Status Report - HTR50S (Japan)

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1. Overview

- ☐ **In Operation**
- ☐ **Under Construction**
- ☐ **Described in**

Link to PRIS	--

- ☑ **New Concept**

Number of Units	--
Year	--

Reference Plant

Name of Site	High Temperature Gas-cooled Reactor
Link to PRIS	--
Net Power Output (MWe)	--
Gross Power Output (MWe)	17.2

1.1 Introduction

HTR50S is 50 MWt small-sized high temperature gas-cooled reactor (HTGR) for multiple heat applications with the reactor outlet coolant temperature of 750°C for the reference design. The reactor is designed to increase to outlet temperature up to 900°C. The system is designed by JAEA in conjunction with Japanese nuclear vendors.

The design builds on using the existing technology and experience obtained in the HTTR construction and operation to minimize initial construction uncertainty and potential delay.

Figure 1. Plant layout (Phase II) [1]

Figure 2. System Configuration

1.2 Development Milestones

2010	Start of design
2013	Concept design completed
2017	Graphite irradiation test project completed
2019	High burnup fuel irradiation test project completed

2023	Monolithic fuel element specimen irradiation test project completed

1.3 Design organization or vendor company

sato.hiroyuki09@jaea.go.jp

1.4 Links to designer/vendor website

https://www.jaea.go.jp/04/o-arai/nhc/en/index.html

1.5 Design Description

1.6 Licensing Application Support Documents

Technical report of preliminary safety analysis (JAEA-Technology 2013-017)

1.7 Reactor Unit in PRIS

2. Category Fields

Table 1: ARIS Category Fields

ARIS Category	Value	Units of Examples
Current/Intended Purpose	Demonstration	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Off - grid / Remote, Non-electric	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Inland	e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Single Unit	e.g. Single Unit, Dual Unit, Multiple Unit (# units)
Core Coolant	He	H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Reactor Core Size (1 core)	30 MWth <= Thermal power < 1000 MWth	e.g. Thermal Power < 30 MWth, 30 MWth ≤ Thermal power < 1000 MWth, 1000 MWth ≤ Thermal power ≤ 3000 MWth, Thermal power > 3000 MWth

Reactor Type	GCR	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	SMR	e.g. PWR, SMR
Neutron Moderator	Graphite	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout	Loop-type	e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced	e.g. Forced (# pumps), Natural
Thermodynamic Cycle	Rankine	e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	H2O	e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Coated Sphere	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Hexagonal	e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	33	e.g. #, n/a
Fuel Material Type	Oxide	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual Design	e.g. Conceptual, Detailed, Final (with secure suppliers)
Licensing Status		e.g. DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)
Neutron Spectrum	Thermal	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		

Design Life	40	Years
Lifetime Capacity Factor	90	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	TBD	# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	TBD	# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design	1	n Units/Modules
Capacity to Electric Grid	17.2	MWe (net to grid)
Non-electric Capacity	25	e.g. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	TBD	MWe
Plant Footprint	TBD	m2 (rectangular building envelope)
Site Footprint	TBD	m2 (fenced area)
Emergency Planning Zone	TBD	km (radius)
Releases during Normal Operation	TBD	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	TBD	x – 100%, % per minute
Seismic Design (SSE)	TBD	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	4	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)	12.5	MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)	TBD	kg
Nominal Coolant Flow Rate (primary)	22.3	kg/s
Nominal Coolant Flow Rate (secondary)		kg/s
Core Inlet Coolant Temperature	325	ºC

Core Outlet Coolant Temperature	750	ºC
Available Tempeature as Process Heat Source	533	ºC
NSSS Largest Component	RPV	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length	13800	mm
- NSSS Largest Component Diameter	5650	mm
- NSSS Largest Component Thickness		mm
- NSSS Largest Component Weight		tonne
Reactor Vessel Material	SA533/SA508	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	Vertical Helical Coils	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory	TBD	kg
Pressurizer Design	N/A	e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume	N/A	m3 / m3 (total / liquid)
Containment Type	Dry (single)	Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume		m3
Spent Fuel Pool Capacity and Total Volume	TBD	Years of full-power operation / m3
Non Electric Application		-
Core Delta Temperature	425	ºC
Fuel/Core		
Single Core Thermal Power	50	MW(th)
Refuelling Cycle	24	months or “continuous”
Fuel Material	UO2	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	5.9/ 9.4	%
Average Neutron Energy	Epithermal core	eV

Fuel Cladding Material	TRISO coated fuel particle	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”	180 fuel blocks	Specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit	TBD	kg
Total Fissile Loading (initial)	TBD	kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation	TBD	Applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge	TBD	%
Core Discharge Burnup	49	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)	49	MWd/kgHM
Breeding/Conversion Ratio	N/A	Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing	Possible	e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Rods	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber	B4C	e.g. Gd2O3
Core Volume (active)		m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary	TBD	n/(cm²*s)
Max. Fast Neutron Flux	TBD	n/(cm²*s)
Core Control Rod Absorber		-
Core Soluble Neutron Absorber		-
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	Active	100 / - / -
- core injection	N/A	- / - / -

- decay heat removal	Passive	- /100 / -
- containment isolation and cooling	N/A	- / - / -
- emergency AC supply (e.g. diesels)	N/A	- / - / -
DC Power Capacity (e.g. batteries)		Hours
Events in which Immediate Operator Action is required	none	e.g. any internal/external initiating events, none
Limiting (shortest) Subsequent Operator Action Time	Not required	Hours (that are assumed when following EOPs)
Severe Accident Core Provisions	no core melt	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	N/A	x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions	N/A	e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)	N/A	x/reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)	TBD	Months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort	TBD	Person-years (PY) [DP&P]
Construction and Commissioning Effort	TBD	PY [C&C]
Material and Equipment Overnight Capital Cost	TBD	Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C]/%[M&E]	
- Site Development before first concrete	TBD	(e.g. 25/10) (30/40) (20/25) (20/10) (5/15) (----------) (to add up to 100/100)
- Nuclear Island (NSSS)	TBD	
- Conventional Island (Turbine and Cooling)	TBD	
- Balance of Plant (BOP)	TBD	

- Commissioning and First Fuel Loading	TBD	
Factory / On-Site split in [C&C] effort	TBD	%/% of total [C&C] effort in PY (e.g., 60/40)
Nuclear System		
System Steam Flow Rate		kg/s
System Steam Pressure		MPa
System Steam Temperature		ºC
System Feedwater Flow Rate		kg/s
System Feedwater Temperature		ºC
Reactor Core		
Active Core Height		m
Equivalent Core Diameter		m
Average Linear Heat Rate		kW/m
Average Fuel Power Density		kW/kgU
Average Core Power Density		MW/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

Site layout and bird's eye view of HTR50S are shown in Fig.3 and 4. Regarding the building layout, the steam turbine building was placed adjacent to the reactor building in the same direction as the steam generator (SG) in the reactor building, and the gas turbine building was placed adjacent to the reactor building in the same direction as the intermediate heat exchanger (IHX) in order to minimize the main steam piping, feed water piping, and secondary coolant heat piping between buildings, considering the amount of piping and other materials.

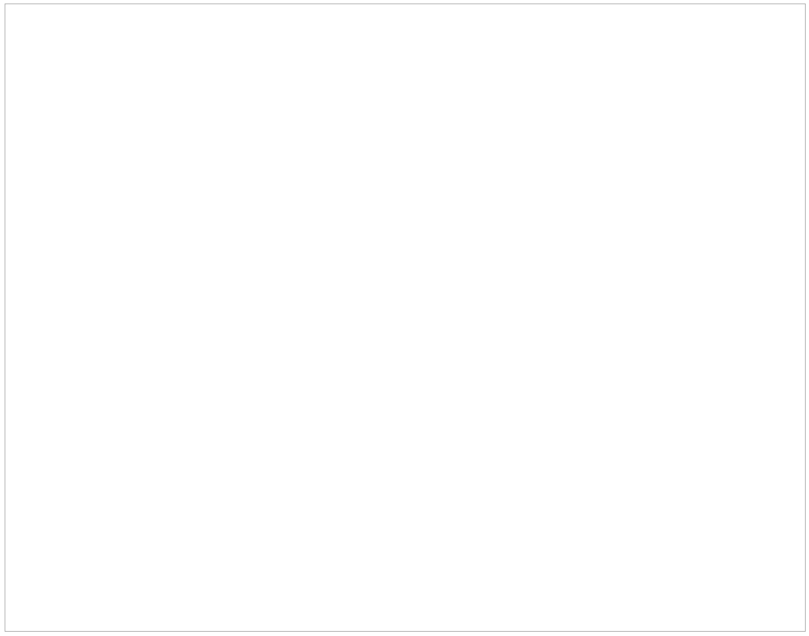


Figure 3. Site Layout of HTRS50[2]

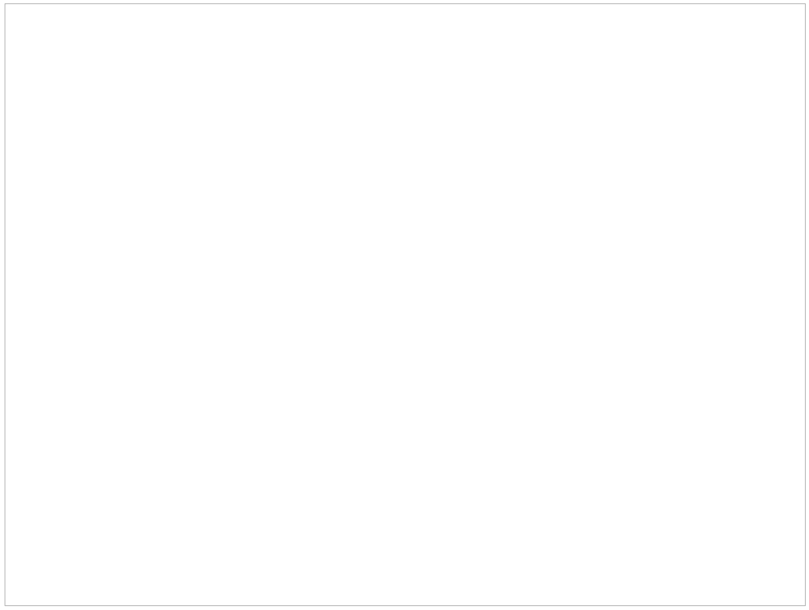


Figure 4. Bird's eye view of HTR50S [2]

4.1 Site Requirements during Construction

Site layout and bird's eye view of HTR50S are shown in Fig.3 and 4. Regarding the building layout, the steam turbine building was placed adjacent to the reactor building in the same direction as the steam generator (SG) in the reactor building, and the gas turbine building was placed adjacent to the reactor building in the same direction as the intermediate heat exchanger (IHX) in order to minimize the main steam piping, feed water piping, and secondary coolant heat piping between buildings, considering the amount of piping and other materials. The hydrogen production facilities were located away from the reactor building to protect against leakage of flammable and toxic gases.

The reactor building consists of four underground floors and two above-ground floors, with dimensions of 53.0 m x 56.0 m between exterior walls and a floor height of 32.2 m below ground and 24.8 m above

ground. As for the steam turbine building, a two-story above-ground building configuration was used, with building plan dimensions of 25.0 m x 32.0 m between exterior walls and 19.4 m above-ground floor height.

In order to shorten the pipe length, the main steam piping is routed horizontally from the SG outlet nozzle with a piping room on the middle third basement floor of the reactor building, and leads to the first floor of the steam turbine building via a 3 m wide trench installed between the reactor building and the steam turbine building. Similarly, the water supply piping is routed horizontally from the SG inlet nozzle and led to the first floor of the steam turbine building via a 3 m wide trench, the same width as the main steam piping, with the piping room on the fourth basement floor of the reactor building. The secondary helium piping to be used in the later phase were designed to rise vertically from the IHX nozzle and be routed to the gas turbine building via a 3 m wide trench located between the reactor building and the steam turbine building with a piping room on the first basement floor of the reactor building.

There are two air coolers in the Vessel Cooling System (VCS), one for each of the two independent systems, and they will be installed on the upper north side of the reactor building, not facing the hydrogen production facility, to ensure the distance between the centres of the transmission surfaces required by the design requirements. It will be installed approximately 4 m away from the wall so as not to obstruct the air intake. From the viewpoint of explosion protection for the hydrogen production facility to be installed in the future, the building opening is not located on the south side of the reactor building

4.2 Site Considerations during Operation

HTR50S is designed to have site flexibility considering potential deployment in inland area based on the experience of the HTTR design. The HTTR is located in inland and all of the waste heat in cooling system is discharged to the atmosphere. The heat sink temperature is set to 29 C which is equivalent to that of the HTTR [2].

Because of the inherent safety characteristic of the HTGR, the amount of radionuclide released to environment during accident conditions is small [1]. It is expected that emergency planning and response will be reasonable and the emergency planning zone will be limited by the site boundary.

4.3 Grid Integration

The HTR50S is designed to cope with 50% partial load operation. The exhaust pressure of the steam turbine system is set in optimum range to avoid turbine blade failures due to erosion and vibration. [2]. The capability of partial load operation of the reactor is demonstrated by the safety demonstration test in the HTTR [3] .

5. Technical NSSS/Power Conversion System Designn

SUMMARY FOR BOOKLET

- Primary Circuit

Figure 2 shows system configuration. A SG is installed in the primary cooling system, and the heat

generated in the reactor is transferred to secondary system to produce steam and used in a heat supply system that supplies heat to a steam turbine power generation system, district heating, etc. In addition, if a core with a reactor coolant outlet temperature of 900°C is adopted as the latter phase, an IHX is added between the reactor pressure vessel and the SG, and the high-temperature helium in the secondary side is used to generate gas turbine power, supply high-temperature steam. The system also considers the possibility of using the heat in a hydrogen production facility.

- Reactor Core and Fuel

Figure 5 and Fig.6 show the longitudinal and horizontal view of the reactor. The core region of the HTR50S is an assembly of stacked hexagonal graphite blocks, consisting of a fuel region with 30 fuel columns and 7 control rod guide columns for a total of 37 columns, and a reflector region surrounding the fuel region with 18 movable reflector columns and 6 control rod guide columns for a total of 24 columns. The core consists of 61 columns in total. The core is surrounded by a fixed graphite reflector block, and a side shield and core restraint mechanism are installed outside the block.

As shown in Fig. 7, the fuel elements (fuel rods) are loaded in a graphite block with a height of 580 mm and a face-to-face distance of 360 mm, and the cooling channels are secured. The graphite block has 33 fuel rod insertion holes and is a pin-in-block type fuel loaded with fuel rods.

- Fuel Handling

The fuel handling system is for loading and unloading fuel bodies, movable reflector blocks, control rod guide blocks, fuel-limited irradiation samples, etc., into the reactor, and consists of a fuel handling machine and auxiliary equipment.

- Reactor Protection

The reactor protection system, which is the safety protection system, is a facility that inserts control rods and automatically shuts down the reactor to protect the reactor coolant pressure boundary and the reactor containment boundary by signals from the reactor instrumentation and the process instrumentation of the safety protection system that send signals to the safety protection system.

- Secondary Side

The HTR50S power generation system is designed to convert the energy held by the steam generated in the steam generator into rotational energy in the steam turbine, which is then effectively converted into electrical energy by the generator. The system consists of a steam turbine, generator, condenser, degasser, feed water pump, feed water heater, piping, and valves. The heat supply system is a facility to extract a part of the steam generated in the steam generator and use it as a heat source, and the heat is used to supply hot water for district heating and high-temperature steam for chemical industries.

Figure 5. Longitudinal view of the reactor [1]

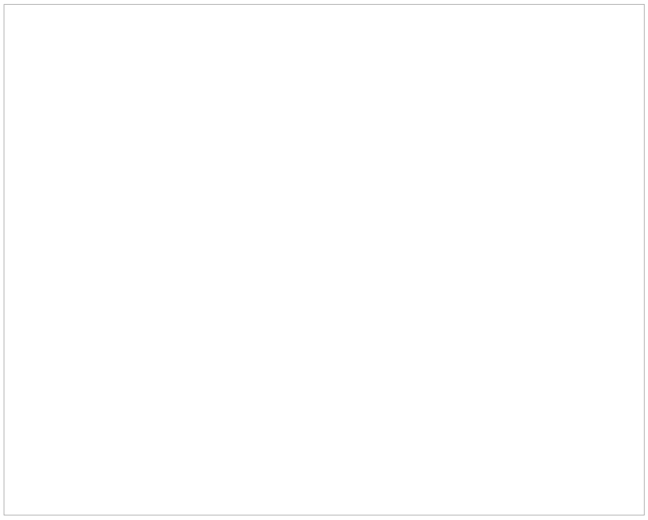


Figure 6. Horizontal view of the reactor [1]

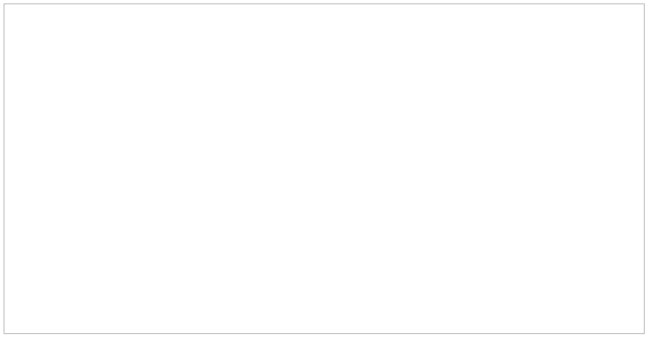


Figure 7. Fuel element [1]

5.1 Primary Circuit

A SG is installed in the primary cooling system, and the heat generated in the reactor is transferred to secondary system to produce steam and used in a heat supply system that supplies heat to a steam turbine power generation system, district heating, etc. In addition, if a core with a reactor coolant outlet temperature of 900°C is adopted as the latter phase, an IHX is added between the RPV and the SG, and the high-temperature helium in the secondary side is used to generate gas turbine power and supply high-temperature steam. The system also considers the possibility of using the heat in a hydrogen production facility.

The layout of the RPV, IHX (Phase II), and SG, which will be the main components of the primary cooling system, will be based on a side-by-side arrangement to minimize the high-temperature piping, utilizing the results of the GTHTR300 design [4].

5.2 Reactor Core and Fuel

Figure 5 and Fig.6 show the longitudinal and horizontal views of the reactor. The core region of the HTR50S is an assembly of stacked hexagonal graphite blocks, consisting of a fuel region with 30 fuel columns and 7 control rod guide columns for a total of 37 columns, and a reflector region surrounding the fuel region with 18 movable reflector columns and 6 control rod guide columns for a total of 24 columns. The core consists of 61 columns in total. The core is surrounded by a fixed graphite reflector block, and a side shield and core restraint mechanism are installed outside the block.

The core region of the HTR50S is a collection of stacked hexagonal graphite blocks, consisting of a fuel region with 30 fuel columns and 7 control rod guide columns for a total of 37 columns, and a reflector region surrounding it with 18 movable reflector columns and 6 control rod guide columns for a total of 24 columns. The core consists of 61 columns in total. The core is surrounded by permanent graphite reflector blocks, and a side shield and core restraint mechanism are installed outside the block.

The core load is supported by the RPV vessel through core support graphite structures such as high-temperature plenum blocks, support posts, and insulation layer at the reactor bed, and core support steel structures such as support plates, support columns, and core support grids.

As shown in Fig. 7, the fuel elements (fuel rods) are loaded in a graphite block with a height of 580 mm and a face-to-face distance of 360 mm. The graphite block has 33 fuel rod insertion holes and is a pin-in-block type fuel loaded with fuel rods.

The primary coolant enters at 325˚C through the outer side of cross duct at the side of the vessel, flows

upward while cooling the reactor floor, side metal structures, permanent reflector, and RPV, then reverses in the upper plenum to form a downward flow. The flow is then reversed in the upper plenum to form a downward flow, which is distributed to the cooling channels of the fuel body and control rod guide blocks. The coolant distributed to the fuel column flows downward, heated by the fuel elements, mixes with coolant from the other channels in the hot plenum, and directed out of the core through the inner tube of cross duct. In addition to the designed flow paths, other coolant flow paths exist in the core, such as between columns, between fixed reflectors, between graphite blocks, and through gaps such as graphite block stacking surfaces.

The upper plenum is heated by the hot coolant plume from the core during depressurized accidents. In order to prevent the overheating of upper part of RPV by thermal radiation from the upper surface of the core block, an upper plenum shroud is installed. The shroud is installed at the upper end of the side shields and integrated with the side shields to prevent the coolant from transferring heat directly to the inner surface of the pressure vessel from the vessel body to the upper mirror. The shroud is made of low thermal conductivity material such as carbon that act as a thermal insulation.

5.3 Fuel Handling

The fuel handling system is for loading and unloading fuel bodies, replaceable reflector blocks, control rod guide blocks into the reactor, and consists of a fuel handling machine and auxiliary equipment. The system is designed considering the following requirements:

- In the fuel handling process, from the loading of new fuel to the unloading of spent fuel, the design shall be such that the relevant fuel can be loaded and unloaded in cooperation with the related equipment.
- The fuel handling system such as the fuel handling machine and the fuel loading/unloading machine, shall be designed to limit the number of fuel bodies handled at one time, and shall be designed to prevent criticality in any condition in which the equipment holds enough fuel for its capacity.
- Spent fuel is transferred to the spent fuel storage facility in the reactor building by the fuel exchanger, and then transferred into the spent fuel storage building by the fuel in/out machine. The design for removing decay heat from spent fuel shall be air-cooled in the spent fuel storage building.
- Spent fuel handling facilities shall be designed with appropriate shielding for radiation protection.
- Fuel handling facilities shall be designed to prevent fuel from falling during transfer operations.

5.4 Reactor Protection

The reactor protection system, which is the safety protection system, inserts control rods and automatically shuts down the reactor to protect the reactor coolant pressure boundary and the reactor containment boundary by signals from the reactor instrumentation and the process instrumentation of the safety protection system.

The reactor protection system consists of a two-train logic circuit that receives signals from the reactor instrumentation that sends signals to the safety protection system and from the process instrumentation and generates a reactor scram signal and an interlock circuit operation signal, and a reactor scram barrier that automatically opens upon a reactor scram signal.

The power supply to the reactor protection equipment is supplied independently from the uninterruptible power supply, and the wiring, panels, etc. are made of non-flammable or flame-retardant materials to the greatest extent practicable

5.5 Secondary Side

The HTR50S power generation system is designed to convert the energy held by the steam generated in the SG into rotational energy in the steam turbine which is then effectively converted into electrical energy by the generator. The system consists of a steam turbine, generator, condenser, degasser, feed water pump, feed water heater, piping, and valves. The heat supply system is a facility to extract a part of the steam generated in the steam generator and use it as a heat source. The heat is used to supply hot water for district heating and high-temperature steam for the chemical industry.

For the HTR50S power generation facility, a regeneration cycle of three-stage extraction to a deaerator and two high-pressure feed-water heaters is employed, taking into account the feed-water temperature rise. During summer operation, when all the heat exchanged in the steam generator is used for power generation, the power output is 17.2 MWe, resulting in a power generation efficiency of 34.4%.

On the other hand, during winter operation, 25 MWt of the 50 MWt of heat exchanged in the SG is used for district heat utilization, and 37.8 t/h of superheated steam out of a total flow rate of 44.2 t/h is sent from the degasser extraction line to the heat supply facility and returned to the high hot water tank. The power generation output is 13.5 MWe and the generation efficiency is 27.0%, which is lower than that of summer operation; however, the heat utilization ratio of the combined heat and power plant increases to 77.0% by using the heat discarded by the condenser for local heat application.

5.6 Containment/Confinement

The reactor containment vessel is one of the engineering safety facilities in the HTR50S, which is designed to prevent the release of radioactive materials to the outside and to ensure the safety of the general public and workers in the vicinity of the reactor facility. Isolation valves are installed in the piping that penetrates the reactor containment vessel in order to form a pressure barrier in the event of a double pipe rupture accident, etc. and to form a barrier against the release of radioactive materials. For the design of the containment vessel of the HTR50S, a reinforced concrete structure with a steel liner lining (RCCV) was adopted from the viewpoint of reducing the amount of steel materials.

5.7 Electrical, I&C and Human Interface

Equipment in the reactor facility should be classified into those related to engineering safety facilities and other equipment, and connected to the emergency bus bar and the normal bus bar, respectively. Two or more units of equipment should be connected to each bus bar separately for both emergency and normal use as much as possible to ensure a stable power supply.

Emergency generators will be installed as emergency power sources to supply power to each emergency bus bar in the event of a loss of commercial power. In addition, a DC power supply facility and an AC uninterruptible power supply facility shall be provided as uninterruptible power sources necessary for the safety of the reactor facilities. The DC power supply facility shall be equipped with two sets of storage batteries to secure DC power, each supplying power to one DC bus line. The AC uninterruptible power supply facility will supply power to measurement and control system equipment, etc. that require stable AC power.

5.8 Unique Technical Design Features (if any)

The VCS is one of the engineering safety facilities, which is designed to remove decay heat of fission products and other residual heat from the core to maintain the integrity of the reactor pressure vessel, in-core structures, core components, etc. and to prevent excessive damage to the fuel during abnormal conditions.

Figure 8 shows system configuration of the VCS. The system consists of water-cooled tube panels, air coolers, pressurized/expansion tanks, gas venting circulating pumps, and a water-cooling system for the RPV. The system is oriented toward passive safety, and is designed to increase the reliability of the system. The system is composed of two independent systems.

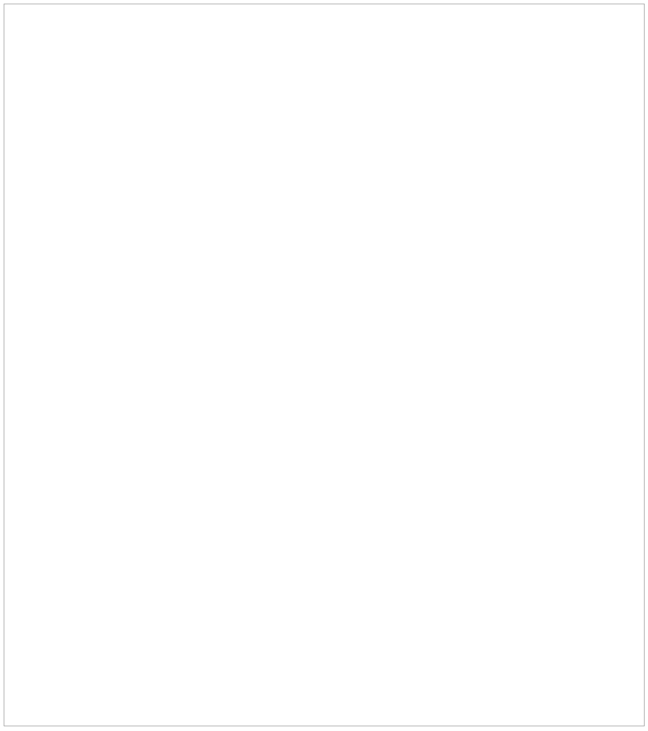


Figure 8. Vessel Cooling System [1]

6. Technology Readiness

SUMMARY FOR BOOKLET

The HTR50S aims for potential near-term deployment. Therefore the design process will utilize the knowledge obtained from the HTTR design, construction, operation and maintenance. In addition, conventional technologies in other industries are also incorporated.

HTR50S licensing approach will depends on the regulation of the country to be deployed, however, the experience of the licensing of the HTTR will be fully utilized.

6.1 Deployed Reactors

The HTR50S aims for potential near-term deployment. Therefore the design process will utilize the knowledge obtained from the HTTR design, construction, operation and maintenance.

Construction of the HTTR, the first HTGR in Japan, began in 1991. The reactor employs a prismatic type core and achieved first criticality in 1998 [5] and full power operation (30 MW) at the reactor outlet helium gas temperature of 850oC in 2001 [6]. In 2004, full power operation at reactor outlet helium gas temperature of 950oC was achieved [7], and in 2010, continuous high-temperature operation for 50 days

under rated thermal power condition was successfully achieved [8].

6.2 Reactors under Licensing Review

HTR50S licensing approach will depends on the regulation of the country to be deployed, however, the experience of the licensing of the HTTR will be fully utilized. In February 1989, the Japan Atomic Energy Research Institute (JAERI), former name of JAEA, submitted the application for HTTR installation permit to the Prime Minister of Japan. In November 1990, the safety review was completed by the Nuclear Safety Commission which was the regulatory authority of the time and the Prime Minister issued the installation permit of the HTTR to JAERI.

After the 2011 Tohoku Earthquake, the Nuclear Regulatory Authority (NRA) established a stringent new regulation standard. JAEA had submitted the application to the NRA in 2014 and conducted many discussion with the national regulator. JAEA has obtained the permission from the NRA for design changes to the Reactor Installation for the HTTR. The HTTR has restarted its operation on July 30, 2021.

JAEA established a safety design that can be applied to HTR50S through the licensing. One of the examples is the seismic classification. The HTTR safety demonstration test was conducted in 2010 at 30% of rated power and reduced core flow rate to zero by tripping all circulators and no control rods were inserted [9]. The test demonstrated that the HTTR can maintain in a stable state under loss-of-cooling and/or reactivity control conditions because of the inherent characteristics of basic elements of HTGR. Based on the demonstrated results, the permission from NRA was obtained to reclassify seismic classification of SSCs to lower class. The core heat removal function and the reactor internal structure are re-classified from S to B.

The other example is the defence in depth implementation. The concept is based on the HTGR safety features that the maximum fuel temperature is always below the safety limit in all accidents and possibility of significant fuel damage and large releases of radioactive materials are practically eliminated. In the NRA review for the HTTR, it was concluded that significant core degradation including core melting may not occur by postulated beyond design basis accidents (BDBAs) and specific SSCs are not required to cope with BDBAs. As a result, the HTTR has restarted its operation without significant additional reinforcements due to the inherent safety features.

6.3 Reactors in the Design Stage

As mentioned previously, HTR50S design is based on the matured technology established through the HTTR design, construction, operation and maintenance. In addition, conventional technologies from other industries are also incorporated. The following approaches are employed to meet the design strategy:

- The reactor outlet temperature was set at 750°C, considering that the steam generator with a main steam temperature of 538°C so that an existing heat-resistant alloy, Alloy 800H, can be used for the steam generator heat transfer tubes.
- The reactor inlet temperature was set at 325°C taking into account that SA533B/SA508, low-alloy steels for light water reactors, can be used as RPV materials (normal service temperature limit: 371°C; accident temperature limit: 538°C.
- The primary coolant pressure was set to 4 MPa, the same as in the HTTR, in order to take advantage of the HTTR's knowledge. In addition, assuming the transportation of the RPV to users abroad, the reduction of the RPV thickness was considered.

- The fuel specifications were set to be the same as those of the HTTR in order to take advantage of the experience gained with the HTTR.

Steam temperature/pressure was set at 538°C/12.5 MPa, considering the steam conditions of the Fort St. Vrain reactor, constructed as a demonstrator in the U.S. (538°C/16.6 MPa) and the manufacturer's experience of existing small steam turbines.

7. Safety Concepts

SUMMARY FOR BOOKLET

In order to ensure reactor safety, basic safety functions, namely reactivity control, heat removal from the core, and confinement of radioactive materials are employed. In addition, graphite oxidation control has to be considered.

As for reactivity control, two independent reactor shutdown systems with different means are provided: a control rod system consisting of control rods and a back-up shutdown system consisting of boron carbide and sintered graphite pellets.

As for the control of heat removal from the core, a passive indirect cooling system, the VCS is installed to take advantage of the inherent safety features of the HTGR. The system removes heat from the reactor by radiation heat transfer to water-cooled panels installed on the bio-shielding concrete surface around the RPV

The confinement of radioactive materials is designed by providing multiple barriers against radioactive materials including fuel particle coating, graphite sleeve, reactor coolant pressure boundary and RCCV.

As for the control of chemical attack, the design approach is to limit the total amount of air that can enter the reactor after a depressurization accident. A drain facility that can drain all the water of the SG is installed for facility protection; however, the drain facility is not expected to be a safety function.

Accident behaviour analyses for representative accidents are performed. The analysis results demonstrated that evaluation items for the safety analysis met the evaluation criteria

7.1 Safety Philosophy and Implementation

In order to ensure reactor safety, the following basic safety functions have to be accomplished, namely (1) reactivity control, (2) heat removal from the core, and (3) confinement of radioactive materials. In addition, for HTGRs, (4) graphite oxidation control have to be considered.

(1) Reactivity control

In the HTR50S, as in the HTTR, two independent reactor shutdown systems with different means are provided: a control rod system consisting of control rods, and a back-up shutdown system consisting of

boron carbide and sintered graphite pellets.

The reactor shutdown system with control rods shall be designed to bring the core subcriticality and maintain it without exceeding design limits of the fuel, even if a pair of control rods with maximum reactivity cannot be inserted in their full withdrawal position during normal operation and abnormal conditions. In the event that the control rod system cannot be inserted, the core should be designed to be subcritical and maintained subcritical by a back-up shutdown system.

(2) Heat removal from the core

As for heat removal from the reactor core, the HTTR has an auxiliary cooling system, which is a forced circulation cooling system, and a VCS. The HTTR50S, however, only has a passive indirect cooling system, the VCS, to take advantage of the inherent safety features of the HTGR. The VCS remove heat from the reactor by radiation heat transfer to water-cooled panels installed on the bio-shielding concrete surface around the RPV. In other words, heat removal from the core during abnormal transients and accidents during operation is not performed by forced circulation cooling of the core. In addition, while the HTTR uses a forced circulation water cooling system with circulation pumps, the HTR50S employs a passive system with natural circulation of water, and is designed to have two independent systems. The VCS also operates during normal operation to cool the bio-shielding concrete.

(3) Confinement of radioactive materials

The confinement of radioactive materials shall be designed to prevent the release of large amounts of radioactive materials not only during normal operation, but also in the event of an accident, by providing multiple barriers against radioactive materials as follows:

1. Fuel particle coating

In the fuel design of small HTGR systems, as in the HTTR, a method is used to limit the fission product (FP) release from the core below a certain amount from a safety design perspective, taking into account the FP retention characteristics of the fuel as described below.

The fuel kernel has the ability to retain the FPs. Fission products released from the fuel kernel are retained by the fuel particle ceramic coatings.

Each coating layer has the following different functions: The low-density PyC layer (buffer layer) provides a void for fission gas, and at the same time avoids interaction between the fuel and the high-density layer (fuel swelling and nuclear migration). The high-density PyC and SiC layers act as barriers against diffusive transport of various FPs. In particular, the PyC layer is an effective diffusion barrier for noble gases and volatile nuclides, and the SiC layer for metallic nuclides. The fuel coating layer is made of ceramics with excellent high-temperature resistance.

2) Graphite sleeve

Even if the fuel particle coating layer fails, FPs are retained by the fuel compacts and graphite sleeves. Therefore, the fuel compact and graphite sleeve also have the function of confinement.

3) Reactor coolant pressure boundary

Fission products leaked into the primary coolant are retained in the reactor coolant system and confined within the reactor coolant pressure boundary. Reactor coolant pressure boundary of HTR50S refers to a facility that encapsulates the reactor coolant during normal operation of the reactor and is subject to the same pressure conditions as the reactor and forms a pressure barrier during an abnormal condition, the failure of which could result in a depressurization accident.

4) Reactor containment boundary

In the HTR50S, as in the HTTR, even if FPs leak from the reactor coolant pressure boundary, the containment vessel holds them and confines them within the reactor containment boundary. In addition, radioactive materials leaking from the containment vessel to the reactor building are discharged from the exhaust stack to a higher level by an emergency air purification system.

(4) Control of chemical attack

In the HTR50S, as in the HTTR, the approach is to limit the total amount of air that can enter the reactor after a depressurization accident through the fracture opening, thereby limiting the oxidation of the in-core graphite structure to an acceptable level. In other words, the containment space volume should be kept as small as possible, and the total amount of air that contributes to the oxidation of the in-vessel graphite structures should be limited to a small amount. In addition, the amount of combustible gas (CO) generated by the oxidation of the in-vessel graphite structure is small and does not reach the explosion limit concentration. In the HTR50S, as in HTTR, no facilities are required to prevent graphite oxidation and to control the concentration of combustible gas.

In case of failure of heat transfer tubes in SG, water /steam mixture may enter the primary cooling system. Therefore, in the event of an accident and water leakage to the primary side, the system is designed to detect the event occurrence immediately, insert control rods to scram the reactor, and isolate the SG by closing the isolation valves to minimize water intrusion into the primary cooling system, thereby minimizing the impact on the reactor. The HTR50S has a drain facility that can drain all of the SG held water; however, the facility is designed as non-safety related system.

7.2 Transient/Accident Behaviour

(1) Depressurized accident behaviour

The transient behaviours of maximum fuel and RPV temperatures during a depressurized accident are shown in Fig. 9.

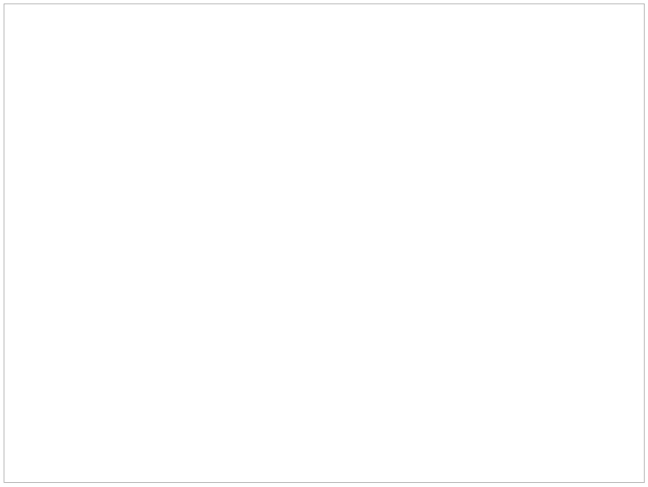


Figure 9. Depressurized accident behaviour [1]

The maximum fuel temperature decreases after the reactor scram and then increases again, however, does not exceed the initial value, reaching a peak after 28 hours and then decreasing to about 500°C after 2000 hours. The maximum fuel temperature is 1386°C, which does not exceed the criteria. The maximum RPV temperature is observed at the side of the RPV and reaches about 364°C at about 20 hours after the accident initiation; however, it does not exceed the temperature limit.

(2) Water ingress accident behaviour

The plant behaviour during a rupture of steam generator heat transfer tube is shown in Fig.10. The reactor scrams by a signal of high neutron flux in one second, and the reactor automatically shuts down. Although the reactor power increases to 129%, the maximum fuel temperature increase is 2°C. Although the steam generator isolation signal is sent at the same time as the reactor scram, it takes about 73 seconds after the accident for the main steam and feedwater shutoff valves to close, and the amount of water vapor entering the primary cooling system reaches approximately 568 kg. The reactivity added at this time is about 1.3E-3 $\Delta k/k$, however, sufficient margin for reactivity shutdown is secured. The primary cooling system flow rate decreases immediately because of the stop of primary gas circulators at the same time as the reactor scram. The reactor coolant pressure boundary temperature does not exceed the initial value.

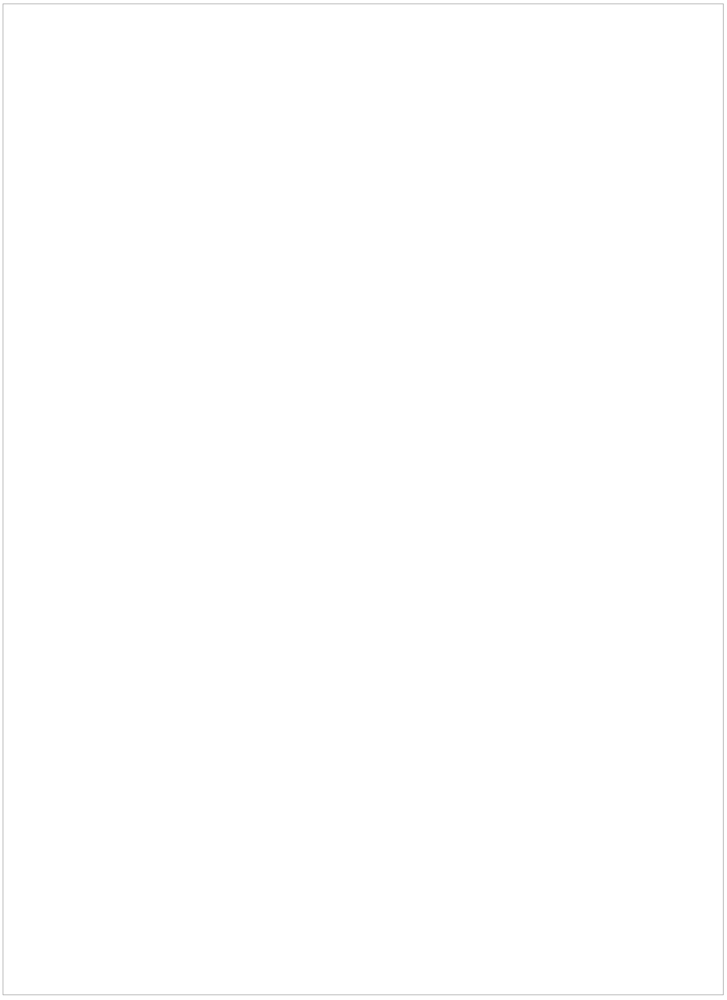


Figure 10. Water ingress accident behaviour [1]

8. Fuel and Fuel Cycle

SUMMARY FOR BOOKLET

HTR50S offers flexible fuel cycle options and can adopt the spent fuel management policy in the country to be deployed.

HTR50S is designed to use heat efficiently according to the heat demand. Up to 25 MWt of the 50 MWt of heat exchanged in the SG can be used for district heat utilization. In this case, the heat utilization ratio of the combined heat and power plant increases to 77.0%.

8.1 Fuel Cycle Options

HTR50S offers flexible fuel cycle options and can adopt ~~to~~ the spent fuel management policy in the country to be deployed.

In order to reprocess spent fuel from HTGRs, it is necessary to remove coated fuel particles from fuel compacts and remove the coating.

Two methods have been proposed for removing coated fuel particles from fuel compacts: roasting and electrolytic deconsolidation. The electrolytic deconsolidation method was used for the inspection of HTTR fuel.

The roller method, jet mill method, and rotating disk method have been proposed as methods to remove the coating from the coated fuel particles. The roasting method has also been proposed as a method to remove the carbon layer inside the SiC layer. Among these methods, the rotating disk method has been used to recover uranium from rejected products generated in the HTTR fuel manufacturing. Specifically, the coated fuel particles are fed into a rotating disc with a predetermined gap between it and a stationary disc, and all the coating layers of the coated fuel particles are broken and removed between the gaps, and the fuel nuclei are dissolved in nitric acid to recover the uranium.

8.2 Resource Use Optimization

HTR50S is designed to use heat efficiently according to the heat demand. Up to 25 MWt of the 50 MWt of heat exchanged in the SG can be used for district heat utilization, 37.8 t/h of superheated steam out of a total flow rate of 44.2 t/h is sent from the degasser extraction line to the heat supply facility and returned to the high hot water tank. In this case, the power generation output is 13.5 MWe and the generation efficiency is 27.0%, which is lower than that of summer operation, but the heat utilization ratio of the combined heat and power plant increases to 77.0% by using the heat discarded by the condenser for local heat utilization

8.3 Unique Fuel/Fuel Cycle Design Features

9. Safeguard & Physical Security

SUMMARY FOR BOOKLET

HTR50S safeguards system will be implemented based on the experience of the HTTR. Therefore the HTR50S can adhere strictly to IAEA Safeguards because the IAEA has been safeguarding the HTTR.

HTGR has inherent safety features that leads to high resistant to attacks or threats of attack on nuclear facilities. The TRISO coated fuel particle is robust and requires crushing of the coating to extract the specific nuclear fuel material. The amount of specific nuclear fuel material per unit weight is small. These features contribute to the mitigation of risk associated with the potential fissile material theft.

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contribute to the mitigation of risk associated with the potential fissile material theft.

9.3 Unique Safeguards and/or Security Features

10. Project Delivery & Economics

SUMMARY FOR BOOKLET

JAEA and the National Nuclear Center of Kazakhstan (NNC) have conducted a collaboration in nuclear energy research and development for early realization of deployment of the HTGR in Kazakhstan, and to support for the Kazakhstan HTGR (KHTR) Project by utilizing the technologies developed under the HTTR Project. HTR50S was used to support NNC for the preparation of the feasibility study of KHTR.

The construction cost of HTR50S was estimated based on the database developed under the HTTR design and construction. Operational and maintenance costs of HTGR was estimated using the method utilized in the Power Generation Cost Analysis Working Group (organized in the Japanese government in 2015) and specific features of the HTGR.

10.1 Project Preparation and Negotiation

The small-sized HTGR with an electric power rating of less than 300 MWe can greatly facilitate decentralized energy supply and create new industries and stimulate economical development in cities and localities as well as in those remote regions to which power transmission grids are undeveloped in developing countries.

JAEA and the National Nuclear Center of Kazakhstan (NNC) have conducted a collaboration in nuclear energy research and development for early realization of deployment of the HTGR in Kazakhstan, and to support for the Kazakhstan HTGR (KHTR) Project by utilizing the technologies developed under the HTTR Project. HTR50S design was used to support NNC for the preparation of the feasibility study of KHTR [10].

10.2 Construction and Commissioning

The construction cost of HTR50S was estimated based on the database developed under the HTTR design and construction.

10.3 Operation and Maintenance

Operational and maintenance costs of HTGR was estimated using the method utilized in the Power Generation Cost Analysis Working Group (organized in the Japanese government in 2015) [11] and specific features of the HTGR [12].

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