

*First Meeting of the Technical Working Group for
Small and Medium-sized of Modular Reactor (TWG-SMR)
23-26 April, 2018
IAEA Headquarters, Vienna International Centre*



SMR Design, Technology Development and Construction Status in China

Prof. Jiejuan TONG
Institute of Nuclear and New Technology (INET)
Tsinghua University, Beijing, China



Outline

- *SMR programs in China*
 - *Non-PWR fleet*
 - *PWR fleet*
- *Regulatory Review Principles of Small PWR's Safety (Trial Version)*
- *Coordinated Research Program “Key Issues of SMR Development”*



SMR PROGRAMS IN CHINA

SMR PROGRAMS IN CHINA

■ *Non-PWR fleet*

■ *INET*

HTR-PM, HTR-PM600



INET

■ *CNNC*

Fast Reactor Demonstration Project



■ *CAS*

Thorium-based Molten Salt Reactor



SMR PROGRAMS IN CHINA

■ PWR fleet

■ CNNC

ACP25S, **ACP-100**, ACP-100S, DHR...



■ CGN

ACPR50S, ACPR100



■ INET

NHR200



■ SPIC

CAP200



*S~~Offshore floating
HR~~ heating*

搜地点、查公交、找路线



下载公测版APP

全国 | 8

中

路线

中华人民共和国

00 公里
00 英里

HTGR Roadmap in China

Key feature of HTGR: extend the application of nuclear energy to process heat, a similar market volume to nuclear power



**Supplement to
LWR for power
generation**

HTGR Roles in China



**Hydrogen production
as next step**

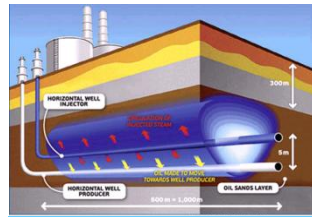
Co-generation to supply steam



Water desalination



District heating



Oil recovery



Petroleum refinery



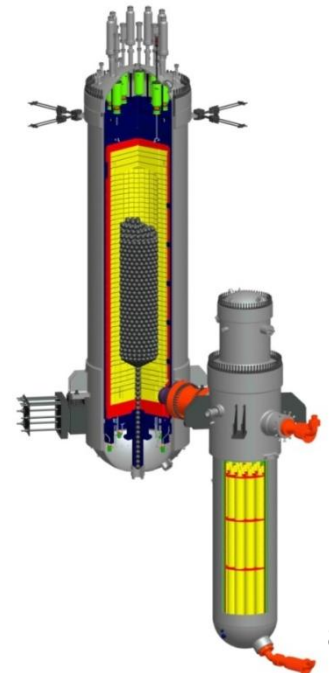
Coal liquefaction

HTR-PM

1 Module = 1 reactor + 1 SG

- 2004 *Investment Agreement Signed*
- 2006 *Accepted by the National Science & Technology Important Project Program*
- 2008 *Demo-project General Design Approved*
- 2012.12 *First Concrete Deployment*
- 2019 *Will connect to the grid*

	Value
Power, MWth	2x250
Power, MWe	211
Primary Pressure, MPa	7
Helium Temperature, °C	750
Main Steam Temperature, °C	566
Number of Fuel balls	420,000



HTR-PM



Civil Work of Nuclear Island



*Production line of Fuel Element,
360,000 Elements have been produced
(as of 2017)*



Reactor Vessels Installed



Metallic Internal, Water-cooled Wall, DCS, Full scope simulator, . . .

HTR-PM

First of the kind

■ *Engineering Verification Tests*



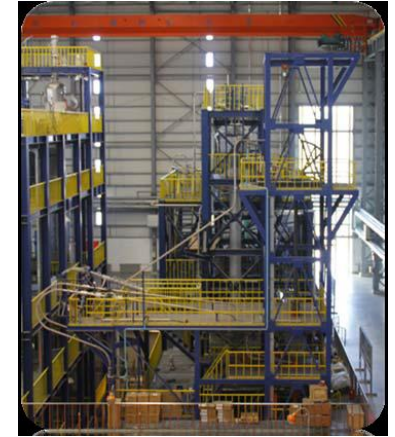
Fuel Element



Steam Generator



Main Helium Blower

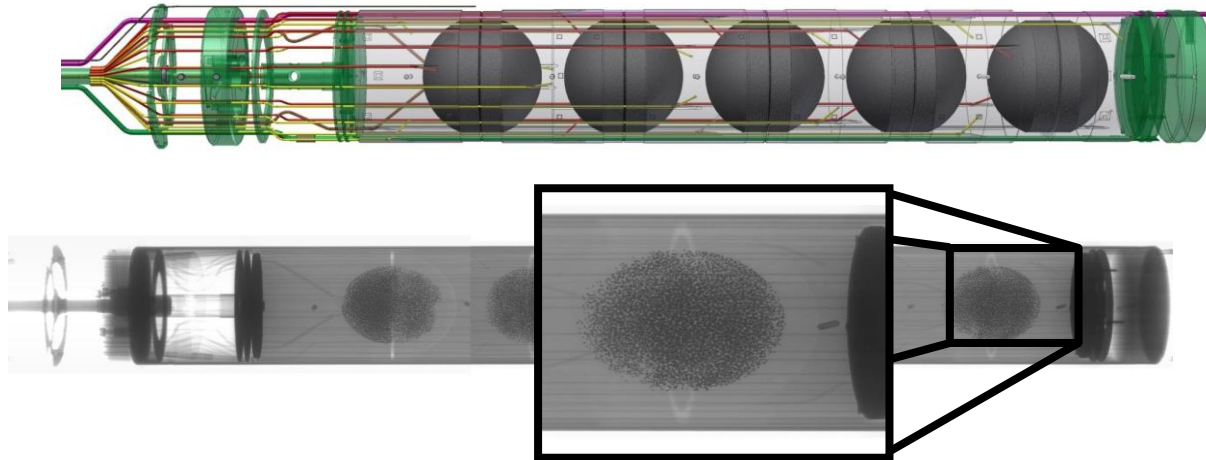


Fuel Loading /Unloading System

- *Control Rods Driven Mechanism*
- *Spent fuel Storage System*
- *Absorption Balls Shutdown System*
- *Helium Purification System*
- ...

HTR-PM

- Irradiation Test of Fuel element
 - PETTEN HFR
 - 2012.9.8-2014.12.30



- *Best records in the world up to now*
 - *5 elements, ~60,000 coated particles, 0 failure observed*

HTR-PM

■ *Performance test of main blower with magnetic bearing*

■ **Prototype 1**

full scale motor, oil bearing



Prototype No.1

■ **Prototype 2**

full scale motor, magnetic bearing



Prototype No.2

■ **Prototype 3**

full scale blower, magnetic bearing



Prototype No.3

■ **Prototype 4**

Final whole set product, Fall-down test



Prototype No.4

HTR-PM

- *Performance test of main blower with magnetic bearing*

100 hrs, Nitrogen, 2014.7

500 hrs, Nitrogen, 2014.10

50 hrs, Helium, 2015.6

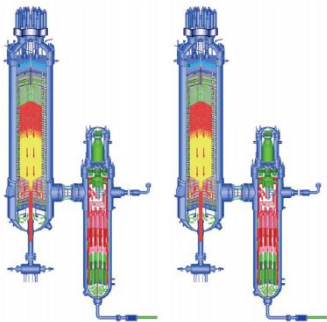
**50 circles of lifetime transients,
Helium, 2016.5 (500 times of
transients, 6 months)**



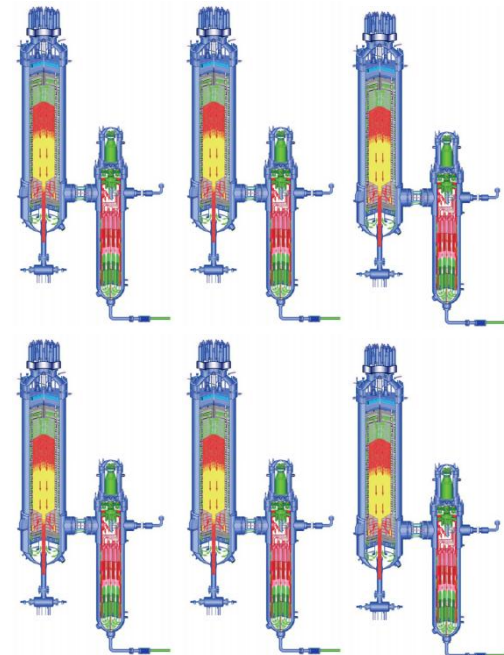
General Design of HTR-PM600

Following HTR-PM: commercialization based on HTR-PM experiences

HTR-PM



HTR-PM600



Engineering verification tests
Design
Manufacture
Construction
Commissioning
Licensing
Project management



General Design of HTR-PM600

■ ***Objectives of HTR-PM600***





General Design of HTR-PM600

Potential markets

Small to medium size power generation

- Displacement of coal-fired plant
- Supplement to LWR
Constrained siting
Lack of water
Limited grid capacity

Cogeneration

- Electricity
- District heating
Residential
Commercial
- Process steam
Industrial

Overseas markets

Maturity

- Design
- Supply chain
- Project management
- Licensing

General Design of HTR-PM600





Cost Estimate

- ***The current approved investment is 8 billion RMB for a 210 MWe plant (based on HTR-PM)***
- ***Among the reasons of the cost increased:***
 - ***Civil work and equipment: 35%***
 - ***Manpower: 31%***
 - ***FCD delaying and financial costs: 33%***

Cost Estimate

- **Total cost of the 2 × HTR-PM600 is estimated to be 20,000-22,000RMB/kWe, price to the grid 0.5RMB/kWhr, which is about 110-120% of the same size PWR constructed recently in China, under the condition:**
 1. *reduce the first of a kind costs,*
 2. *increase the plant power to 2 × 650 MWe,*
 3. *order 12 reactor modules at the same time.*

	600 MW PWR	HTR-PM600
Total, excluding Components in nuclear Island		
Components in nuclear Island		
RPV and Reactor Internals		

Industrialization Activities

■ Organization

INET

*R&D, general design,
engineering of key
systems and components
in Nuclear Island*

Chinergy Co.

*Contractor of Nuclear
Island*

Established in 2003

- TSINGHUA HOLDING
- CNEC
- CGNPC

Owner

- China HUANENG Cor.,
- China Nuclear
Engineering Cor.(CNEC)
- China General Nuclear
Power Cor.(CGNPC)



Industrialization Activities

Supply chain (not limited to the following...)

<i>Key components / systems</i>	<i>Manufacturer</i>
<i>fuel</i>	<i>China North Nuclear Fuel Co., LTD</i>
<i>RPV</i>	<i>Shanghai Electric</i>
<i>Steam Generator</i>	<i>Harbin Electric</i>
<i>Graphite internal</i>	<i>Toyo Tanso, Japan</i>
<i>Carbon internal</i>	<i>China FANGDA Group</i>
<i>Metallic internal</i>	<i>Shanghai Electric</i>
<i>CR drives</i>	<i>Shanghai Electric</i>
<i>Main helium circulator</i>	<i>Harbin Electric & Shanghai Electric</i>
<i>DCS & Simulator</i>	<i>China General Nuclear Power Corporation</i>



Industrialization Activities

- ***Domestic site study***

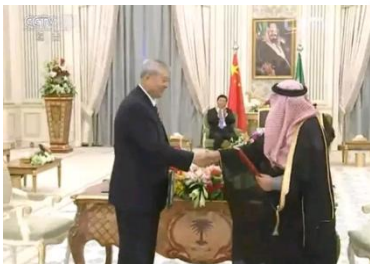
<i>Company</i>	<i>Site</i>	<i>Status</i>
<i>China Huaneng Group</i>	<i>Xiapu, Fujian</i>	<i>Early site study</i>
<i>China Nuclear E&C Group (CNEC)</i>	<i>Ruijin, Jiangxi</i>	<i>Preliminary feasibility study reviewed</i>
	<i>Wan'an Fujian</i>	<i>Preliminary feasibility study reviewed</i>
	<i>Bai'an, Guangdong</i>	<i>Preliminary feasibility study reviewed</i>
	<i>Taizhou, Zhejiang</i>	<i>Preliminary feasibility study underway</i>

Industrialization Activities

■ *International cooperation*

A series of MOUs on jointly-development of HTGR were signed between CNEC and the following countries & organizations

- *Saudi Arabia*
- *Dubai, The United Arab Emirates*
- *South Africa*
- *Amec Foster Wheeler (AMEC), UK*
- *ASEAN Centre for Energy (ACE, hosted by Indonesia)*





Briefing of HTR Development in China

- ***China has a clear, step-by-step roadmap of developing modular HTGR technology and commercialization***
- ***As HTR-PM project is processing generally as scheduled, design of HTR-PM600 is largely based on HTR-PM experiences, and its economic competitiveness in comparison with PWR is expected***
- ***Tsinghua University and industrial partners are collaborating to push forward HTGR projects domestically and overseas***



Fast Reactor Demonstration Project

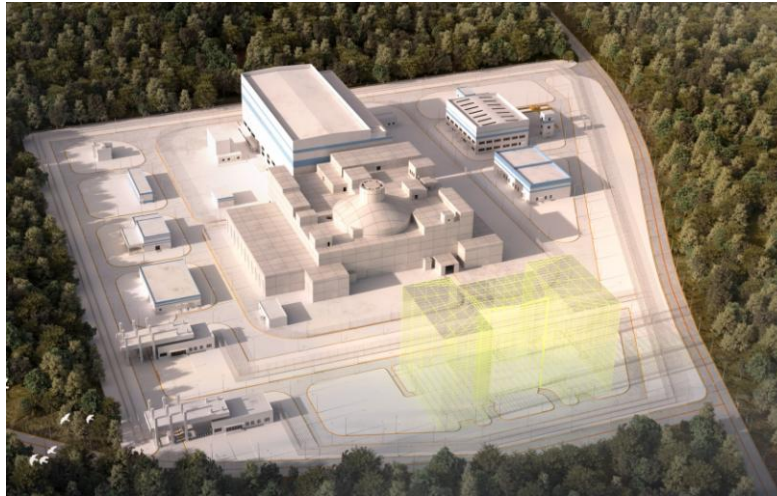
SMR PROGRAMS IN CHINA(2)

Xiapu Fast Reactor Demonstration Project



- 600MW
- 2017-12-29 FCD
- Be completed in 2023





ACP100

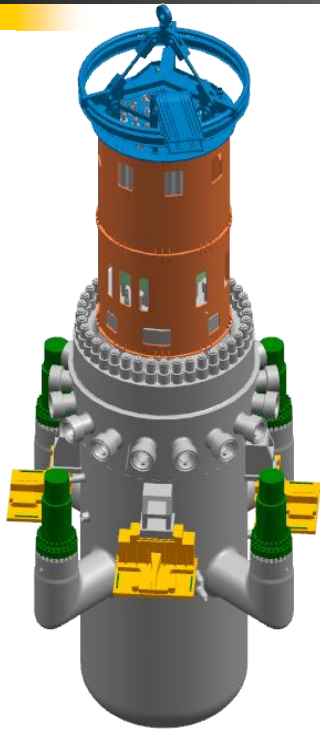
SMR PROGRAMS IN CHINA(3)



ACP100 Progress

- *2016.12 , Application of the Hainan site submitted*
- *2017.7 , Feasibility Study Report and
Environmental Impact Evaluation Report submitted*
- *2017.10 , Feasibility Study Report Reviewed*
- *2018.1 , Preliminary Design Completed*

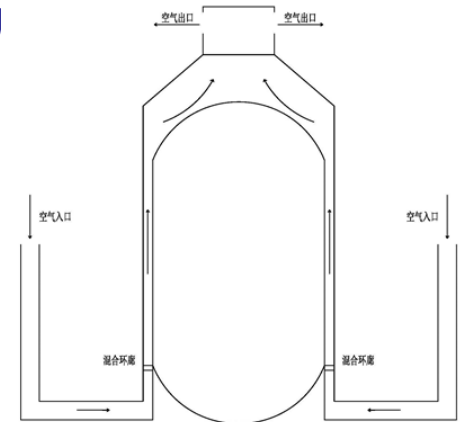
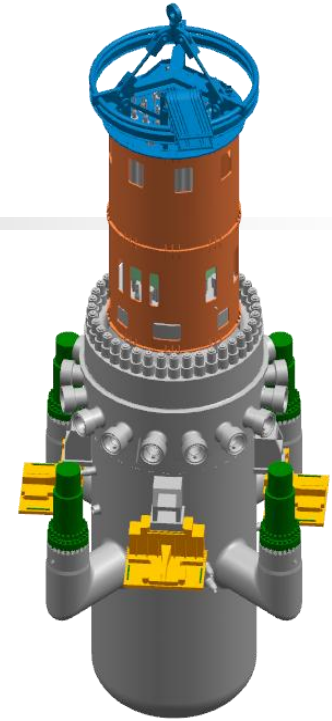
ACP100 features



Reactor type	PWR
Thermal power	385MWt
Electrical power	125MWe
Design life	60 years
Fuel cycle	24 months
Coolant average temperature	303℃
Operation pressure	15.0MPa (a)
Fuel assembly type	CF3S shortened assembly
Fuel assembly number	57
Fuel enrichment	≤4.95%
Steam generator type	OTSG
Steam pressure	4.5MPa (a)
Steam temperature	> 290℃
CDF	< 1 × 10 ⁻⁶

ACP100 features

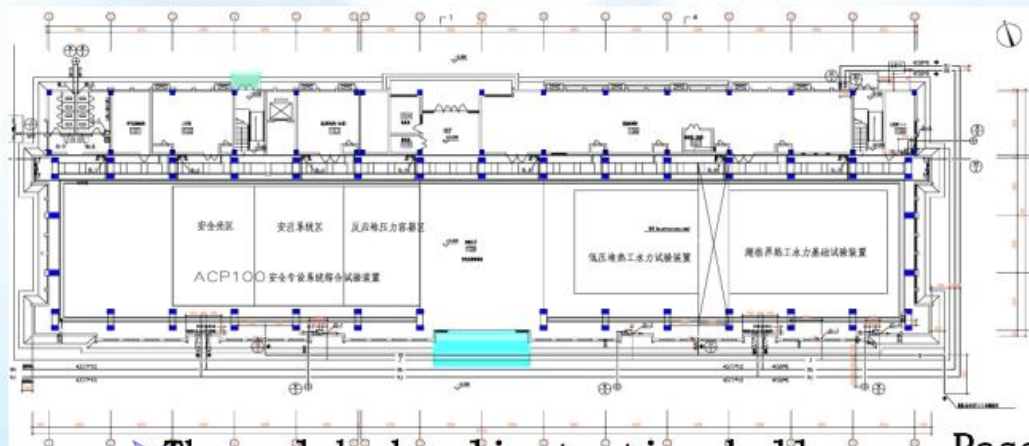
- Compact layout of Primary systems, small size primary pipe (~8cm)
 - 4 main pumps (canned)
- Passive residual heat removal system
- Passive core cooling system
- Passive cavity cooling system
- Passive containment heat removal system
- Reactor and spent fuel pool are laid lower than the ground level for better protection against external events and release containing.



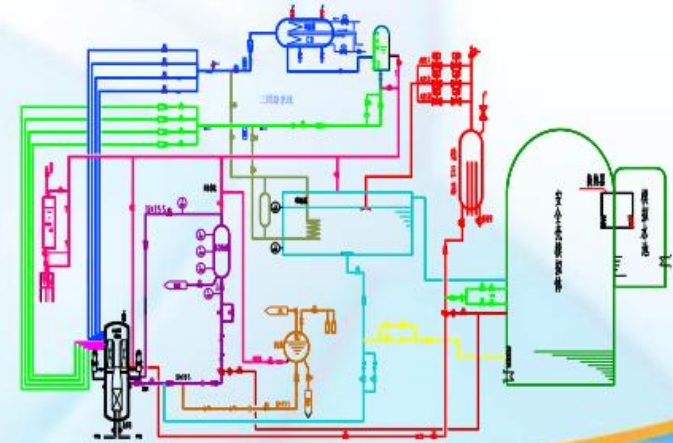
Testing & Verification

Six test research subjects

- ❑ Control rod drive line cold and hot test
- ❑ Control rod drive line anti-earthquake test
- ❑ Internals vibration test research
- ❑ Fuel assembly critical heat flux test research
- ❑ Passive emergency core cooling system integration test
- ❑ CMT and passive residual heat removal system test research



➤ Thermal hydraulic testing hall



Passive emergency core cooling system



NHR200-II

SMR PROGRAMS IN CHINA(4)

NHR Roadmap in China

Pool type
NHR test
reactor

1st reactor
designed
by
Chinese

1964

INSTIT

Vessel type
NHR test
reactor
(NHR-5)

1989

NHR200-I

Regulatory
reviewed,
Construction
permit
approved

1996

NHR200-II

Design
completed

2006

NHR200-II

Verification
tests
completed
Demonstration
project being
setup

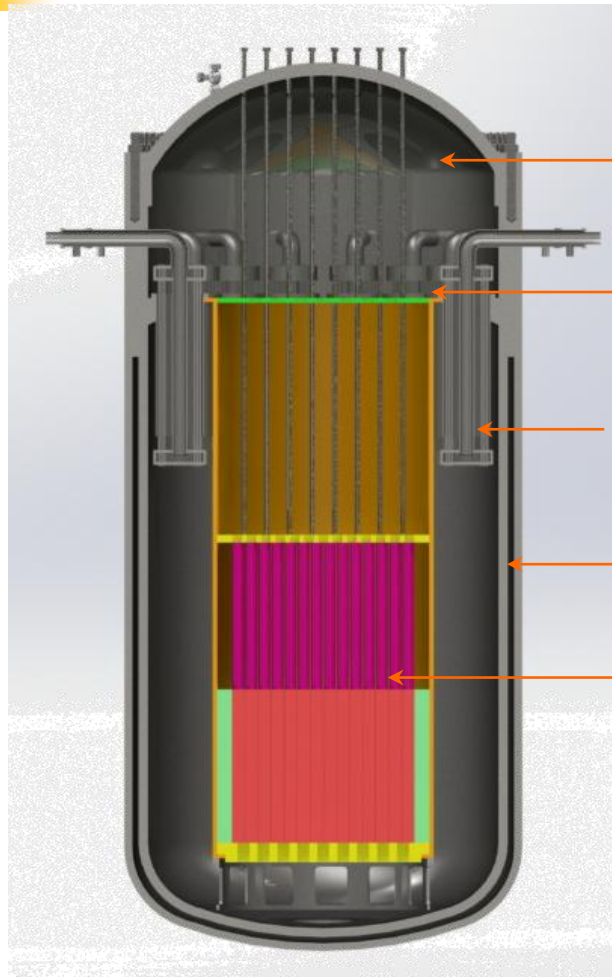
2016



NHR200-II

- ***201 °C saturated steam***
- ***Purpose***
 - ***Heating, industrial steam supply, steam/water cogeneration, heat-electricity cogeneration, sea water desalination***

NHR200 features



Completely integrated, without primary pipe
Full scope natural circulation, without main pump
Self stabilization of pressure by Nitrogen and Steam

In-vessel hydraulic type control rod driven mechanism (INET property)

Main heat exchanger

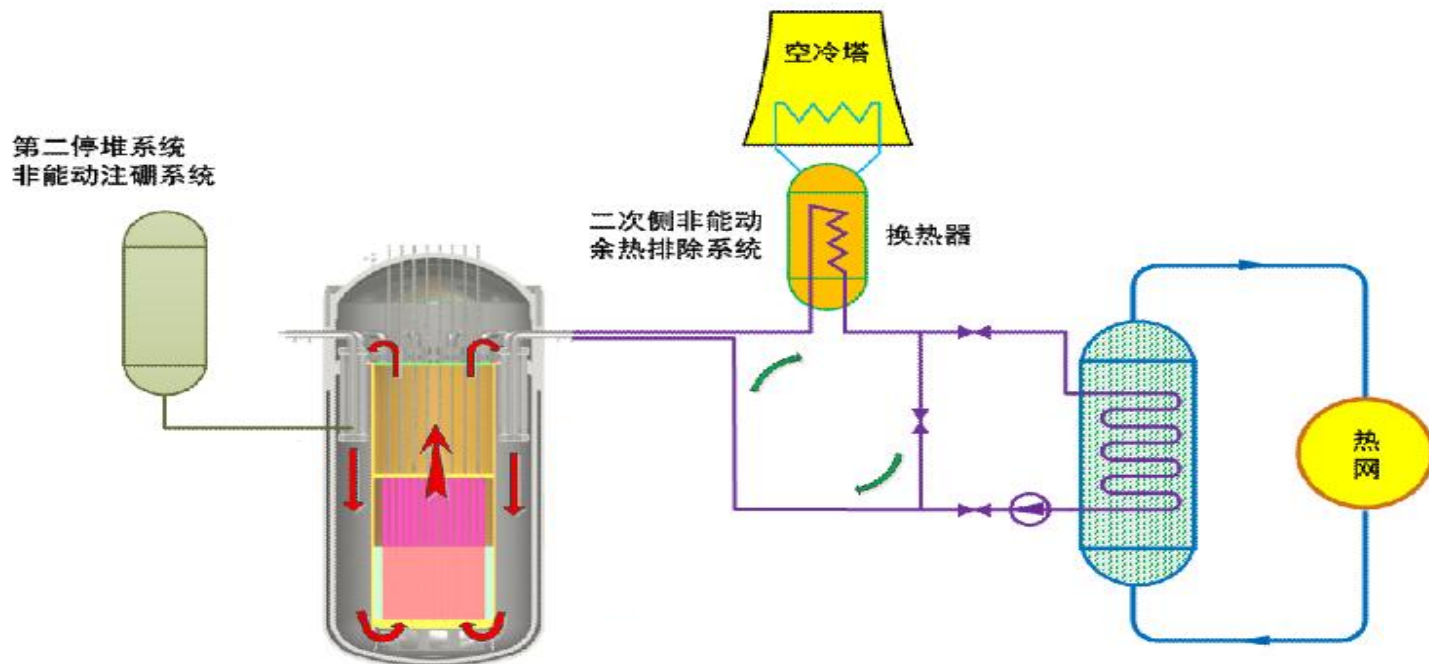
Double layer Pressure Vessel

Reactor core

- ✗ Large LOCA**
- ✗ Control Rod ejection**
- ✗ Main pump failure**
- ✗ Vessel rupture**
- ✗**

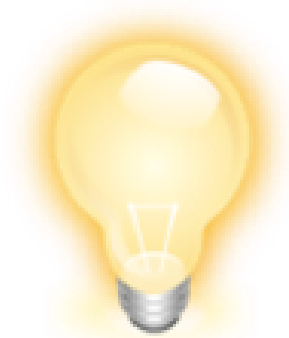
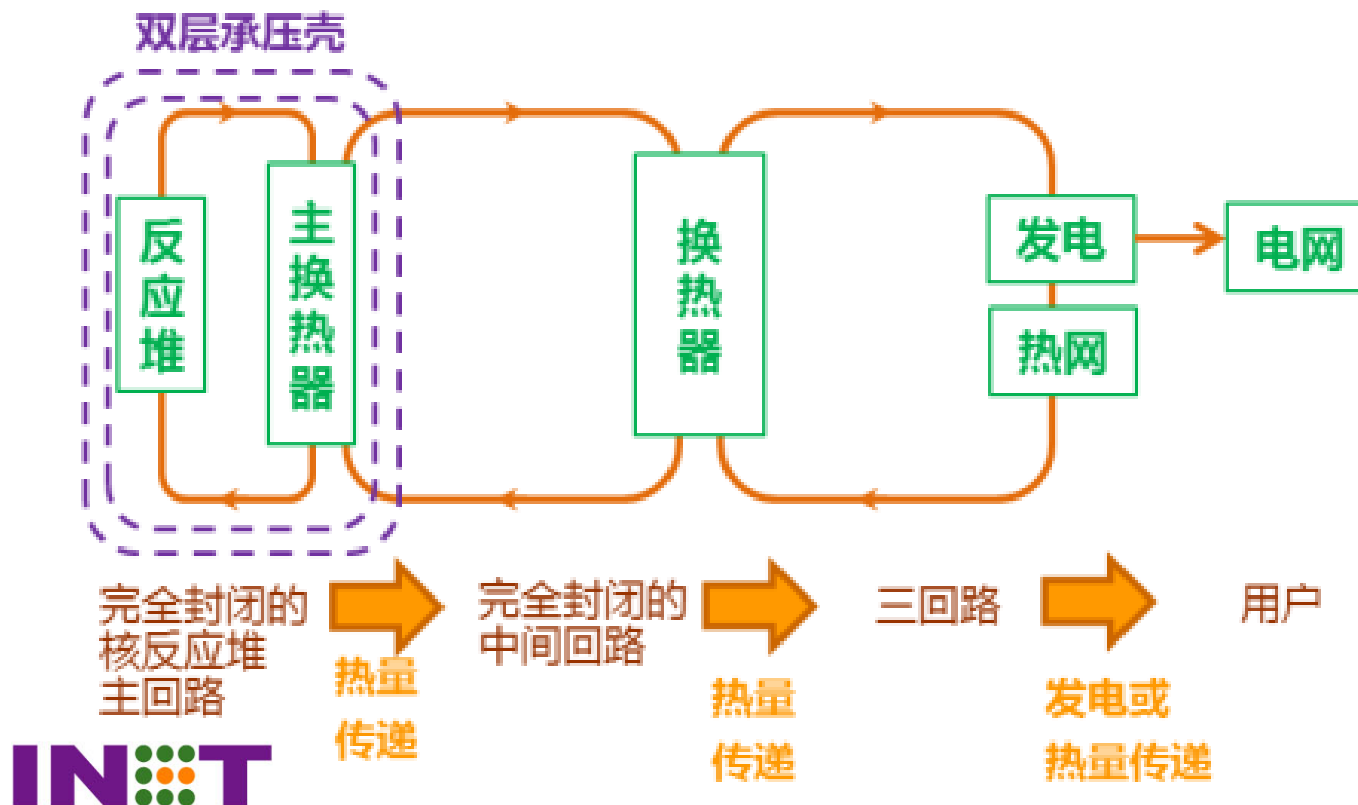
NHR200 features

- ***Passive safety***
 - ***Passive residual heat removal***
 - ***Passive boron injection***



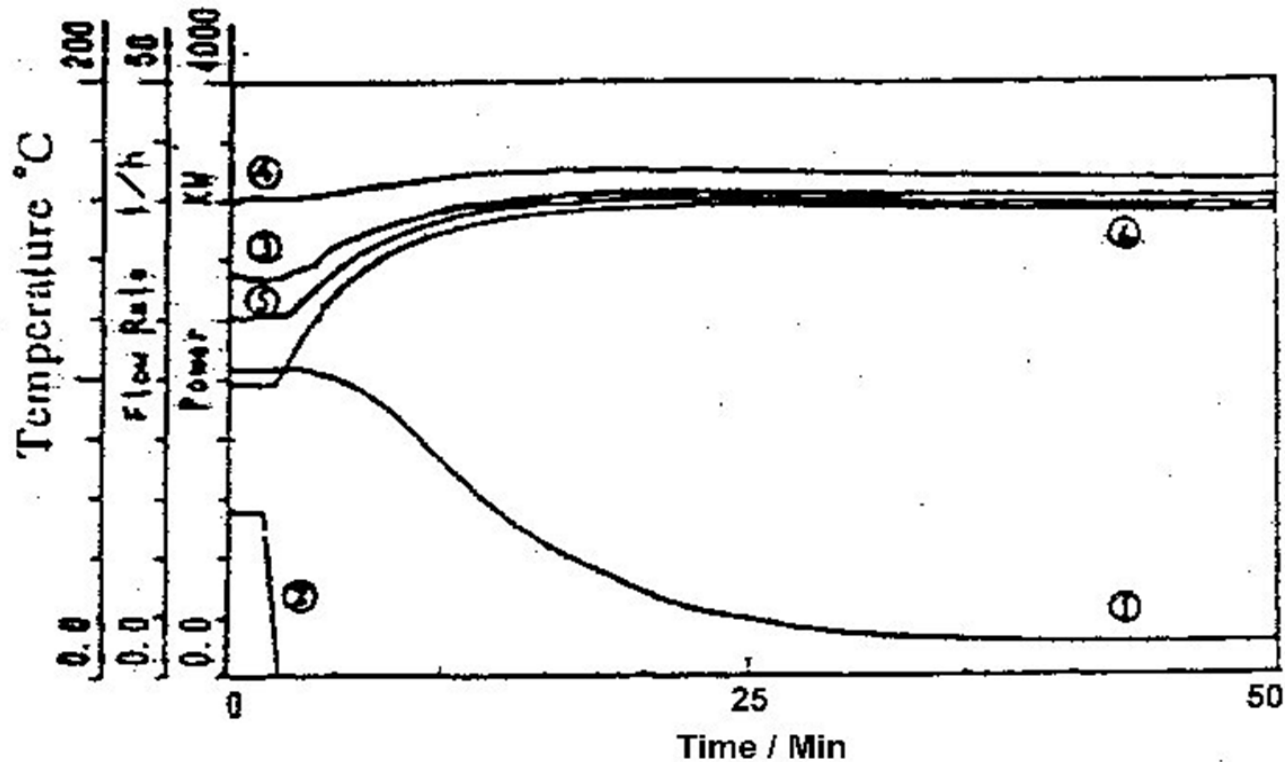
NHR200 features

- *Multiple layers of isolation*
 - 3 loops, $P_{intermediate} > P_{primary}$



NHR Tests

■ NHR-5 ATWS test

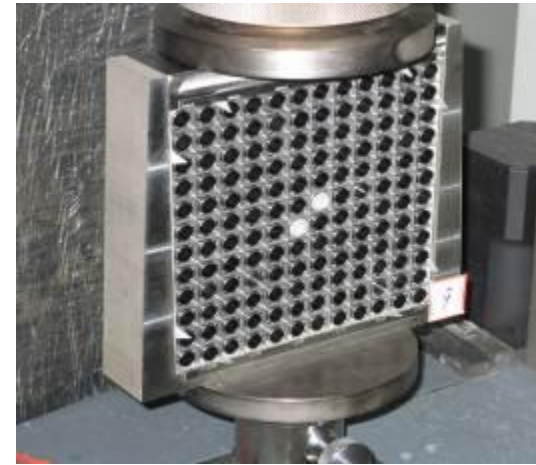


1-反应堆功率, 2-中间回路通过中换流量, 3-堆芯入口温度

INOT 4-堆芯出口温度, 5-主换二次水出口温度, 6-主换二次水入口温度

NHR Tests

- *More than 50 tests*





Industrialization Activity

- ***2014.11 CGN initialized Hebei Heat-Electricity Cogeneration Program with NHR200-II as the reactor design***
- ***2015.4 CGN, INET and CHINERGY signed the agreement***
- ***2016.5 Project Proposal submitted***
- ***2016.12 PSAR rev1***
- ***2017.5 Project Feasibility Analysis Report completed***

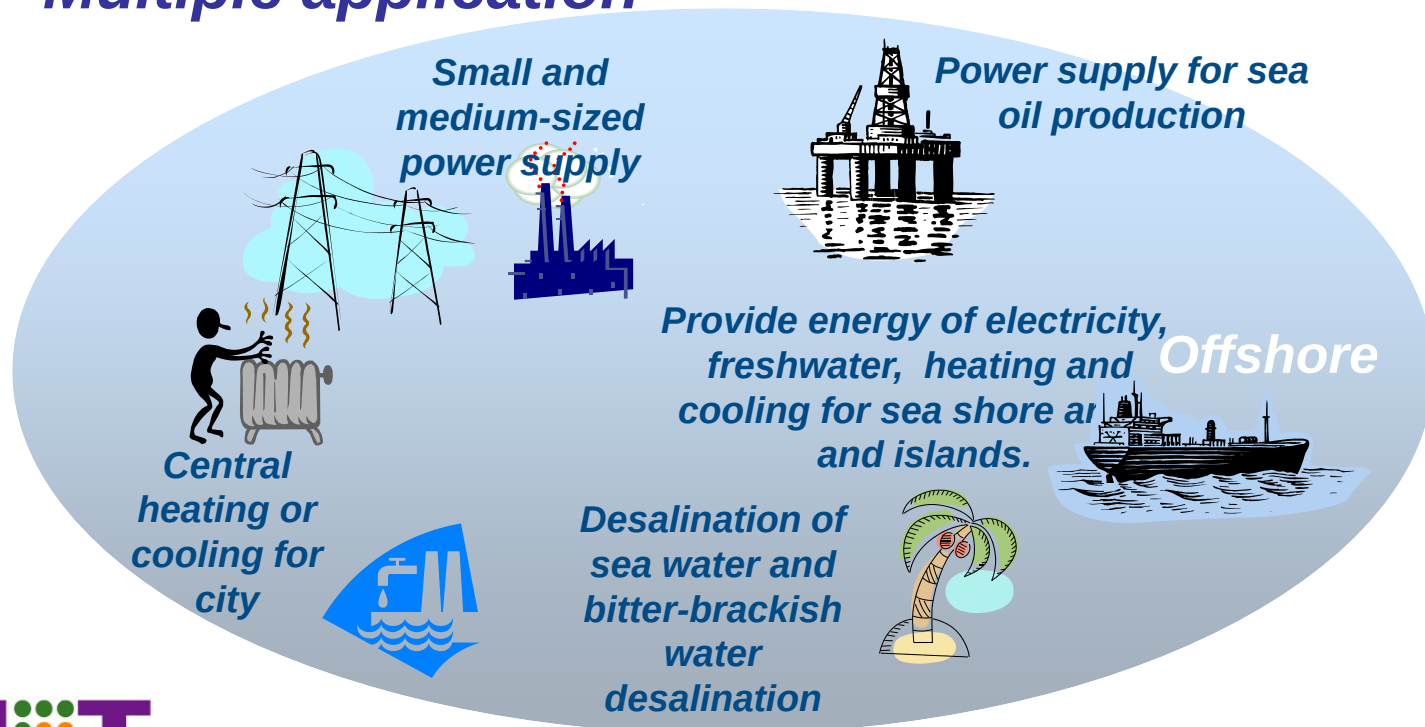


ACPR50S

SMR PROGRAMS IN CHINA(5)

ACPR50S

- **Floating NPP of compact SMR**
 - Thermal output: 200 MW
 - Electrical output: 50 MW
- **Multiple application**





ACPR50S roadmap

- ***2011*** ***CGN included Compact SMR into its strategic programs***
- ***2012*** ***Technical proposal of FNPP completed***
- ***2013*** ***Conceptual design of Compact SMR completed***
- ***~2015*** ***Schematic design of Compact SMR***
- ***Present*** ***Preliminary design of ACPR50S is undergoing.***
- ***ACPR50S demonstration project approved by Chinese government in 2015***

ACPR50S roadmap



- *Procurement contracts of RPV has been signed in 2016.*
- *Procurement contracts of all main components have been signed in 2017.*

ACPR50S features

<i>Thermal output (MWt)</i>	200	<i>Main steam pressure(MPa)</i>	3.79
<i>Electrical output (MWe)</i>	~50	<i>Inner diameter of RPV (m)</i>	2.3
<i>Primary loop pressure (MPa)</i>	15.5	<i>Generation efficiency</i>	~25%
<i>Fuel arrangement</i>	17 × 17	<i>RPV height (m)</i>	7.2
<i>Assembly number</i>	37	<i>Primary loop design pressure(MPa)</i>	17.23
<i>Burnable poison</i>	Gd	<i>Reactor cabin size(m)</i>	12.5*12.5*14
<i>CR material</i>	Ag-In-Cd	<i>Designed life (Year)</i>	40
<i>Fuel enrichment</i>	<5%	<i>Average reload burnup of fuel assembly (MWd/tU)</i>	<20000
<i>Core coolant average temperature(°C)</i>	300	<i>Equivalent Full Power Days(day)</i>	~400
<i>CDF(One core per year)</i>	$<1.0 \times 10^{-7}$	<i>LRF(One core per year)</i>	$<1.0 \times 10^{-8}$



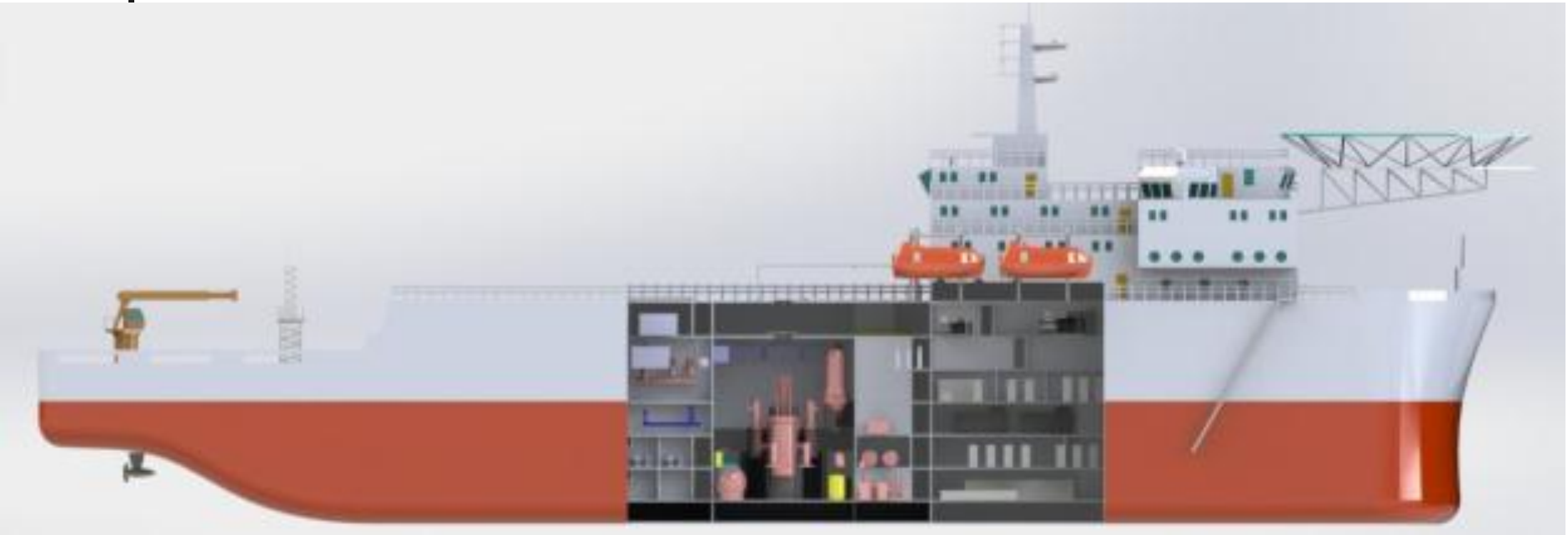
ACPR50S features

Compact arrangement	Compact layout of reactor module	Welding/pipe in pipe connection; Modular installation
	Compact layout in reactor cabin	Compact layout of safety systems in reactor cabin
System design	Simplifying configuration of systems	89 main systems as total.
	Reactor coolant system	2-loop design
	Engineered Safety System	Passive and active systems, 2+x configuration
	Main nuclear auxiliary system	Chemical and volume control system(CVS)
	Containment system	Containment (reactor cabin) and containment isolation system
	Fuel handling and storage system	Special designed for ACPR50S
	CI systems	Simplified configuration and design

ACPR50S features

Main component	Main pump	Canned-motor pump/Wet Winding Motor RCP
	OTSG	Helical-coiled tube OTSG
	CRDM	Electromagnetic stepping CRDM of PWR with Spring mechanism
	PRZ	Proven technology of PWR, optimal design, miniaturization
	RPV	Proven technology of PWR, optimal design, miniaturization
	Pipe in pipe	Pipe in pipe connects main components
	RVI	Proven technology of PWR, optimal design, miniaturization
In-core instrumentation	IIS, NIS	In-core: IIS, out-core: NIS
I&C	Overall scheme	A integrated technical solutions using DCS , PLC, field bus and remote IO.
electrical system	power supply configuration	Finished power supply configuration for DC & AC

ACPR50S features

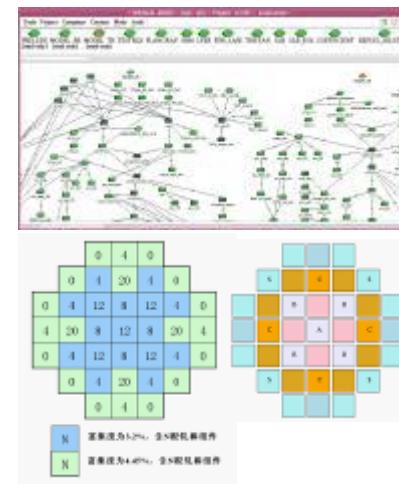


8 cabin totally
moulded length:~135m
moulded width:~30m
moulded depth:~18m

ACPR50S tests

Thermal Hydraulic test and design

- SMR safety test platform (6 test facilities)
- SMR equipment and key technology test platform (4 test facilities)
- SMR wave condition test platform (2 test facilities)



ACPR50S tests

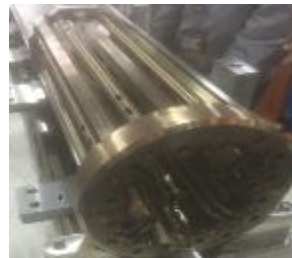
No.	Tests Completed
1	Once-through steam generator (OTSG) principle test
2	OTSG spiral tube heat transfer and resistance test
3	Passive safety system experiment
4	Natural circulation transient experiment
5	The principle experiment of the suppression pool

No.	Tests Ongoing
1	Control rod driving system test
2	Overall performance of safety system test
3	Heat flux density of fuel critical test
4	Reactor integrated hydraulic simulation test
5	Reactor Vessel Internal flow-induced vibration test
6	Pipe in pipe seal test



No.	Tests Ongoing
1	Control rod driving system test
2	Overall performance of safety system test
3	Heat flux density of fuel critical test
4	Reactor integrated hydraulic simulation test
5	Reactor Vessel Internal flow-induced vibration test
6	Pipe in pipe seal test

ACPR50S Tests





2. REGULATORY REVIEW PRINCIPLES OF SMALL PWR's SAFETY (TRIAL VERSION)



Regulatory Review Principles of Small PWR's Safety (Trial Version)

- *NNSA, the China National Nuclear Safety Administration, issued the regulatory position document < **Regulatory Review Principles of Small PWR's Safety** > for trial use in 2016*
- *Scope*
 - *< x hundred MWt per reactor*
 - *Demonstration project with few units*
 - *Land siting*
 - *Electricity Generation, Heating, Steam supply...*
- *Current safety requirements based on traditional large LWR plants are prescriptive, and might not be applicable for small PWR.*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

- 1. Safety goal*
- 2. Defense in Depth Philosophy*
- 3. Design Basis*
 - *Transient and Accident Classification and the corresponding acceptance criteria*
 - *Industrial standards and codes*
- 4. External Events Protection*
- 5. Accident source term*
- 6. Emergency Planning*
- 7. Application of Probabilistic Safety Analysis*
- 8. V&V of safety analysis software*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

1、 Safety goal

- *Generally same as large LWR*
- *Practically elimination of large release*
- *Shall provide the same level or even higher level of protection for the public without offsite countermeasures as the large PWR plants which can achieve with the help of offsite countermeasures*

- *“An essential objective is that the necessity for off-site protective actions to mitigate radiological consequences be limited or even eliminated in technical terms, although such measures might still be required by the responsible authorities”*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

2、 Defense in Depth Philosophy

- *DID shall be applied throughout the activities related with safety*
- *5 levels of defense are generally required while the focus could be different*
 - *Up to Leve 3 or Level 4 preferred*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

3、Design Basis

- *Transient and Accident Classification and the corresponding acceptance Criteria*
 - *Normal Operation*
 - *Anticipated Operational Occurrence*
 - *IE frequency > 1E-2 per reactor year, Dose Constraint limit < 0.25mSv per plant year*
 - *Design Basis Accident*
 - *Category I: IE frequency in 1E-2 ~ 1E-4 per reactor year, Effective whole body dose (30 days) < 5mSv per accident, Thyroid equivalent dose < 50mSv per accident*
 - *Category II: IE frequency in 1E-4 ~ 1E-6 per reactor year, Effective whole body dose (30 days) < 10mSv per accident, Thyroid equivalent dose < 100mSv per accident*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

3、 Design Basis

- *Transient and Accident Classification and the corresponding acceptance Criteria*
 - *Beyond Design Basis Accident*
 - *Focus on the important accident sequences*
 - *How to select: Probabilistic + Deterministic + Engineering judgment*
 - *Effective whole body dose (30 days) < 10 mSv per accident*
 - *Cliff-edge examination required*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

4、 External event protection

- *Establish the protection based on the design basis external natural hazards with appropriate margin*
- *Establish the protection of human made hazards based on the currently available national requirements with appropriate consideration of the state-of-the-art international practice and requirements*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

5、 Accident Source Term

- *The set of Accident Source Terms should be consistent with the safety goal requirement*
- *Accident source terms are chosen from DBAs and important BDBAs in a conservative and bounding manner to support the site selection and emergency planning*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

6、Emergency Planning

- *The necessity for off-site protective actions to mitigate radiological consequences be limited or even eliminated in technical terms is required*
- *It is interpreted as "All the DBAs and the important BDBAs shall not exceed the emergency intervention levels, i.e. shielding and iodine potassium"*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

7、 Application of PSA

More valuable for new reactors

- (1) To support the verification of Safety goal*
- (2) To support the plant state classification*
- (3) To support the selection of important BDBAs*
- (4) To support the accident source terms*
- (5) To support the setup of defense in depth*
- (6) To support the setup of technical specification*
- (7) To support certain safety requirements establishment or adjustment*



Regulatory Review Principles of Small PWR's Safety (Trial Version)

8、 V&V of safety analysis software

- Qualification of safety analysis software is generally required*
- For the demonstration projects, additional approaches might be acceptable, i.e. necessary experiments, benchmarks among similar software*



3. COORDINATED PROGRAM “KEY ISSUES OF SMR DEVELOPMENT”



Coordinated Research Program “Key Issues of SMR Development”

- ***CNEA, the China Nuclear Energy Association, initiated a coordinated research program for the key issues of SMR development in 2017***
 - *All parties concerned had already joined the program, except CAS*
- ***Key Issue List***
 - *Safety requirements and standards*
 - *Licensing related issues*
 - *Non-residential and Development Restricted Area requirements*
 - *Offsite emergency planning and response and Nuclear security*
 - *Economic and application market issue*
 - *Public acceptance and communication*

Comparison of safety goal framework

China

US

Overall safety
Radiation Protection
Technology Safety

Adequate Protection

Based on Risk
Comparison

Qualitative Safety goal

Life and Healthy
Society

Quantitative Safety Goal

The two 0.1%
QHO

Subsidiary Safety Objectives

CDF
LERF

CDF
LERF

(practically
reasonable)
As lower as
possible



Risk communication

(1) RISK-- UNCERTAINTY

$$\text{Risk} = \text{Likelihood} \times \text{Consequence}$$

(2) RISK -- HAZARD

$$\text{Risk} = \frac{\text{Hazard}}{\text{Safety measures}}$$

Risk can never be Zero
Risk-informed ~ Unnecessary burden
Earth life ~ 3E+9 years
Human History ~ 7E+6 years

(3) RISK – Human Perception

$$\text{Risk} = \text{Physical risk} + \text{Human Perception}$$

Most of the public can not see small numbers



Thanks for your attention!
