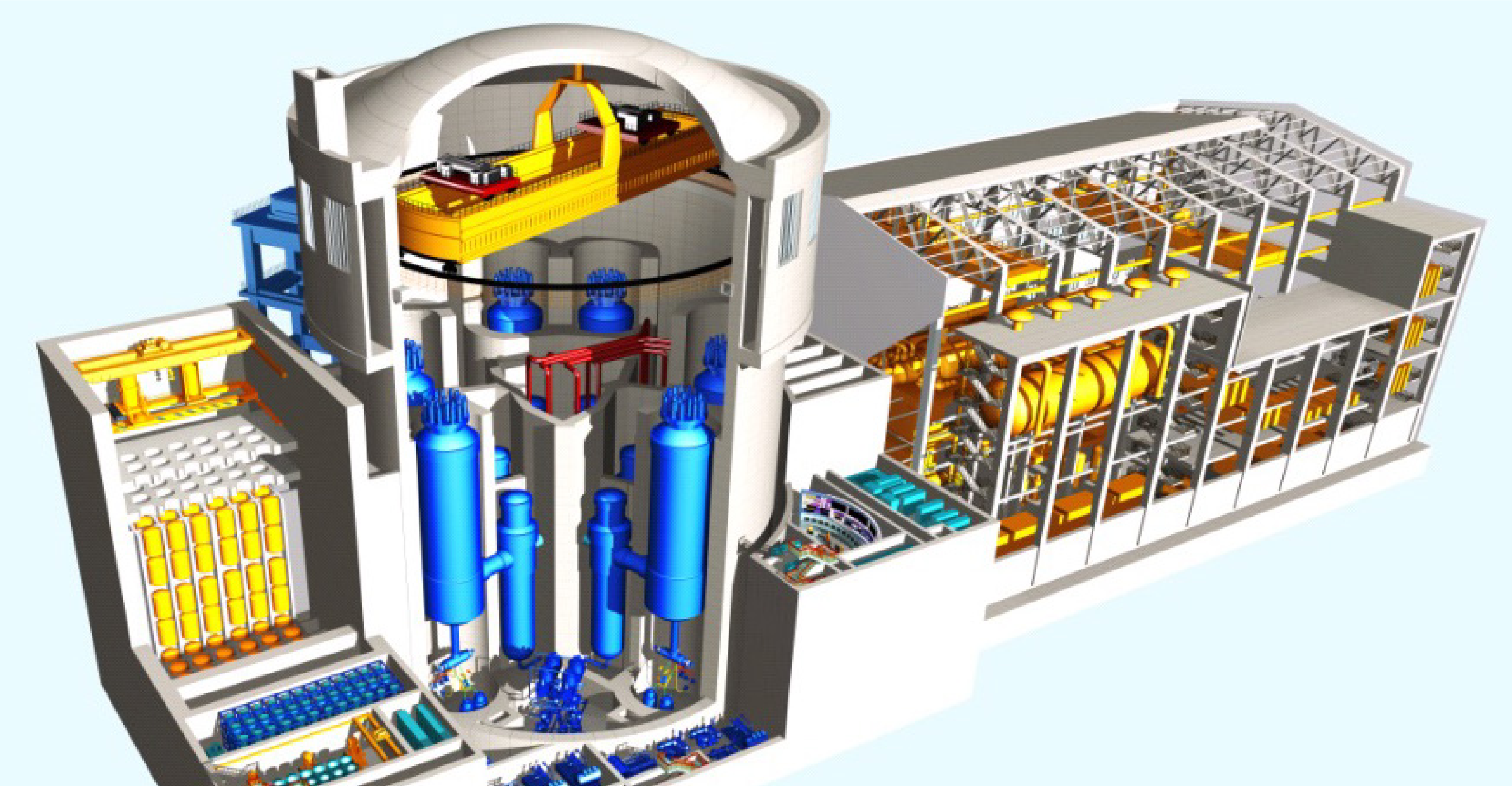
HTR-PM vs. HTR-PM600



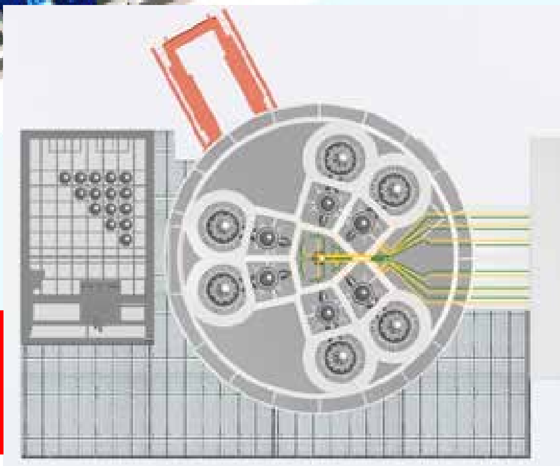








HTR-PM600



HTR-PM600 Parameters		
Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	ºC	250
Reactor outlet temperature	ºC	750
Feed water temperature	ºC	205
Steam temperature	ºC	566
Steam pressure	MPa	13.24

HTR-PM600 main parameters

Thermal power of one Reactor Module	MW	250
Reactor Module number		6
Plant thermal power	MW	1500
Plant electric power	MW	680
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	^oC	250
Reactor outlet temperature	^oC	750
Feed water temperature	^oC	205
Steam temperature in turbine	^oC	535
Steam pressure in turbine	MPa	13.24
Power generation efficiency	%	44

HTR-PM600 Progress

- *2016.12: concept design was released to public*
- *2018: finish the optimization design and standard design*
- *2020: feasibility study, preliminary design, PSAR preparation ongoing*
- *2020.10: internal review of the project proposal by owner, main contractor, designer*
- *2021.04: review of the preliminary feasibility study report, survey of the potential site*
- *2021.12: Basic design completed*

Demands for process heat

- ***China has a huge process heat market, like worldwide***
  - ***290 Mtoe/yr = 385 GW (60/40 heat/electricity) → 231 GWth***
  - ***15.6% of total primary energy, strongly growing***
  - ***Market for steam (< 650°C) 138 Mtoe/yr = 183 GWth (doable with conventional HTGR @750°C, would save 20% of oil imports)***
  - ***District heating in North is also a huge market***
  - ***Currently mainly based on coal***
  - ***Replace with Natural gas & electricity is underway, but expensive***

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Special consideration for steam supply

- ***Recently big demands for high temperature steam supply for Petro-chemistry in China***
- ***Target of Carbon neutrality in 2060 excludes the coal***
- ***HTR can be the the right supplier***
- ***Special version of HTR-PM600S is designed***
  - ***Standard NSSS modules is also used, temperature is enough***
  - ***6 NSSS modules is adopted***
  - ***Higher availability is achieved by sequential shutdown of NSSS modules, independence of modules is increased***
  - ***co-generation of steam and electricity***
  - ***Coupling with LWR is also demonstrated, for even lower cost***

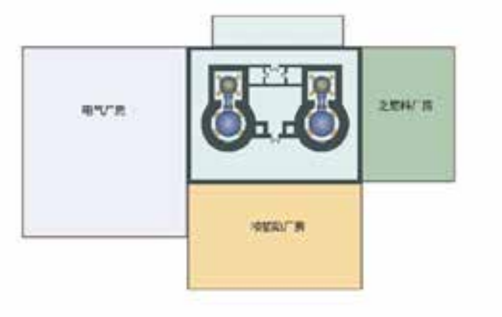
How to improve availability

- ***New nuclear island layout for multiple NSSS modules***

New layout based on multiple NSSS modules, separate sets, independent maintenance capability, standardized NSSS modules from HTR-PM can can improve the availability of steam supply for chemical plant, and technical maturity of the plant.

Based on 2 NSSS modules technology in HTR-PM

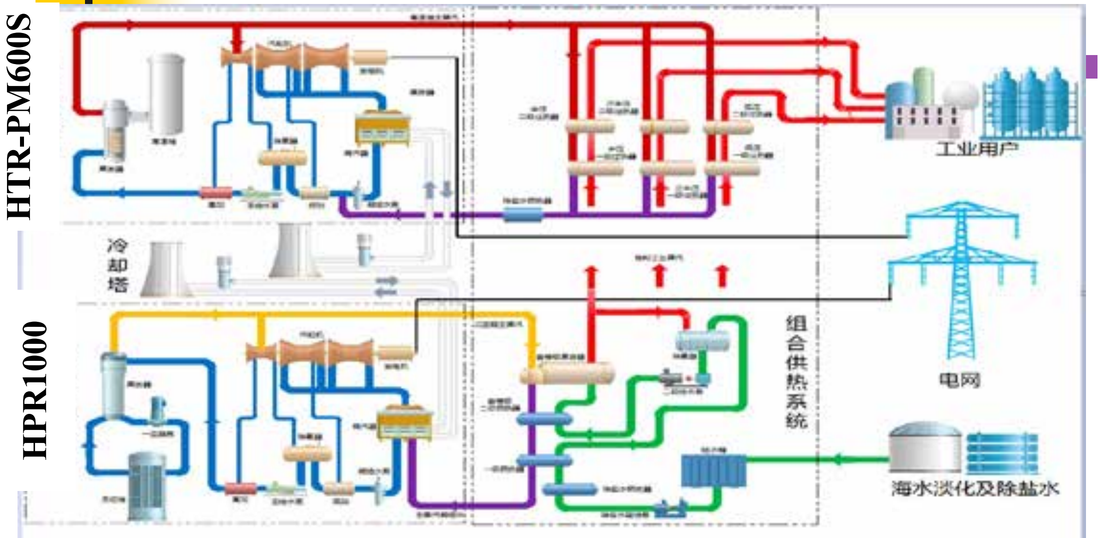
More mudules with independent maintenace

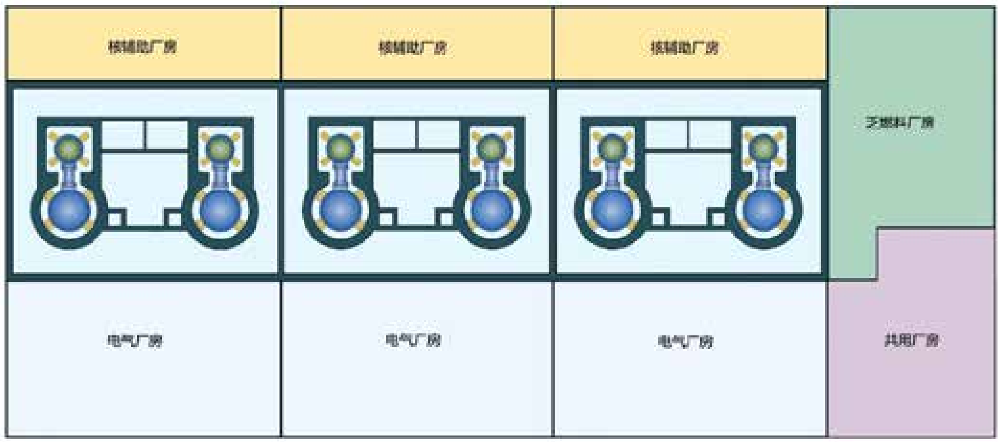


HTR-PM

set 1 ***set 2*** ***set 3*** ***shared buildings***

Concept of HTR-PM600S





HTR-PM600S

HTR-PM600S

- *Basic scheme: copy of three HTR-PM reactor buildings, optimization of the plant configuration and layout*
- *Supply medium and low pressure superheated steam to chemical enterprises*
  - *Water in the third circuit successively heated by HPR1000 unit and HTR-PM600S unit*
- *Remaining capacity for electricity generation*

HTR-PM600S: six-module HTR plant for cogeneration of electricity and steam

Conclusion remarks

- ***HTR featured with inherent safety, high outlet temperature, versatile applications***
  - ***Inherent safety is the basis***
  - ***Currently high temperature steam has huge market demands***
  - ***GIF is also interested in V/HTR***
- ***HTR-PM demonstrates the technology readiness of commercial HTR, the readiness of supply chain, and feasibility of multiple NSSS modules in one unit***
  - ***This is another approach of SMR***

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Conclusion remarks

- ***Larger unit with more standardized NSSS modules can maintain the advantage of SMR, even more economical, as shown in HTR-PM600 and HTR-PM600S design***
  - ***Different number of NSSS modules can be used, to meet the end user requirement***
  - ***HTR-PM1000 is also designed***
- ***What's the real target of SMR?***
  - ***Cheaper, safer, remote area?***
  - ***HTR-PM600/600S meet the criteria?***
  - ***Market requirement: safe, cheap, massive electricity, steam, hydrogen***

HTR-2024 conference

- *Time: 14-18 October 2024 (no change)*
- *Place: Beijing, China*
- *Organization*
  - *International organization committee*
  - *Local organization committee*
  - *Responsible by INET*
  - *Co-organized by IAEA, since 2002*
- *Tracks*
  - *8 tracks are planned, as usual*

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HTR-2024 conference

- ***There are around 200 participates registered through website***
- ***There are around 160 abstracts submitted through website***
- ***Technical tracks + plenary speakers***

Track 1	National research programs and industrial projects
Track 2	Industrial Applications and Markets
Track 3	Fuel and Waste
Track 4	Materials and Components
Track 5	Reactor physics analysis
Track 6	Thermal-hydraulics and Coupled Code Analyses
Track 7	Development, Design and Engineering
Track 8	Safety and Licensing

Thanks for Your Attention!