GEN IV International Forum
Expertise | Collaboration | Excellence

Experience of HTTR Licensing for Japan’s New Nuclear Regulation

Mr. Etsuo Ishitsuka, JAEA, Japan
22 April 2021

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens
Idaho National Laboratory
NEA Nuclear Energy Agency
cea
Argonne NATIONAL LABORATORY
JAEA 国立研究開発法人 日本原子力研究開発機構 Japan Atomic Energy Agency
NATIONAL NUCLEAR LABORATORY
NPS

Meet the Presenter

Dr. Etsuo Ishitsuka is the general manager of the HTTR Reactor Engineering Section at the Department of HTTR project in JAEA, Japan Atomic Energy Agency. He earned his Doctorate of Engineering from the University of Tokyo in 1999. He started his research career at the Japan Atomic Energy Research Institute in 1986 as a research engineer for the Japan Materials Testing Reactor (JMTR) project. He worked in a wide field of neutron irradiation technology development, such as production of medical radioisotopes, fusion blanket materials, plasma facing components and plasma diagnostics components, etc. He was promoted to Senior research engineer in 1994 and managed the experiments of a fusion blanket functional test in JMTR and the ITER project as the deputy general manager. After managing an international cooperation and training of foreign young researchers, he joined HTTR project in 2015 as the general manager. His current works are the technology developments related to core management and operation. His team was in charge of the seismic evaluation of facilities and beyond design basis accidents in this licensing.

Email: ishitsuka.etsuo@jaea.go.jp

Innovation by HTGR

Items	HTGR	LWR
Electric output (thermal output)	SMR (Small Modular Reactor) ~300MW (~600MW)	Large scale NPP ~1000MW (~3,000MW)
Outlet temperature	700 ˚C ~ 950 ˚C	~300 ˚C
Application	Heat application (hydrogen production, high-temperature steam, desalination, district heating), power generation	Power generation

Safety（S）

- ✓ Excellent safety feature (no melting core)

Stable power supply（E）

- ✓ Stable supply of hydrogen energy from nuclear power

Economic efficiency（E）

- ✓ Heat utilization rate: ~80%
- ✓ Electricity generation efficiency: ~50%
- ✓ High burnup (120GWd/t)

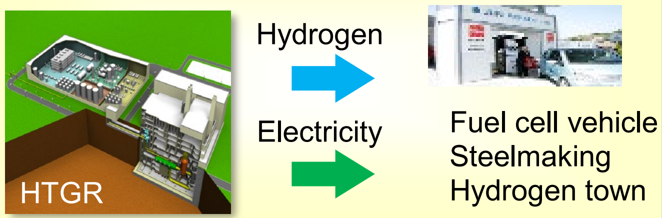
Environmental friendliness（E）

- ✓ ~1/4 spent fuel generated from LWRs
- ✓ Contribute to reduce carbon dioxide emission

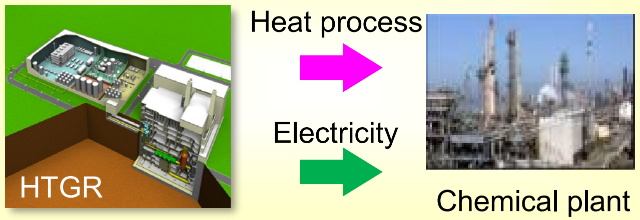
Decarbonized world

Contributing to reduction of greenhouse gas emissions of 30% by introducing HTGR (80% reduction by 2050 - compared to 2013)

Hydrogen production (Hydrogen power cogeneration)



Industrial heat utilization



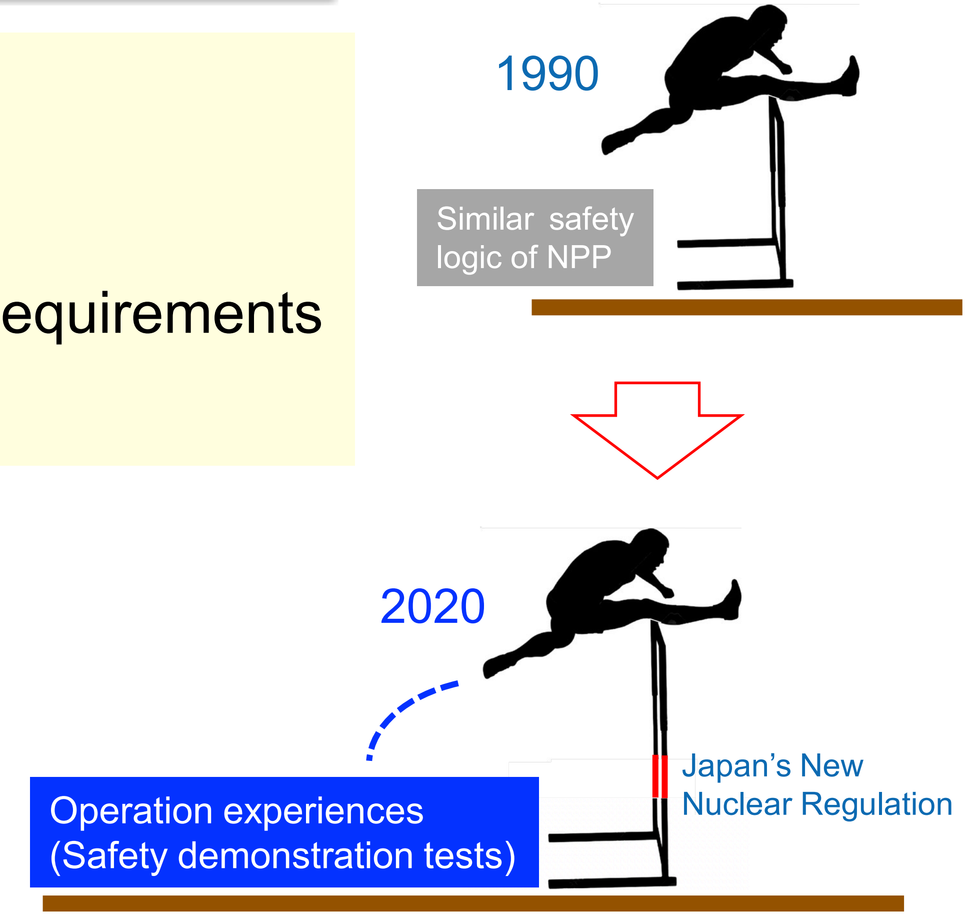
Combined with renewable energy

Contents

Ishi tsuka Etsu o
石 塚 悦 男
pleasure man

1) Outline of HTTR
2) Outline of Japan's New Nuclear Regulation
3) Conformation of Adaptability to New Regulatory Requirements
4) Conclusion

References of HTTR :
-Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
-High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021



1990

Similar safety logic of NPP

2020

Operation experiences (Safety demonstration tests)

Japan's New Nuclear Regulation

Outline of HTTR

Location of HTTR

Oarai Research and Development Institute

https://www.jaea.go.jp/04/o-arai/pamphlet/pdf/pamphlet.pdf?201909021858

Major Specifications of HTTR

Thermal power	30 MW
Average power density	2.5 MW/m^3
Outlet coolant temperature	850 °C / 950 °C
Inlet coolant temperature	395 °C
Primary coolant pressure	4 MPa (He)
Direction of coolant flow (core)	Downward
Moderator / Reflector	Graphite
Core height	2.9 m
Core diameter	2.3 m
Fuel	Low enriched UO_2
- Uranium enrichment	3 ~ 10% (Ave. 6%)
- Fuel element type	Prismatic block
Pressure vessel	2.25Cr-1Mo steel ^{H}13 m × ^{ID}6 m, ^{t}122-160 mm
Containment vessel	Steel containment ^{H}30 m × ^{ID}18.5 m, ^{t}30-38 mm

Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

Outline of HTTR History

Proposal for prototype commercial system

Year	Event
2014	Conformity review on the new regulatory requirements start toward resumption of operation
2010	Start of loss of forced cooling test 950ºC/50 days operation
2007	850ºC/30 days operation
2004	Reactor outlet coolant temperature 950ºC
2002	Safety demonstration test (control rod drawing test)
2001	Reactor outlet coolant temperature 850ºC (30MWt)
1998	First criticality
1997 ∫ 1991	Construction
1990 ∫ 1989	Application and permission of construction
1988 ∫ 1985	Detail design
	H T T R
1984 ∫ 1981	Basic design
1980 ∫ 1974	System integrity design
1973 ∫ 1969	Conceptual design
	Experimental multi-purpose Very High Temperature Reactor (VHTR)

Great East Japan Earthquake (11 Mar. 2011)

First in the world

Construction of reactor

Permission : 3rd June 2020

Operation Experiences

Purpose of HTTR

☐ Establishment of HTGR technologies
☐ Establishment of heat application technologies

Research and development

Fuels･Materials

In-pile helium loop (OGL-1)

Reactor physics

Very High Temperature Reactor Critical assembly (VHTRC)

Thermal hydraulics

Helium Engineering Demonstration Loop (HENDEL)

Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

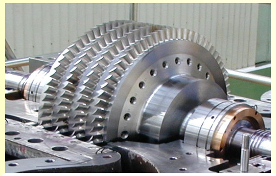
Overview of the HTTR Project

(1) Reactor technology

- 30 MW_{th} and 950˚C prismatic core advanced test reactor (Operation start in 1998)

- Safety evaluation by NRA for restart
- Accumulation of validation data
- Advanced fuel development

(2) Gas turbine and H_2 technology

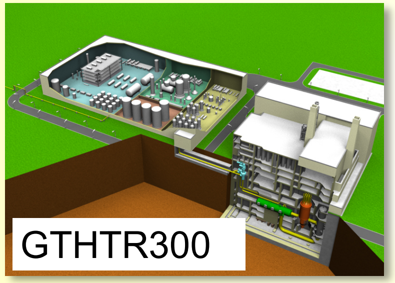

He compressor

- R&D of gas turbine technologies such as high-efficiency helium compressor, shaft seal, and maintenance technology


hydrogen facility

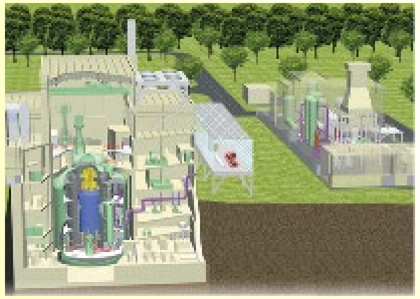
- In October 2016, 31 hours of hydrogen production with the rate of 0.02 m^3/h was successfully achieved.

(3) Innovative HTGR design


GTHTR300

- GTHTR300 for electricity generation and desalination
- GTHTR300C for cogeneration and nuclear-renewable hybrid system.
- Clean Burn HTGR for surplus plutonium burning
- Development of safety standards

(4) HTTR-GT/H2 test



- The connection of a helium gas turbine power generation system and hydrogen production with the HTTR.
- Basic design of the HTTR-GT/H_2 test is completed.

High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

Japanese Technologies as a Front Runner

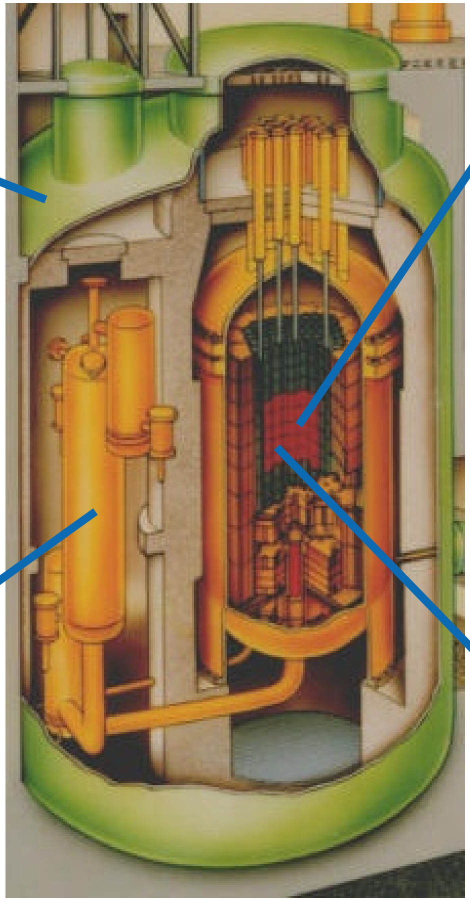
- Experiences of HTTR design, construction, operation
  (MHI, Toshiba/IHI, Hitachi, Fuji Electric, KHI, etc.)

A lot of technical data of HTTR was accumulated.
Optimum design of commercial HTGR can be conducted by only Japanese technology.

- High temperature resistant metal
  (Mitsubishi material)

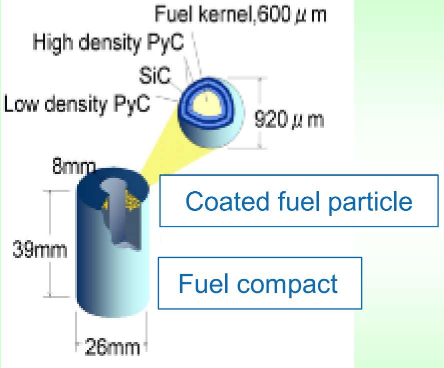

Intermediate heat exchanger (IHX)

Hastelloy XR is applicable at 950°C as the nuclear structural material .
IHX can deliver hot helium gas at 950°C to outside the reactor pressure vessel.



Constructed by domestic technology

- Fuel (Nuclear Fuel Industry)

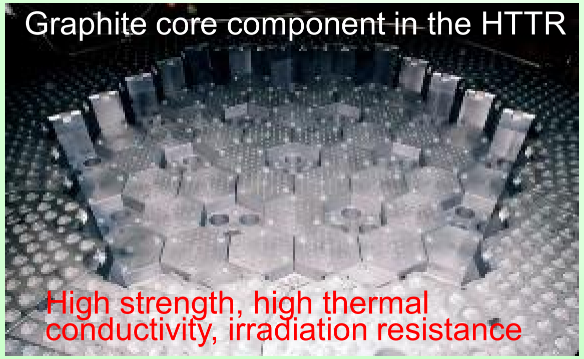


Ceramics coating layer retains fission products inside the coated fuel particle at extreme low leak level.

Ceramics coating is stable for long-term.
(3 times higher burnup than LWR)

- Graphite, IG-110 (Toyo tanso)

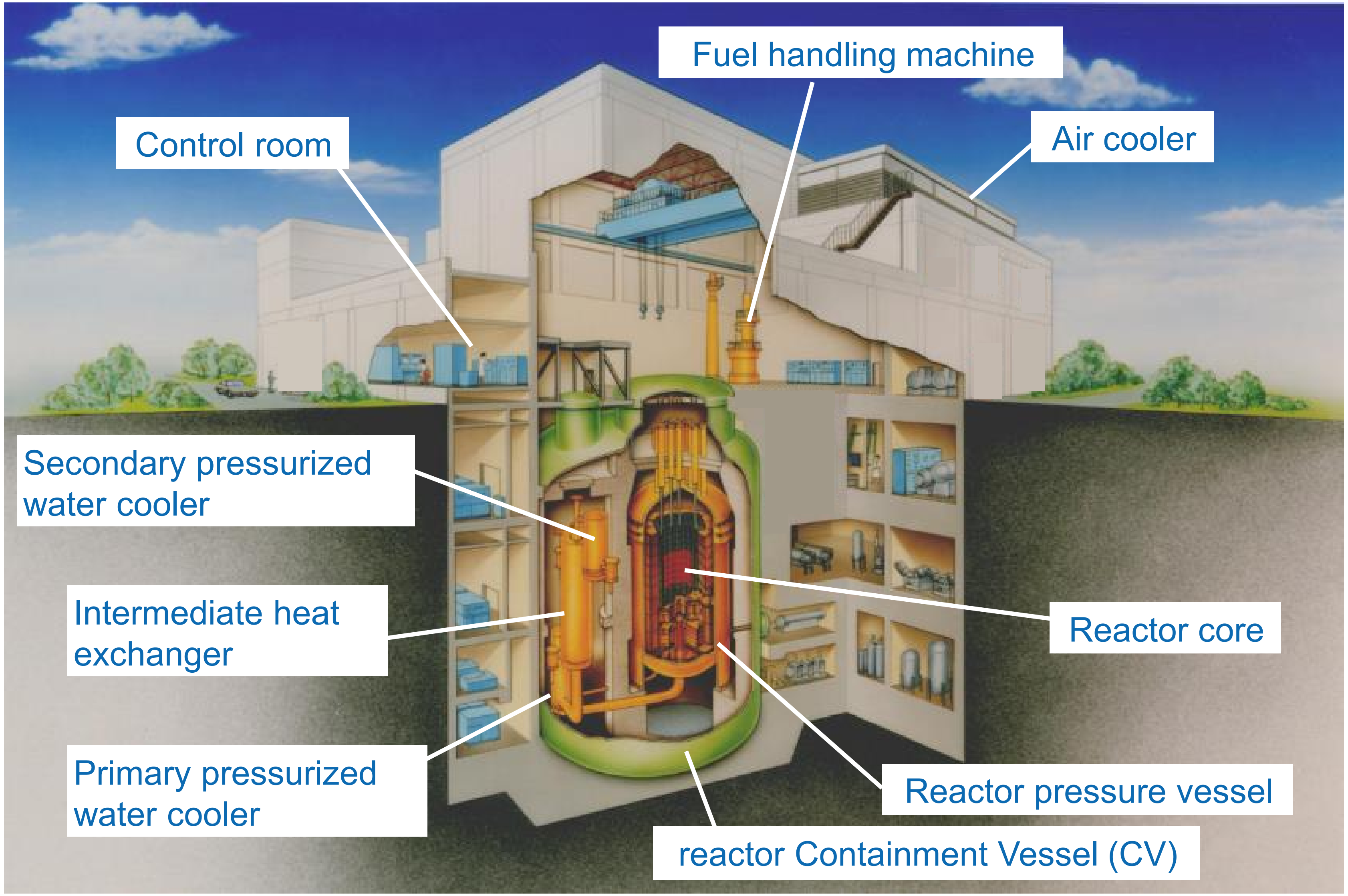
World highest quality graphite
(isotropic, high density)


Graphite core component in the HTTR

High strength, high thermal conductivity, irradiation resistance

High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

Reactor Building of HTTR



Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

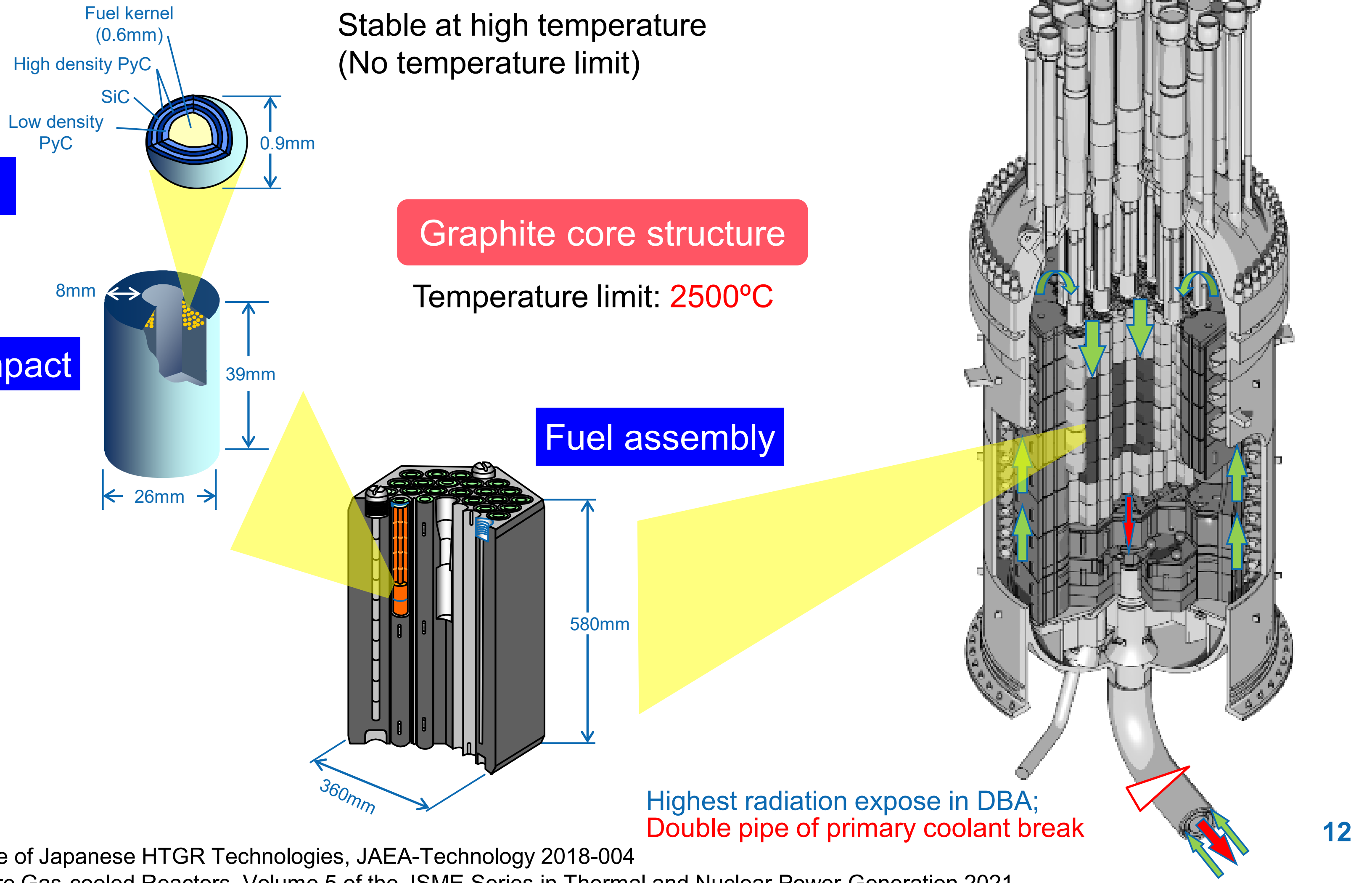
Core components of HTTR

Ceramic fuel coating

Retain radioactive material at 1600ºC

Coated fuel particle

Fuel compact



Helium coolant

Stable at high temperature (No temperature limit)

Graphite core structure

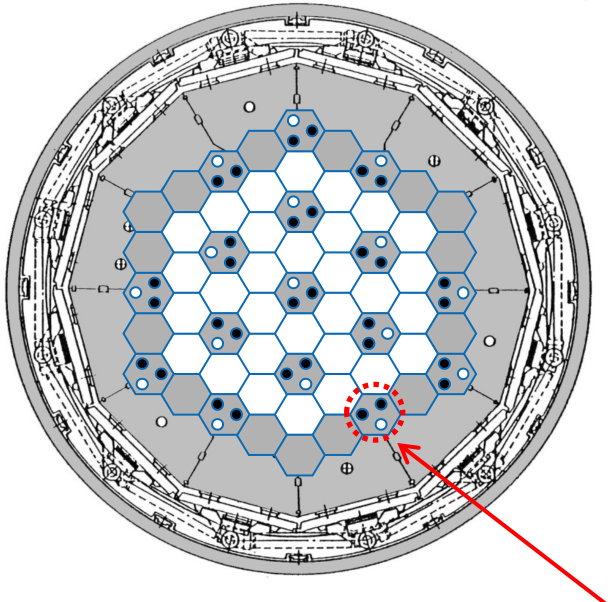
Temperature limit: 2500ºC

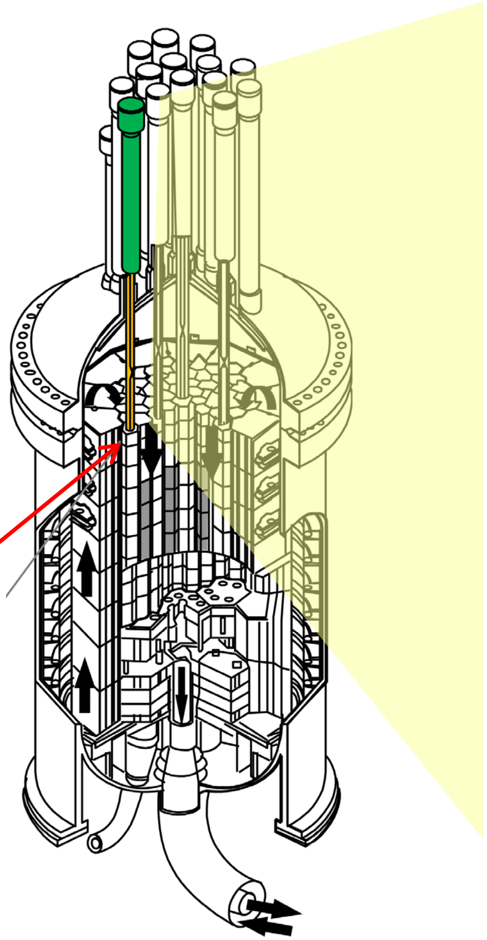
Fuel assembly

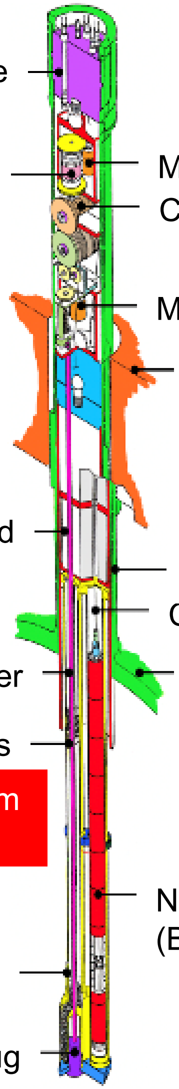
Highest radiation expose in DBA;
Double pipe of primary coolant break

Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

HTTR safety features: Reactor shutdown







Reactor scram signal

Electromagnetic clutch

Drop by gravity
(Fail safe for power loss)

Stand-pipe closure

Motor (control rod)

Cable drum

Motor (reserved shutdown)

Upper shield

Inner shield

Stand-pipe

Control rod support cable

Reserved shutdown hopper

Reactor pressure vessel

for insertion fail

B_4C pellets

Reserved Shutdown System (RSS)

Neutron absorber section
(B_4C cylinders)

Guide tube

Electric plug

Control rod guide block (16)

- ● : Control rod insertion hole
- ○ : B_4C pellets insertion hole

Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

HTTR safety features: Reactor cooling

＜Normal operation＞

Main Cooling System

＜Abnormal condition＞

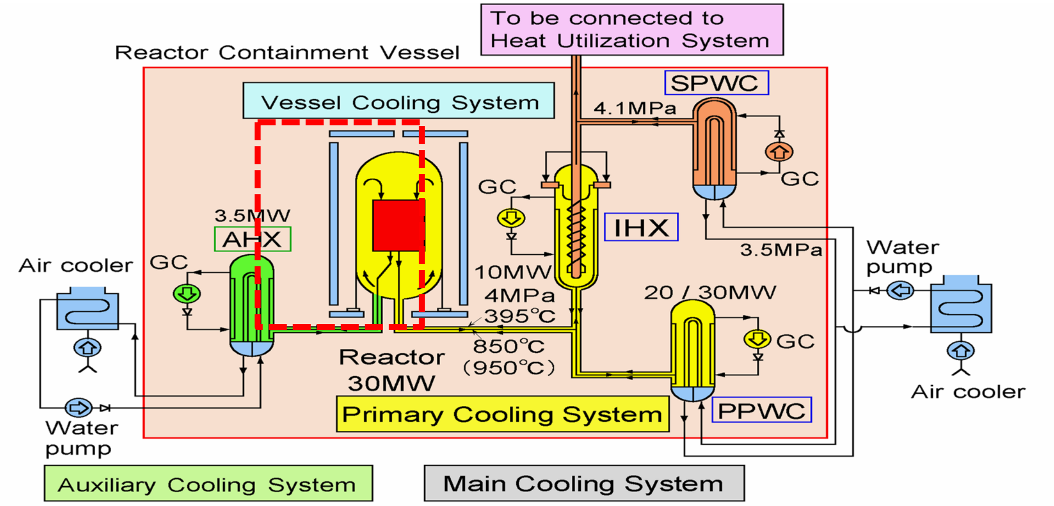
Auxiliary Cooling System

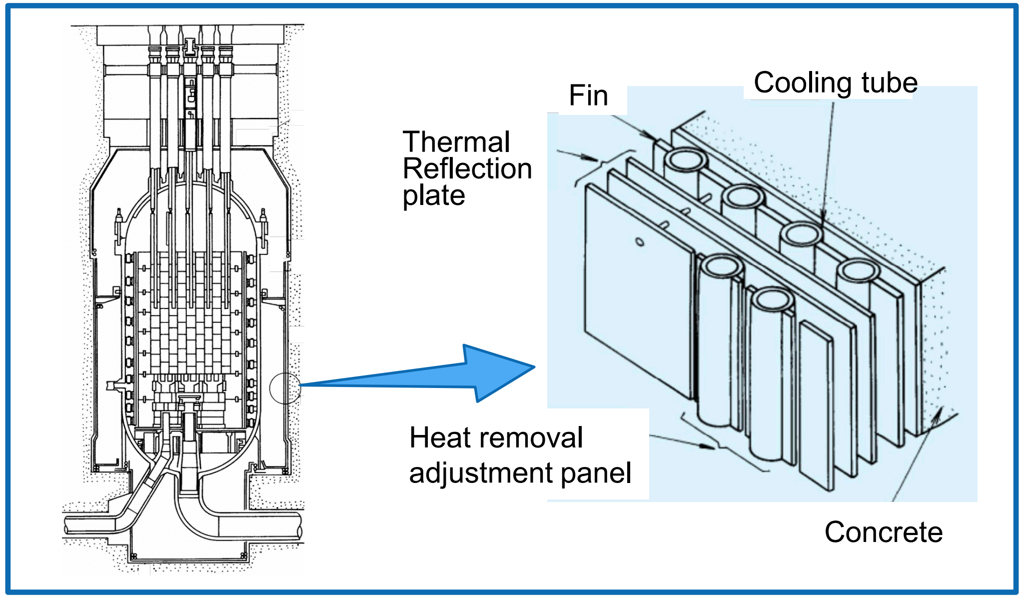
- Forced-circulation core cooling
- 1 system

＜Abnormal condition＞

Vessel Cooling System

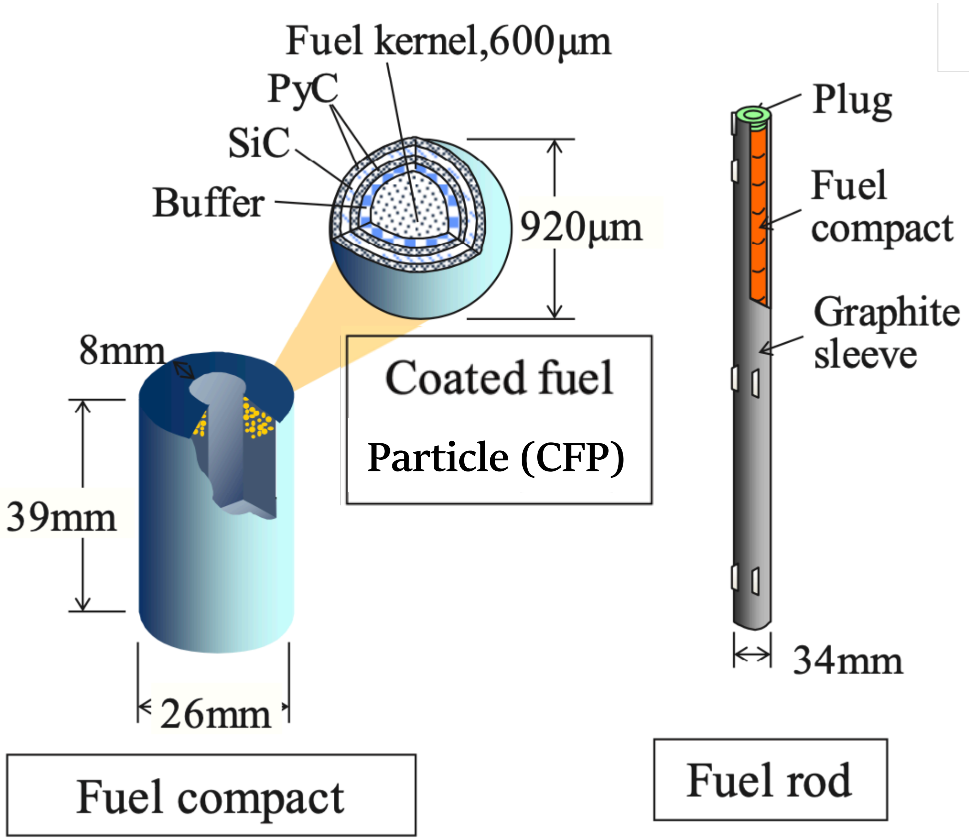
- From outside of pressure vessel
- Forced-circulation cooling water
- Final heatsink: atmosphere
- 2 systems
- Constant operation





Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

HTTR safety features: Fission product containment

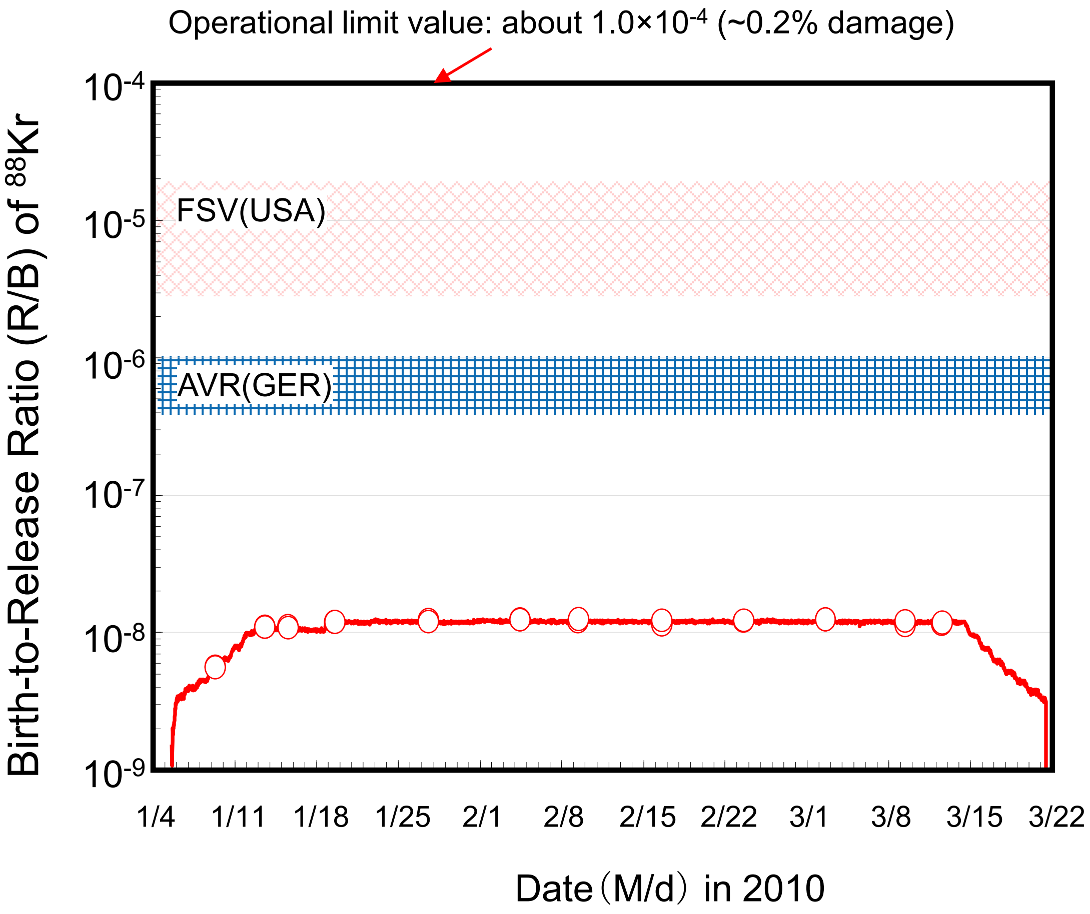


Coated fuel Particle (CFP)

Fuel compact

Fuel rod

Test results of 50 days continuous operation at 950°C

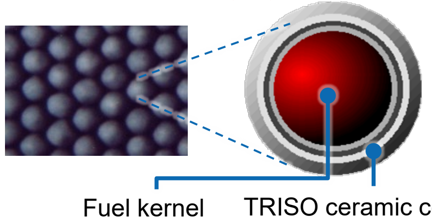


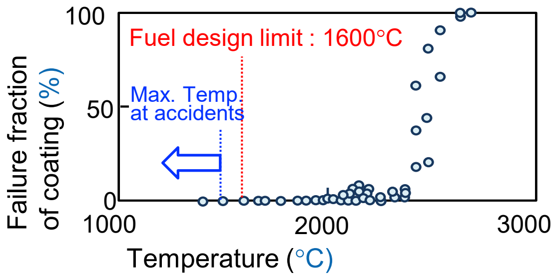
Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

Inherent reactor safety design of HTTR

Ceramic (SiC) coated fuel particle

Proven integrity at 1600°C

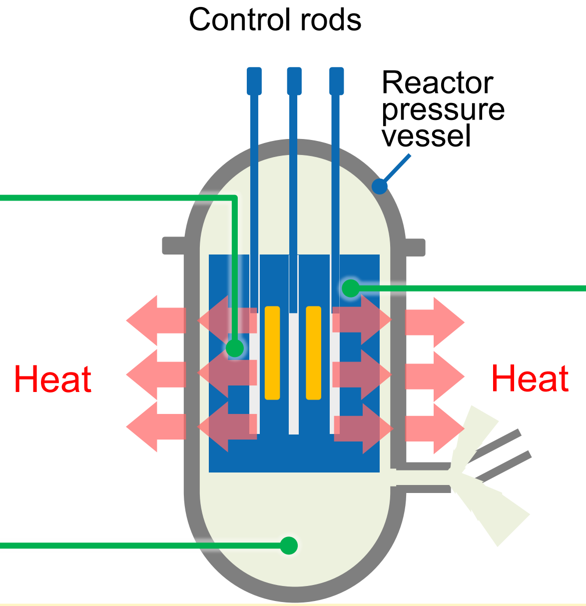




Experimental result

Inert helium coolant

No explosions of H_2 and vapor due to chemical inertness and absence of phase change of He coolant

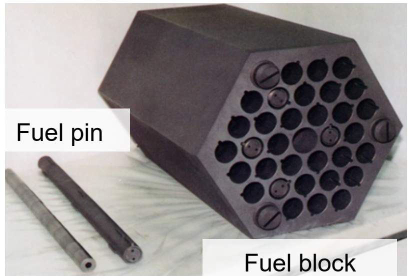


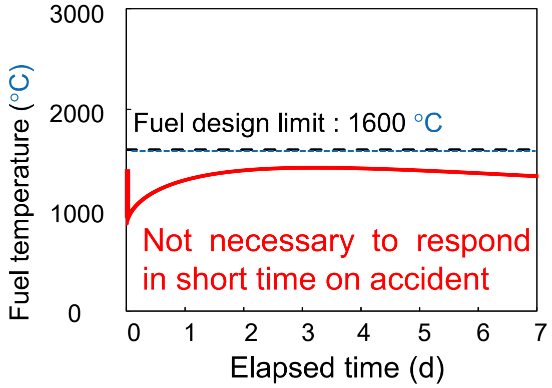
Reactor is safely shutdown and cooled by inherent design features without reliance on any equipment or operator action in the event of loss of coolant or station blackout

Old regulatory standards do not take into account the good points of inherent reactor safety design

Graphite core

Negative reactivity coefficient, high heat capacity and large thermal conductivity of graphite core provide for safe removal of core decay heat



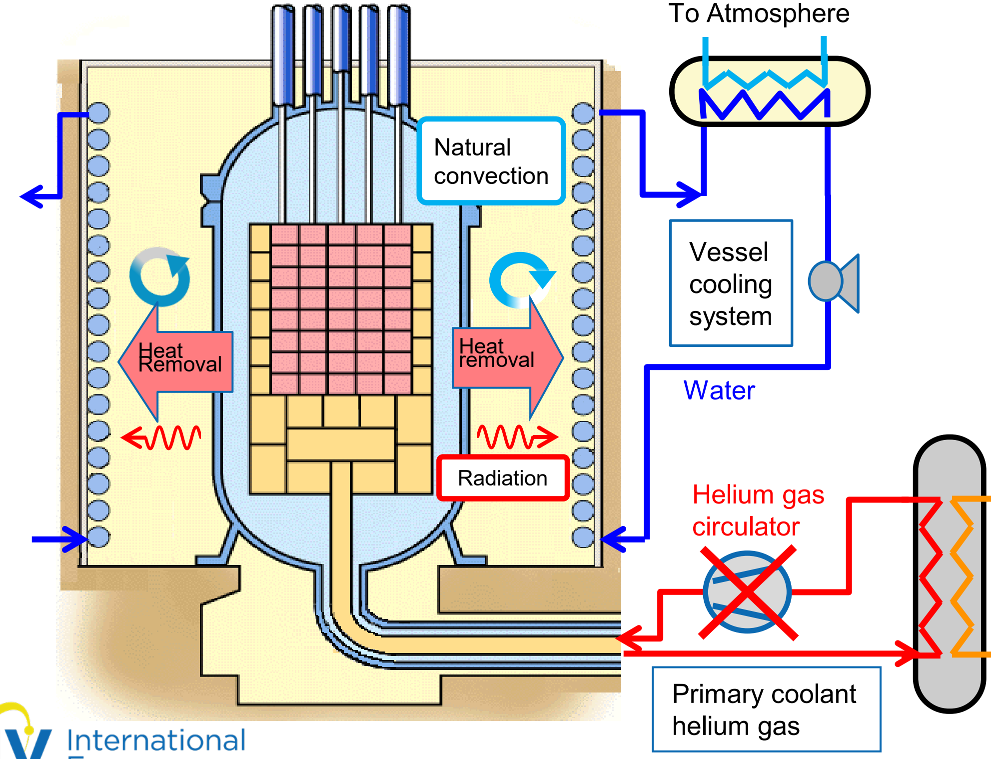


Simulation of loss of coolant

Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

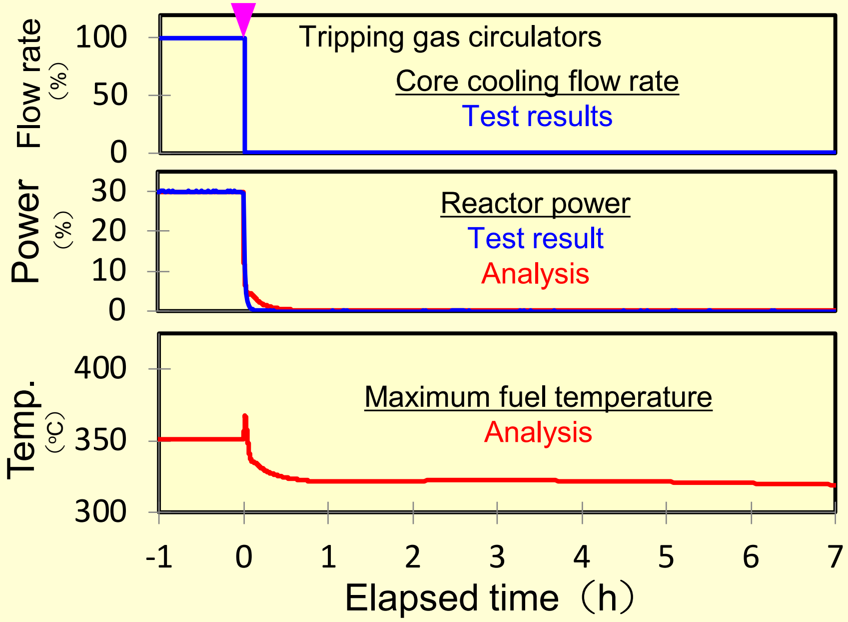
Safety demonstration test

- ☑ 30% power（9MW） Loss of forced cooling test
  （All HGC tripped） ・・・ Finished （2010）
- ☐ 100% power Loss of forced cooling test
  （All HGC tripped） ・・・ Planned
- ☐ 30% power Loss of core cooling test
  （All HGC + VCS tripped） ・・・ Planned



Test condition

- Initial power 30%（9MW）
- Reducing core flow rate to zero
- Keeping VCS operation
- No scram operation (No CR insertion)



Reactor is naturally shut down as soon as the core cooling flow rate to zero. Reactor is kept stable long after the loss of core cooling

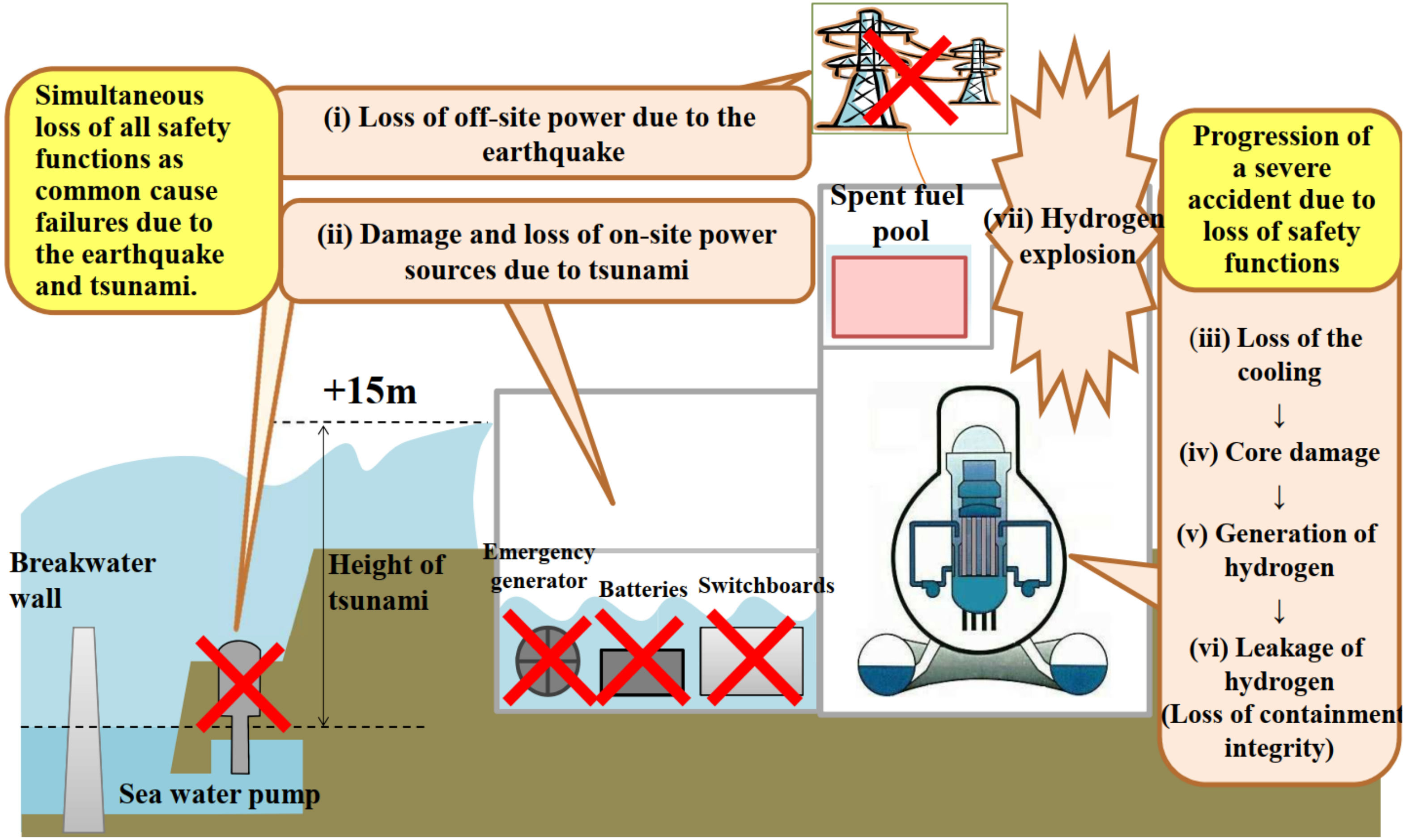
Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

Outline of Japan’s New Nuclear Regulation

Safety Regulation Problems before Fukushima Daiichi Nuclear Accident

Lessons learned from the Fukushima-Daiichi Nuclear Power station accident

- All safety functions were lost simultaneously due to the earthquake and tsunami.
- The initial impact spread and the crisis eventually developed into a severe accident.



Simultaneous loss of all safety functions as common cause failures due to the earthquake and tsunami.

(i) Loss of off-site power due to the earthquake

(ii) Damage and loss of on-site power sources due to tsunami

Progression of a severe accident due to loss of safety functions

(iii) Loss of the cooling
↓
(iv) Core damage
↓
(v) Generation of hydrogen
↓
(vi) Leakage of hydrogen (Loss of containment integrity)

(vii) Hydrogen explosion

https://www.nsr.go.jp/data/000067212.pdf

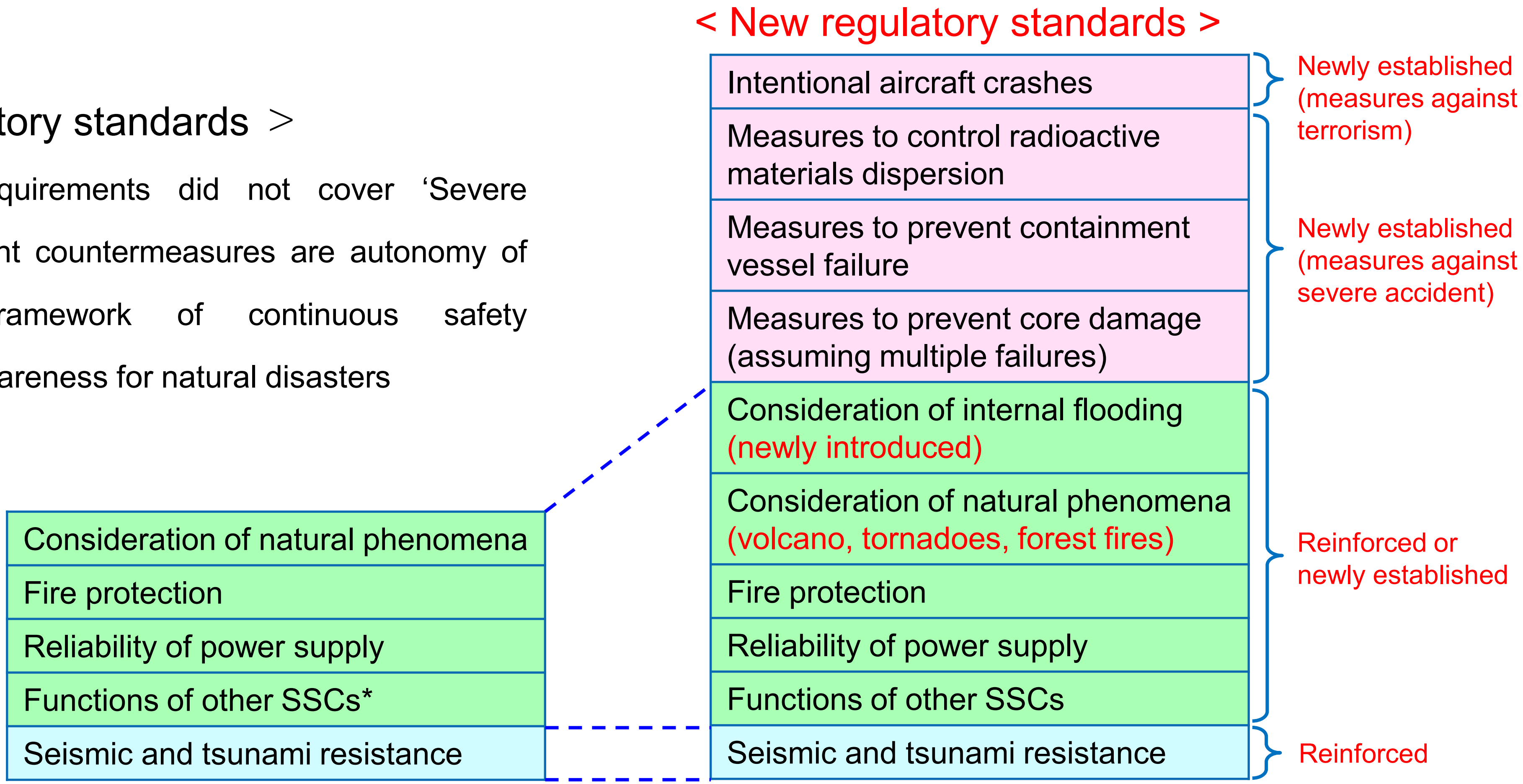
New regulatory requirements for Light-Water Nuclear Power Plants –Outline–. Nuclear Regulation Authority, 2013

Comparison between previous and new regulatory requirements for NPP

The New Regulatory Requirements tighten measures to prevent or deal with severe accidents and acts of terrorism

< Old regulatory standards >

- ✓ Regulatory requirements did not cover ‘Severe accidents’
- ✓ Severe accident countermeasures are autonomy of owner
- ✓ No legal framework of continuous safety improvements
- ✓ Lack of risk awareness for natural disasters
- ✓ …



< New regulatory standards >

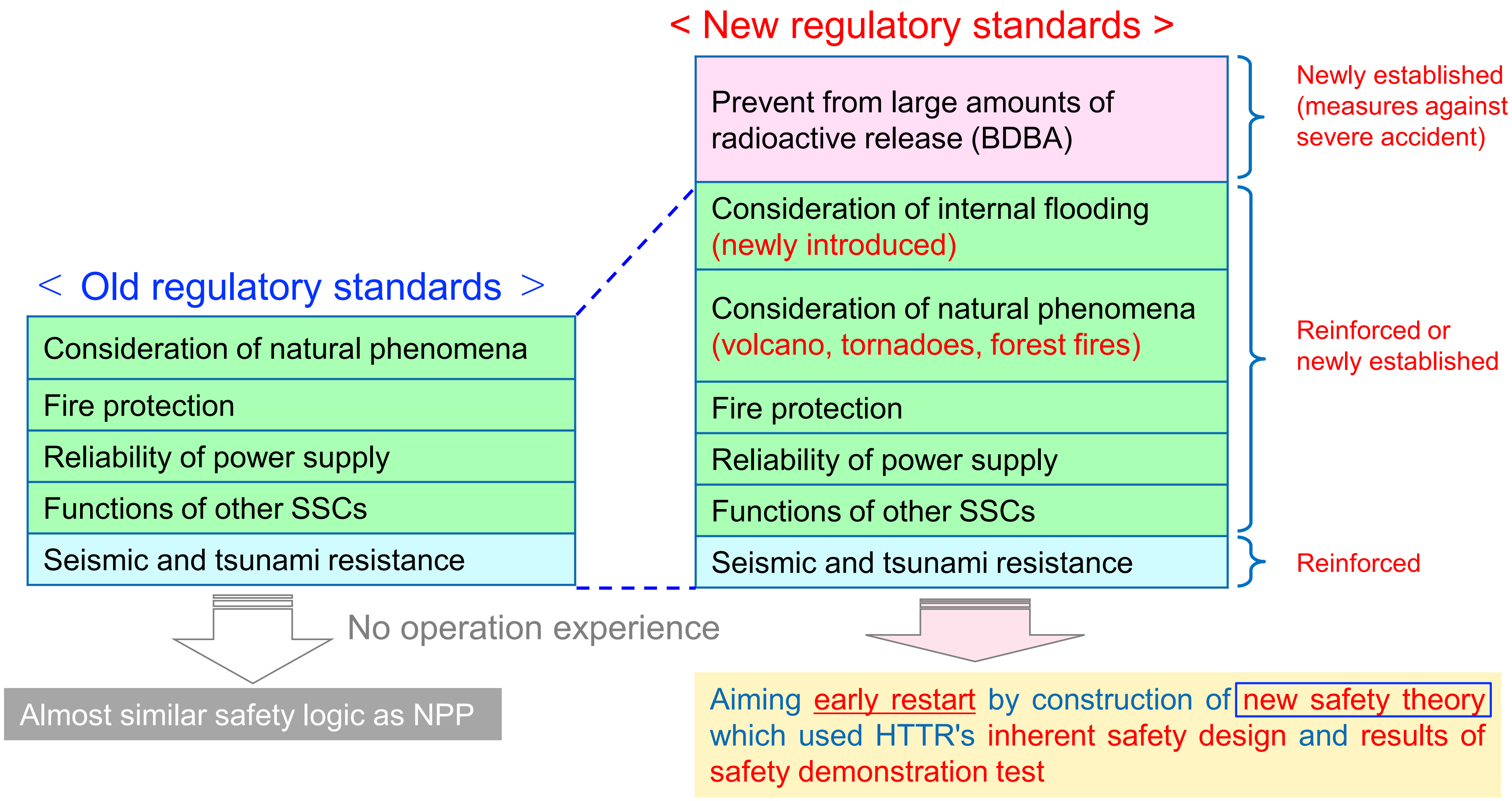
Old regulatory standards:
- Consideration of natural phenomena
- Fire protection
- Reliability of power supply
- Functions of other SSCs*
- Seismic and tsunami resistance

New regulatory standards:
- Intentional aircraft crashes — Newly established (measures against terrorism)
- Measures to control radioactive materials dispersion
- Measures to prevent containment vessel failure
- Measures to prevent core damage (assuming multiple failures)
  - Newly established (measures against severe accident)
- Consideration of internal flooding (newly introduced)
- Consideration of natural phenomena (volcano, tornadoes, forest fires)
- Fire protection
- Reliability of power supply
- Functions of other SSCs
  - Reinforced or newly established
- Seismic and tsunami resistance — Reinforced

*:Structures, Systems, and Components

New regulatory requirements for Light-Water Nuclear Power Plants –Outline–. Nuclear Regulation Authority, 2013

New regulatory requirements for HTTR



< Old regulatory standards >

- Consideration of natural phenomena
- Fire protection
- Reliability of power supply
- Functions of other SSCs
- Seismic and tsunami resistance

No operation experience

Almost similar safety logic as NPP

< New regulatory standards >

- Prevent from large amounts of radioactive release (BDBA)
- Consideration of internal flooding (newly introduced)
- Consideration of natural phenomena (volcano, tornadoes, forest fires)
- Fire protection
- Reliability of power supply
- Functions of other SSCs
- Seismic and tsunami resistance

Newly established (measures against severe accident)

Reinforced or newly established

Reinforced

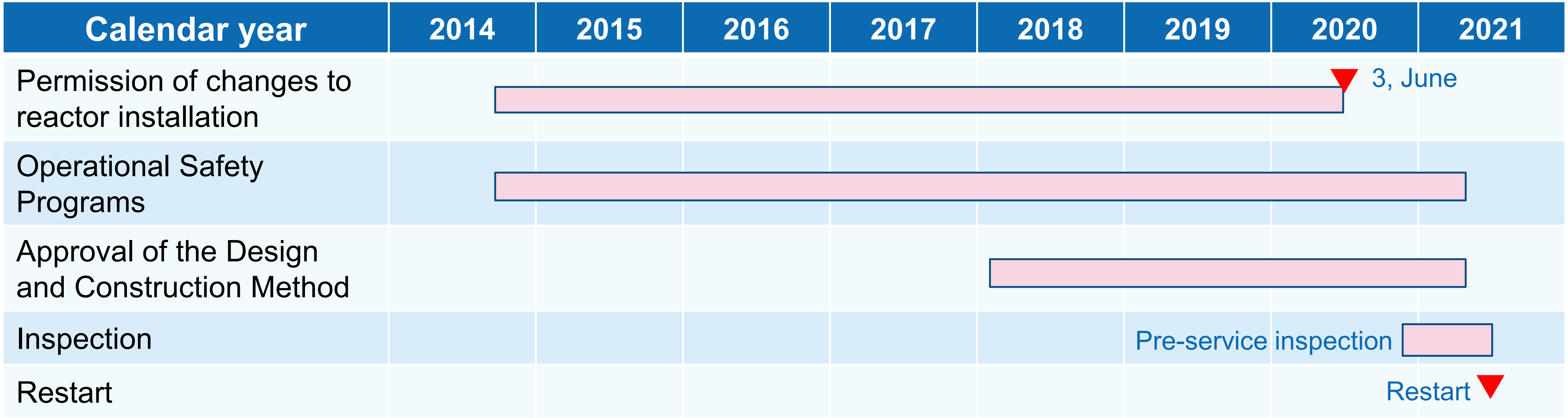
Aiming early restart by construction of new safety theory which used HTTR's inherent safety design and results of safety demonstration test

https://elaws.e-gov.go.jp/document?lawid=425M60080000021
https://www.nsr.go.jp/data/000172364.pdf

Conformation of Adaptability to New Regulatory Requirements for HTTR

Towards the restart of HTTR

- ✓ Following the nuclear accident at the Fukushima Daiichi nuclear power station on March 11, 2011, revised regulatory requirements were issued by the Nuclear Regulation Authority (NRA) in July 2013.
- ✓ JAEA had submitted the application including evaluation results satisfying the New Regulatory Requirements to the Nuclear Regulation Authority (NRA) on Nov. 26th, 2014.
- ✓ Through many discussions with the NRA, on June 3rd, 2020, JAEA obtained the permission by the NRA for changes to Reactor Installation of the HTTR.
- ✓ It is targeted to restart HTTR in July 2021.



Calendar year	2014	2015	2016	2017	2018	2019	2020	2021
Permission of changes to reactor installation	▨	▨	▨	▨	▨	▨	▨ ▼ 3, June	
Operational Safety Programs	▨	▨	▨	▨	▨	▨	▨	▨
Approval of the Design and Construction Method					▨	▨	▨	▨
Inspection						Pre-service inspection	Pre-service inspection ▨	▨
Restart							Restart	▼

"HTTR Licensing Experience and Commercial Modular HTGR Safety Design Requirements including Coupling of Process Heat Applications", "Towards innovative R&D in civil nuclear fission" SNETP FORUM 2021, 2-4 February 2021

NPP(BWR) and HTTR

	LWR (BWR)	HTTR
Thermal power	3,300 MW	30 MW (1/110, 0.9%)
Power density	50 MW/m³	2.5 MW/m³ (1/20, 5%)
Coolant type	Light water	Helium
Coolant temperature	~285 ˚C	~395/850(950) ˚C （inlet / outlet）
Coolant pressure	~7 MPa	~4 MPa
Heatsink	Seawater	Atmosphere
Emergency core cooling system	Necessary	Unnecessary
Decay heat removal	Forced circulation pump	Natural heat transfer

Excellent Feature of Japanese HTGR Technologies, JAEA-Technology 2018-004
High Temperature Gas-cooled Reactors, Volume 5 of the JSME Series in Thermal and Nuclear Power Generation 2021

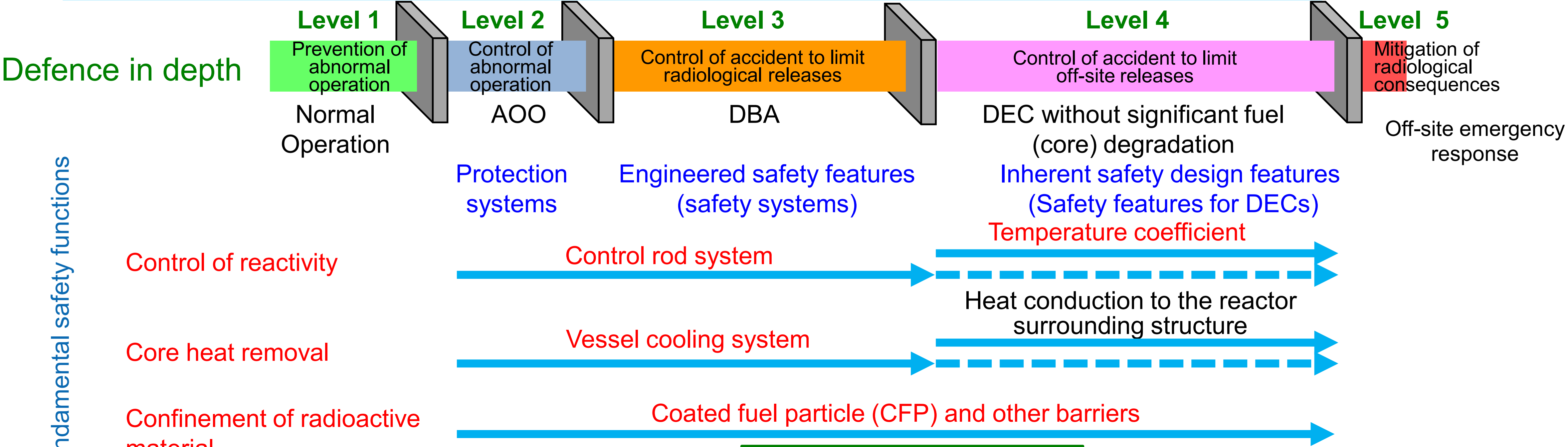
Safety requirements

Safety requirements		Modular HTGRs	LWRs
Design extension condition (DEC)		DEC without significant fuel degradation	DEC without significant fuel degradation DEC with core melting
Reactor shutdown		At least two diverse and independent means (Inherent design features is regarded as one of means)	At least two diverse and independent systems
Heat removal from core		Passive cooling from the outside surface of reactor vessel (Passive cooling)	In shutdown states: Residual heat removal （Forced cooling） In accident condition：Emergency core cooling （Forced cooling）
Confinement of radioactive materials	Fuel integrity	In operational states and in accident conditions	In operational states (normal operation and AOO)
	Containment system	Confinement (i.e., vented low-pressure containment)	Containment Vessel
Additional specific considerations		Mitigation of air and water ingress into core during accidents	-

“HTTR Licensing Experience and Commercial Modular HTGR Safety Design Requirements including Coupling of Process Heat Applications”, “Towards innovative R&D in civil nuclear fission” SNETP FORUM 2021, 2-4 February 2021

Safety design approach

- ✓ No significant fuel (core) degradation
- ✓ Fission product is confined by the combination of coated fuel particle and other barriers
- ✓ Passive engineered safety features and Inherent safety design features



Defence in depth

Level 1
Prevention of abnormal operation
Normal Operation

Level 2
Control of abnormal operation
AOO
Protection systems

Level 3
Control of accident to limit radiological releases
DBA
Engineered safety features (safety systems)

Level 4
Control of accident to limit off-site releases
DEC without significant fuel (core) degradation
Inherent safety design features (Safety features for DECs)

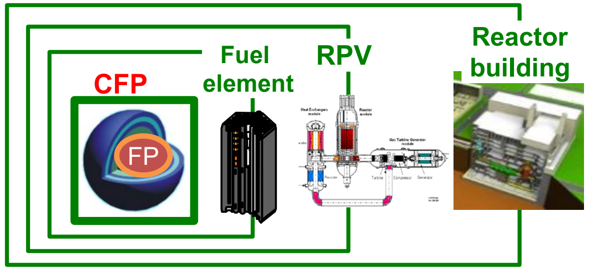
Level 5
Mitigation of radiological consequences
Off-site emergency response

Fundamental safety functions

Control of reactivity
Control rod system
Temperature coefficient

Core heat removal
Vessel cooling system
Heat conduction to the reactor surrounding structure

Confinement of radioactive material
Coated fuel particle (CFP) and other barriers



“HTTR Licensing Experience and Commercial Modular HTGR Safety Design Requirements including Coupling of Process Heat Applications”, “Towards innovative R&D in civil nuclear fission” SNETP FORUM 2021, 2-4 February 2021

Safety importance classification

HTTR safety characteristic

With lower power density than LWRs (~2.5MW/m^3 *vs* >50MW/m^3) and large heat capacity of graphite core, the HTTR can maintain in a stable state when the cooling function is lost completely, and further even the shutdown function and cooling function are lost simultaneously.

Safety importance classification

Reviewed with reference to “The guide* ”.

Classification of importance in seismic design

Reviewed with reference to “The rule of seismic importance classification of research reactor”.

Safety importance
PS1,2: Prevention System
MS1,2: Mitigation System

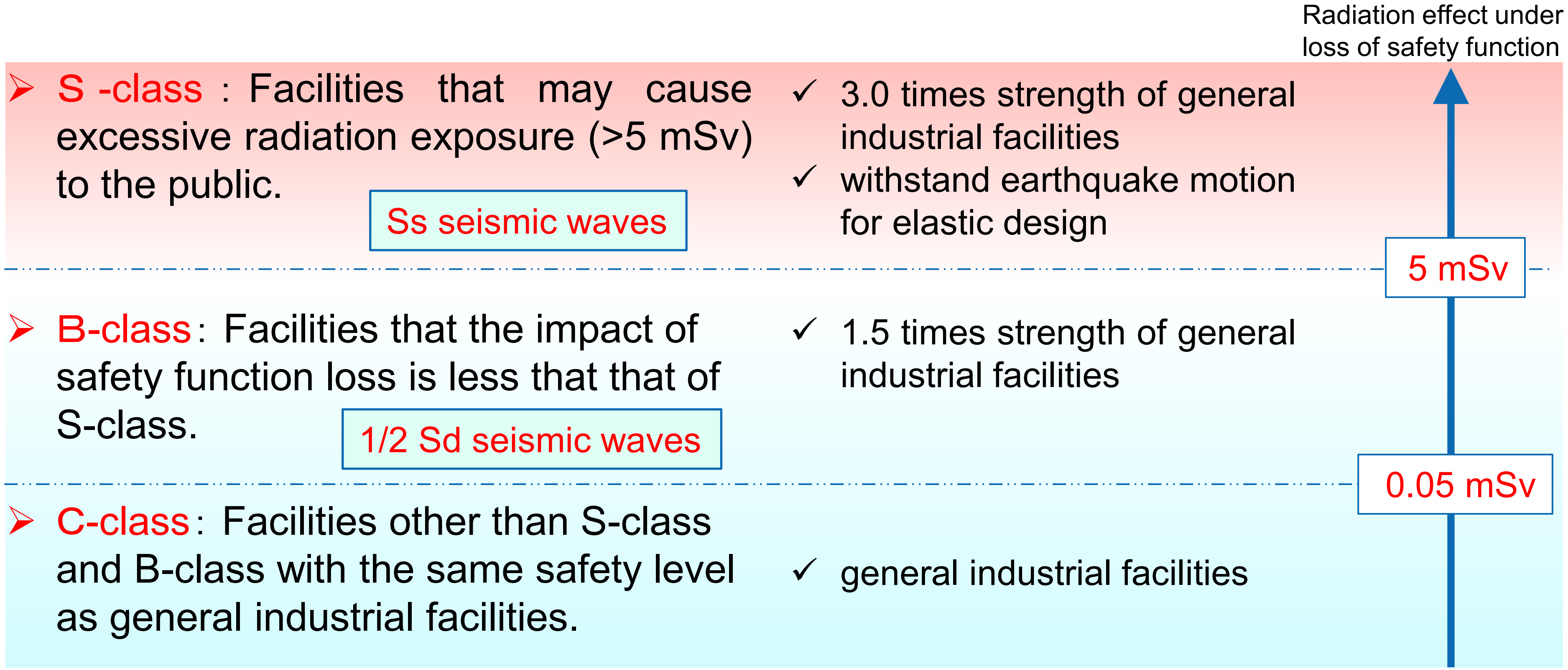
Seismic importance : (S, B, C)

Unique classification of the HTTR different from the NPP was proposed to the NRA by explaining the inherent safety design and results of safety demonstration test.

* https://elaws.e-gov.go.jp/document?lawid=425M60080000021
https://www.nsr.go.jp/data/000172364.pdf

Classification of importance in seismic design

In order to prevent the loss of safety functions and impact of radioactive materials on the public by earthquake, each facility must be designed sufficiently withstand the seismic force according to its importance.



Radiation effect under loss of safety function

- S -class : Facilities that may cause excessive radiation exposure (>5 mSv) to the public.

Ss seismic waves

- ✓ 3.0 times strength of general industrial facilities
- ✓ withstand earthquake motion for elastic design

5 mSv

- B-class: Facilities that the impact of safety function loss is less that that of S-class.

1/2 Sd seismic waves

- ✓ 1.5 times strength of general industrial facilities

0.05 mSv

- C-class: Facilities other than S-class and B-class with the same safety level as general industrial facilities.

- ✓ general industrial facilities

https://elaws.e-gov.go.jp/document?lawid=425M60080000021

https://www.nsr.go.jp/data/000172364.pdf

HTTR safety review results by Nuclear Regulation Authority (1/2)

Major discussion item		Regulatory review condition	Regulatory review results	Additional countermeasures
Earthquake	Design seismic ground motion	Raised from 350 gal to 973 gal	No large-scale reinforcement due to the degradation of the SSCs.	Not required
	Re-evaluation of seismic design classification	Some of structures, systems and components (SSCs) were downgraded taken into account the results of safety demonstration tests. ➢ Core heat removal: S class to B class ➢ Reactor internal structure: S class to B class.		
Tsunami evaluation		Assumption of tsunami height for evaluation：17.8 m from sea level	Tsunami does not reach the site because siting location is 36.5 m high from the sea level.	Not required
Evaluation of integrity of SSCs against natural phenomena such as tornado, volcano, etc.		● Design basis tornado wind speed: 100 m/s ● Thickness of descent pyroclastic material by volcano: 50 cm	● All SSCs needed to be protected are installed inside the reactor building ● Fire proof belt necessary around reactor building.	Fire proof belt was required.

"HTTR Licensing Experience and Commercial Modular HTGR Safety Design Requirements including Coupling of Process Heat Applications", "Towards innovative R&D in civil nuclear fission" SNETP FORUM 2021, 2-4 February 2021

HTTR safety review results by Nuclear Regulation Authority (2/2)

Major discussion item	Regulatory review condition	Regulatory review results	Additional countermeasures
Fire	Burnable materials in and around the reactor building was additionally evaluated.	● Amount of burnable materials in the reactor building is limited. ● Cables necessary to be protected against fire	Cable protection against fire was required.
Reliability of power supply	Emergency power supply failure was evaluated.	Decay heat is removable from the core without electricity.	Only portable power generator for monitoring during accident is required.
Beyond design basis accident (BDBA)	Postulated BDBAs ➢ DBA + failure of reactor scram ➢ DBA + failure of heat removal from the core ➢ DBA + failure of containment vessel	● No core melt occurs in all BDBAs.	

(DBA : Design Basis Accident)

HTTR will restart without significant additional reinforcements due to its inherent safety features.

“HTTR Licensing Experience and Commercial Modular HTGR Safety Design Requirements including Coupling of Process Heat Applications”, “Towards innovative R&D in civil nuclear fission” SNETP FORUM 2021, 2-4 February 2021

Conclusion

- The new safety theory which used HTTR's inherent safety design and results of safety demonstration test has been approved by Nuclear Regulation Authority (NRA) .
- As a result, JAEA obtained permission by NRA toward the restart of the HTTR in conformity to the New Regulatory Requirements on 3rd June 2020.
- HTTR is expected to be restarted without any additional reinforcement due to its own high-level inherent safety features.
- Following the restart of HTTR, number of activities are planned:
  - ✓ Safety demonstration test in OECD/NEA LOFC project.
  - ✓ Technology demonstration test of heat utilization system.
  - ✓ International cooperation and human-resource development utilizing the HTTR.

Application documents

GEN IV International Forum
Expertise | Collaboration | Excellence

“Pitch your Gen IV Research” Competition

View and Vote for your Favorites

- Watch outstanding videos on nuclear reactors by junior researchers from around the world (4 minutes each)
- “LIKE” your favorites
- Vote through April 30, 2021

Watch on YouTube

tinyurl.com/wwauk74

Watch on BiliBili

tinyurl.com/hdrrvfek

ANS

GEN IV International Forum

Expertise | Collaboration | Excellence

Special Webinar Event

20th Anniversary Celebration with the participation of current and former GIF Chairs

"Progress and Future Prospects toward Deploying GEN IV Reactors as Advanced Nuclear Energy Systems"

Wednesday, April 28, 2021 8:30 am EDT (UTC-4)

Register at: https://attendee.gotowebinar.com/register/4928218237397954063

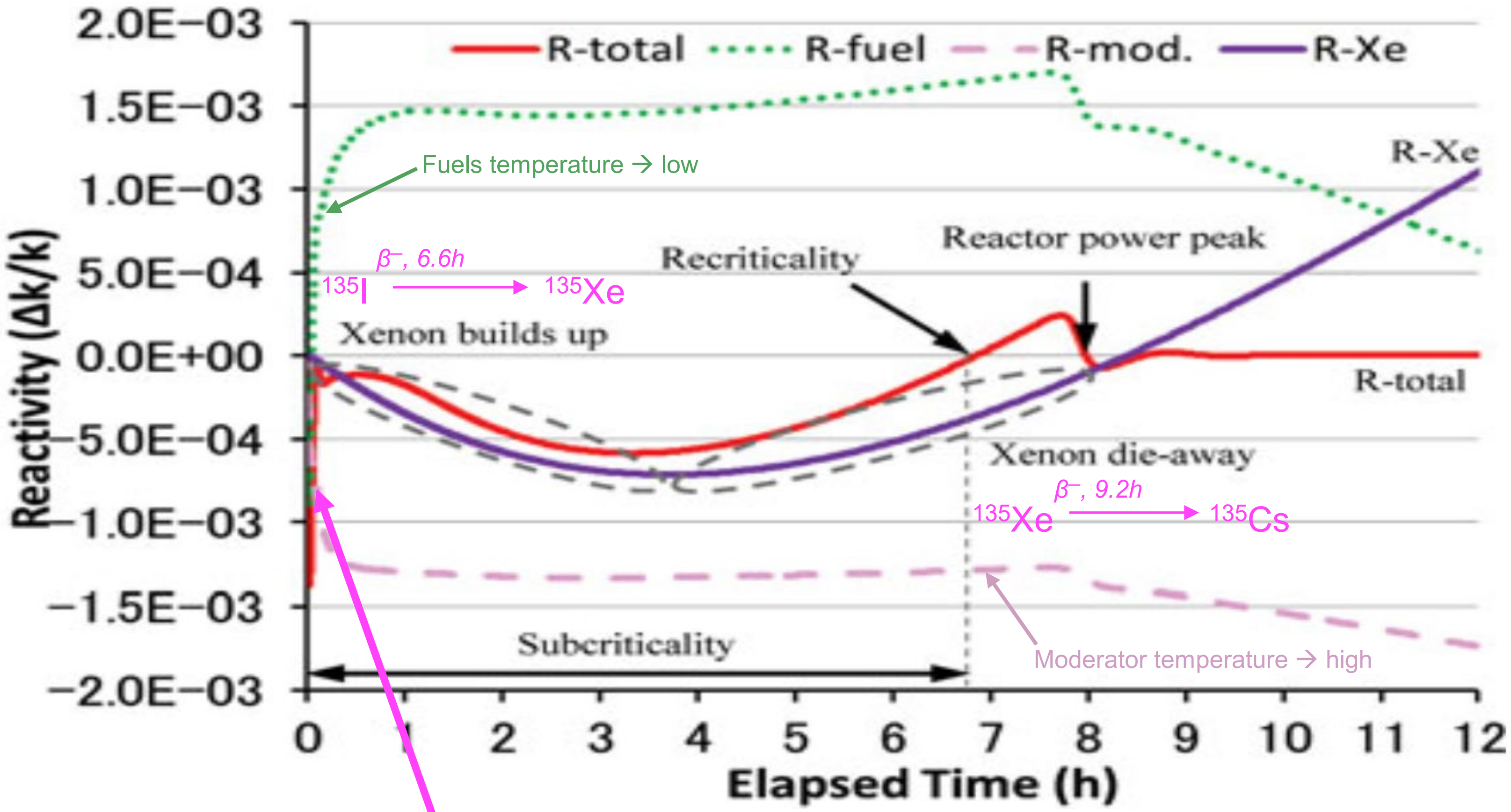
GIF Webinar Series
2016–2021 EDUCATION AND TRAINING WORKING GROUP

Upcoming Webinars

Date	Title	Presenter
28 April 2021	Progress and Future Prospects toward Deploying GEN IV Reactors as Advanced Nuclear Energy Systems	Panel Discussion by Current and Former GIF Chairs
25 May 2021	Advanced Manufacturing for Gen IV Reactors	Dr. Isabella van Rooyen, INL, USA
24 June 2021	In Service Inspection and Repair Developments for SFRs and Extension to Other Gen4 Systems	Mr. François Baque, CEA, France
27 July 2021	Evaluating Changing Paradigms Across the Nuclear Industry	Ms. Jessica Lovering, Carnegie Mellon University, USA

Appendix

Calculation results of LOFC test (1)



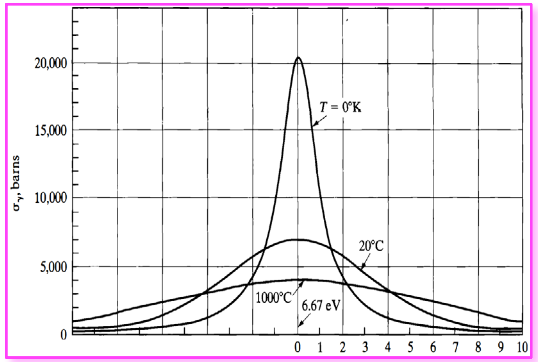
Fuels temperature → low

$^{135}I \xrightarrow{\beta^-,\ 6.6h} {}^{135}Xe$

$^{135}Xe \xrightarrow{\beta^-,\ 9.2h} {}^{135}Cs$

Moderator temperature → high

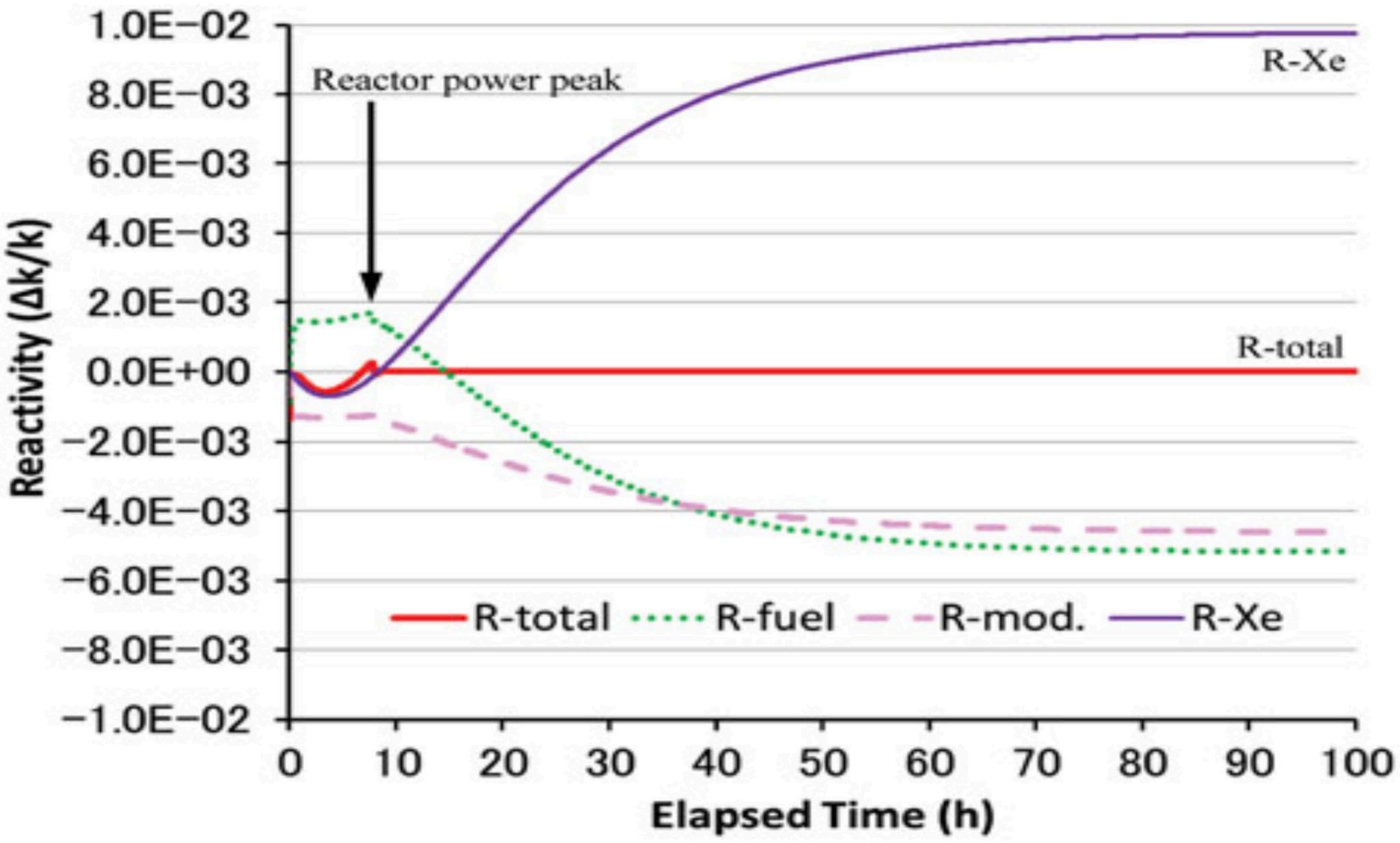
Fuels temperature → high
Negative reactivity of the fuel caused by doppler broadening effect



Capture cross-section of ^{238}U

K. Takamatsu et al. 2014. Journal of Nuclear Science and Technology, 51:11-12, 1427-1443

Calculation results of LOFC test (2)



K. Takamatsu et al. 2014. Journal of Nuclear Science and Technology, 51:11-12, 1427-1443

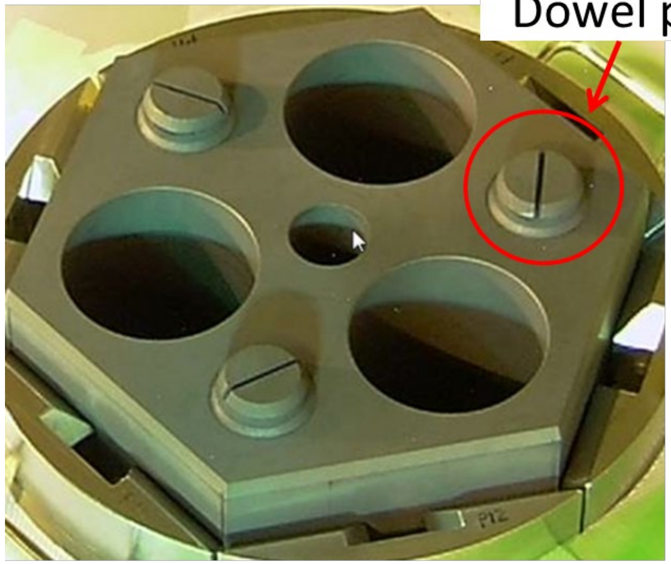
Seismic measurement at 2011 earthquake

Location	Floor	Max of acceleration (m/s²)		
		North-South	West-East	Up-Down
Reactor building	2F	5.19	3.24	2.30
	1F	3.27	2.94	2.87
	B1F	2.58	2.21	1.84
	B3F	1.98	2.22	1.92
Inner concrete (CV)	B1F	3.60	2.71	2.58
	B3F	1.96	1.99	2.13

Red symbol: exceed design value

@ new regulation → 9.73 m/s^2

Integrity of the blocks were visually confirmed



Control rod guide block

M.Ono, et al., Journalof Nuclear Engineering and Radiation Science, April 2018,Vol.4 / 020906-3.