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Review of helium turbomachinery, piping, valves and other technologies for power conversion and heat transport

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Summary

The high-temperature component technologies for power conversion and heat transport to a heat application using High Temperature Gas-cooled Reactor (HTGR) such as helium turbomachinery, hot gas piping and high temperature isolation valve developed by Japan Atomic Energy Agency (JAEA) are reviewed. Since 1998, JAEA has been developing the design of Gas Turbine High Temperature Reactor rated at 300 MWe (GTHTR300) for power generation and for industrial heat cogeneration such as hydrogen production. The key technologies required for the GTHTR300 including multistage axial-flow helium compressor, helium gas turbine rotating shaft seal, and gas turbine blade material. The development for these technologies is reviewed. The concentric hot gas duct and the High Temperature Isolation Valve (HTIV), which are required for high-temperature heat transport from the nuclear reactor to industrial plants, have been largely developed with the construction of JAEA`s 30 MW and 950 oC test reactor HTTR (High Temperature engineering Test Reactor). JAEA performed the demonstration test on the concentric hot gas duct to clarify the structural integrity and thermal insulation performance with the HENDEL (Helium Engineering Demonstration Loop). Based on these results, the concentric hot gas duct is installed in the HTTR and used for the high-temperature operation of HTTR successfully. JAEA also performed the demonstration test on the component test on HTIV to confirm the structural integrity and the seal performance of the valve seat for the future use in the HTGR heat application system. Those results are also reviewed in this chapter.

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Abbreviations

GTHTR300	Gas Turbine High Temperature Reactor 300 MWe
HENDEL	Helium Engineering Demonstration Loop
HTGR	High Temperature Gas-cooled Reactor
HTIV	High Temperature Isolation Valve
HTTR	High Temperature engineering Test Reactor
HTTR-H2	HTTR hydrogen production system
IHX	Intermediate Heat exchanger
JAEA	Japan Atomic Energy Agency
SGC	Secondary Gas Circulator
SPWC	Secondary Pressurized Water Cooler

Summary

The high-temperature component technologies for power conversion and heat transport to a heat application using High Temperature Gas-cooled Reactor (HTGR) such as helium turbomachinery, hot gas piping and high temperature isolation valve developed by Japan Atomic Energy Agency (JAEA) are reviewed. Since 1998, JAEA has been developing the design of Gas Turbine High Temperature Reactor rated at 300 MWe (GTHTR300) for power generation and for industrial heat cogeneration such as hydrogen production. The key technologies required for the GTHTR300 including multistage axial-flow helium compressor, helium gas turbine rotating shaft seal, and gas turbine blade material. The development for these technologies is reviewed. The concentric hot gas duct and the High Temperature Isolation Valve (HTIV), which are required for high-temperature heat transport from the nuclear reactor to industrial plants, have been largely developed with the construction of JAEA`s 30 MW and 950 ºC test reactor HTTR (High Temperature engineering Test Reactor). JAEA performed the demonstration test on the concentric hot gas duct to clarify the structural integrity and thermal insulation performance with the HENDEL (Helium Engineering Demonstration Loop). Based on these results, the concentric hot gas duct is installed in the HTTR and used for the high-temperature operation of HTTR successfully. JAEA also performed the demonstration test on the component test on HTIV to confirm the structural integrity and the seal performance of the valve seat for the future use in the HTGR heat application system. Those results are also reviewed in this chapter.

1 Helium Turbomachinery

1.1 Plant design based on helium turbomachinery

The plant design – GTHTR300 – based on helium turbomachinery is highlighted in **Figure 1**. The design being developed in JAEA combines a high temperature gas-cooled reactor with a gas turbine in direct cycle [1]. The reactor and the gas turbine share the common working fluid of the primary helium gas. The gas turbine rotates an electric generator for power generation while circulating the reactor coolant. Table 1 lists technical parameters for the plant design. Three pressure vessel units contains the reactor core, the gas turbine, and the heat exchangers respectively. The reactor technologies required for the plant have been developed mainly with construction and operation of JAEA's 30 MWt and 950ºC test reactor HTTR (High Temperature engineering Test Reactor).

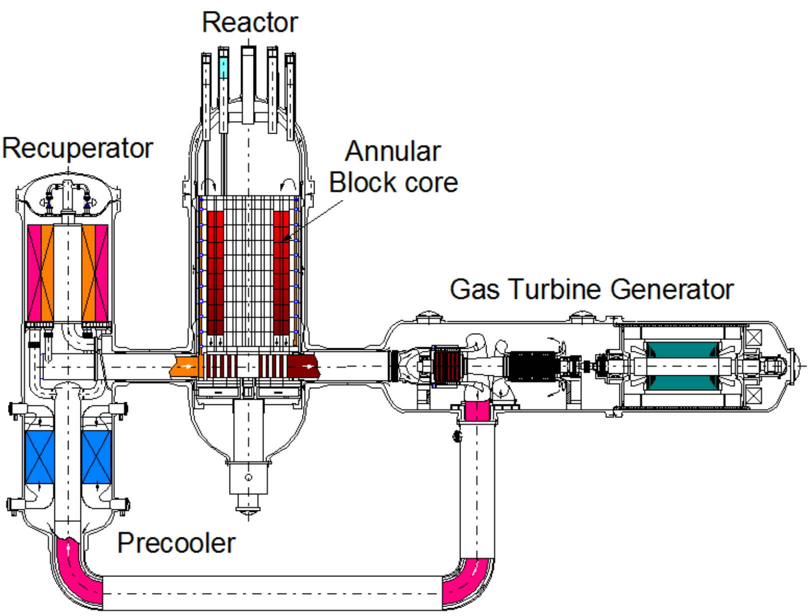


Figure 1: GTHTR300 plant design based on helium gas turbine [1]

Table 1. GTHTR300 Technical Parameters

Reactor design type	Prismatic core
Reactor coolant	Helium
Reactor outlet temperatures	850 ~ 950 ºC
Electrical output	274 ~ 300 MWe
Net power generation efficiency	46% ~ 50%
Primary coolant circulation	forced by gas turbine
System pressure	7 MPa
Fuel	UO_2 TRISO coated particle
Design Status	Pre-licensing basic design completed

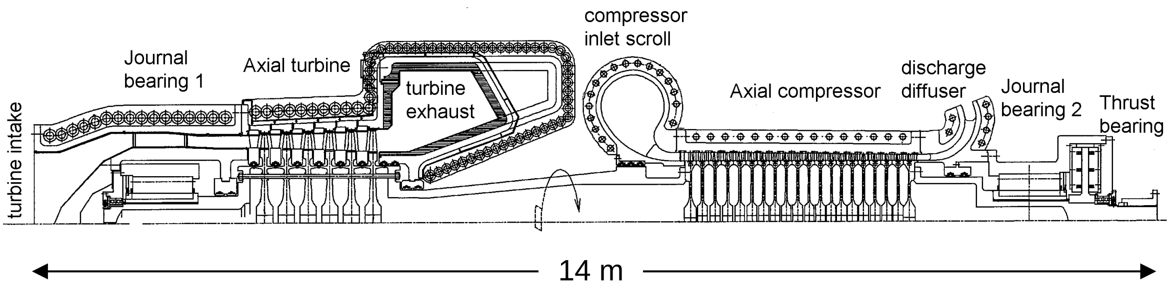


Figure 2: Helium gas turbine design for GTHTR300

Figure 2 shows the 300MWe class helium gas turbine unit design [2] for the GTHTR300. The unit consists of a 6-stage turbine and a 20-stage compressor on a single shaft rotating at 3,600 rpm. The turbine bellmouth intakes hot helium ducted from reactor whereas the compressor radial diffuser discharges high pressure helium back to the reactor. The turbine exhaust and compressor inlet scroll casings in the unit mid-section interface to the power conversion cycle heat exchangers. The bearings are located to the rotor ends. The shaft cold end drives a synchronous generator directly. The unit is installed horizontally and thus structurally designed following largely the practice of industrial gas turbines with comparable rotor disc stresses, bearing span, and casings. However, some technologies are uniquely required for the helium gas turbine including helium compressor, helium shaft seal, and turbine blade. The status of development for these technologies are presented in the following sections.

1.2 Test of multistage axial-flow helium compressor

The helium compressor is the most challenging aerodynamic component of the helium gas turbine. Its multistage slender bladed flow path gives rise to aerodynamic losses particularly associated with blade endwall and tip clearance. To validate its design, in 2004 to 2005 JAEA constructed and tested a helium model compressor at 1/3 of the dimensional scale of the full size commercial unit.

Figure 3 shows the test compressor and the helium test rig. The compressor includes four stages of rotor (S) and stator (C) blade rows of 3-dimentional blade airfoils. There are inlet and outlet guide vanes and inlet and discharge scroll casings. Four stages are selected for two reasons, a) to observe endwall boundary layer growth through multiple rotating blade rows and b) to test blading performance in a stage sufficiently removed from machine entry and exit effects. The bladed flowpath models the forward stages of the full compressor.

The measured performance map is given in **Figure 4**. The data include the measurements made at design pressure of 0.883 MPa in Run 12 and two reduced inlet pressures of 0.543MPa in Run 7 and 0.200MPa in Run 9. The design-point data at all inlet conditions well exceeded the design expectation of flow capacity and surge margin. Similarly, the design-point efficiency measurements of Run 12 and Run 7 are considerably higher than the design expectation. On the other hand, the efficiency is reduced with the partial inlet pressure condition as indicated by the data of Run 9.

Through the test program, JAEA has successfully validated the design method and aerodynamic performance of the multistage axial-flow compressor required for the helium gas turbine. The detailed results have been published elsewhere [2].

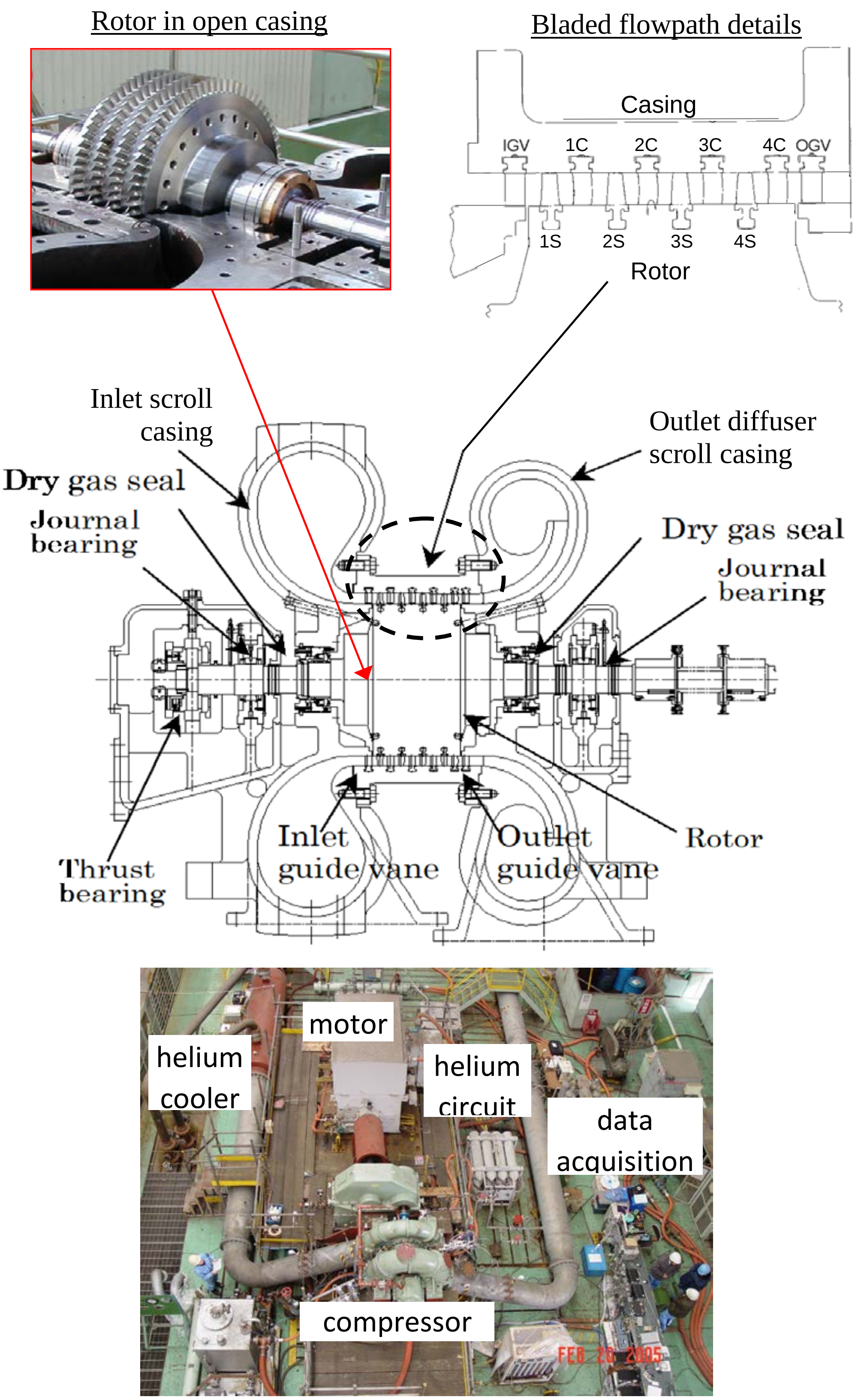


Figure 3: Multistage axial-flow helium compressor tested by JAEA [2]

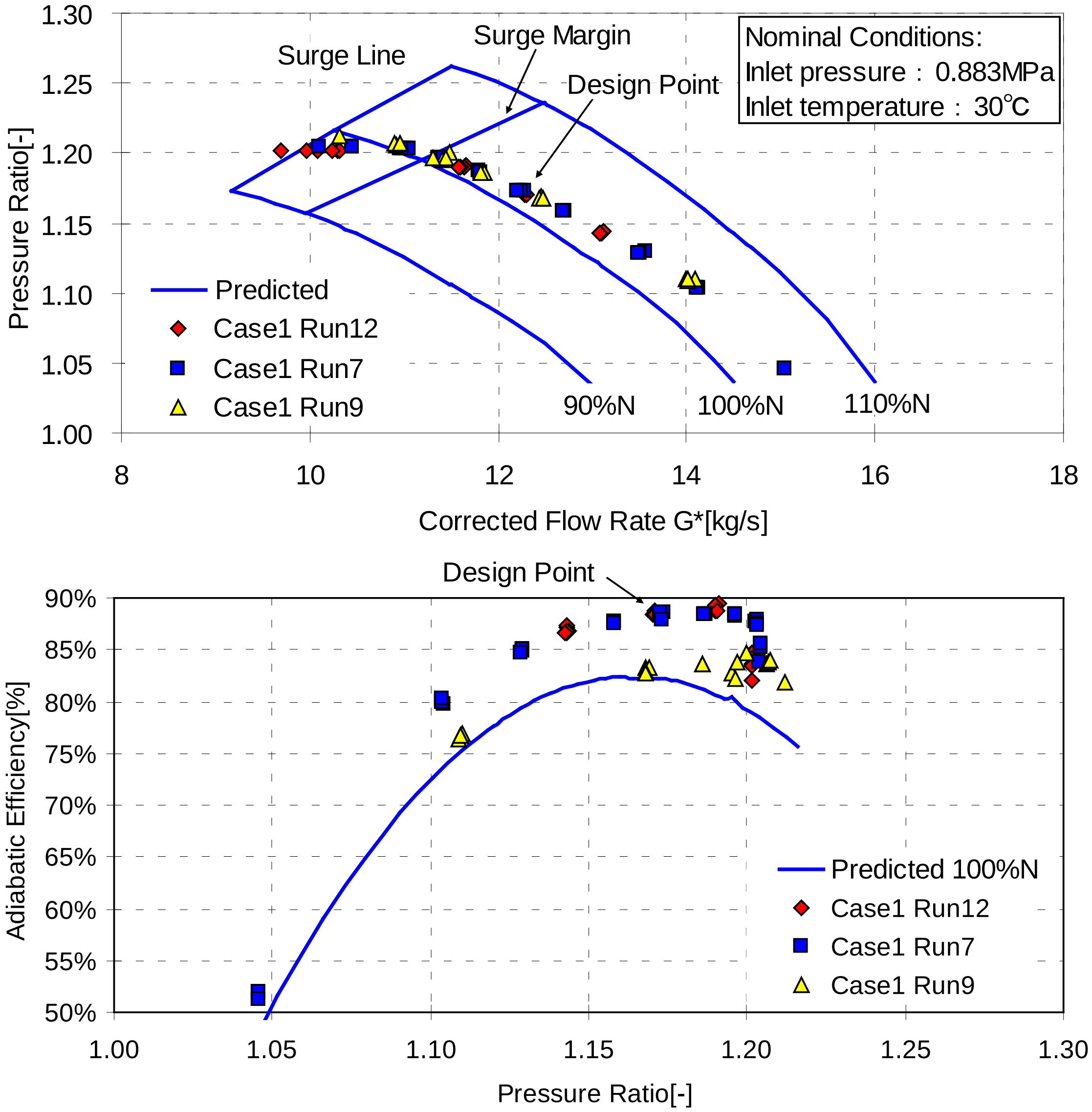
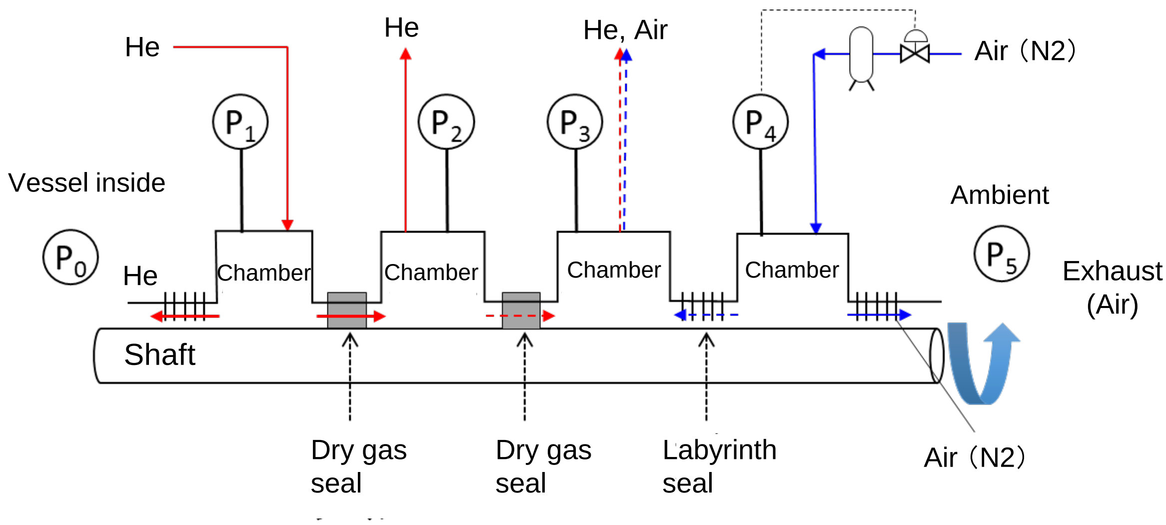


Figure 4: Measured helium compressor performance map [2]

1.3 Shaft seal for helium turbomachinery

In order to utilize the conventional oil bearing while avoiding potential oil lubricant contamination to the reactor coolant circuit, reliable and high-performance shaft seal is required to seal the interface between the reactor working helium and the ambient containing the external oil bearings. JAEA is developing a hybrid shaft seal system consisting of tandem dry gas and labyrinth seals with multiple pressure controls, as illustrated in **Figure 5**. Such seal system design is estimated to limit helium leak from the gas turbine to within 0.05%/day of the plant inventory. In additional, a membrane and cryogenic system is designed to collect and separate the leaked helium from the buffering N2 or air. About 99% of the leaked helium may be recovered and recycled back to the plant circuit, resulting in practically no loss of helium from the gas turbine rotating shaft penetration. JAEA is planning test verification of such seal system under steady and transient conditions.



Pressure control $P_0 < P_1 \gg P_2 > P_3 < P_4 > P_5$

Figure 5: Concept of a hybrid helium turbomachinery shaft seal system

1.4 Turbine blade alloy

Fission products may deposit on the blades of the direct cycle turbomachinery, thus hindering routine maintenance of the blades. Fission product 110mAg is of major concern because a large percent of it is known to diffuse through the coating of the fuel particles into the primary coolant. JAEA in conjunction with Japanese industry is developing turbine blade alloy which can resist the amount of FP plateout and diffusion in the blade material. The development is focused on correlation between silver diffusion behavior and alloy chemical compositions and grain structures. We have performed long term (up to 16,000 hrs) silver diffusion test in candidate turbine blade alloys as shown in **Figure 6**. The development aims to make the conventional industrial maintenance practice of gas turbine to be applicable to the HTGR direct cycle helium turbomachinery.

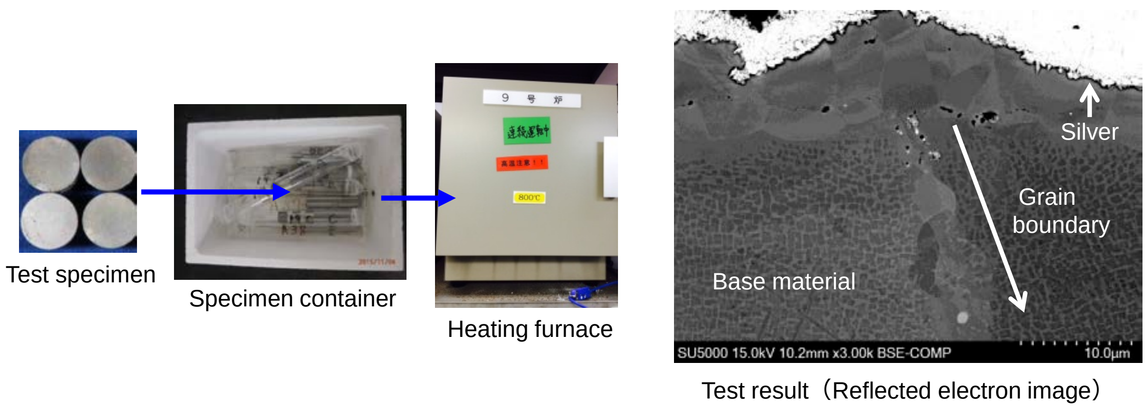


Figure 6: Silver diffusion test to turbine blade alloys.

2 Piping (Concentric hot gas duct)

The concentric hot gas duct is a very important component to transport heat from the core to a heat application system. A concentric hot gas duct with an internal insulator, where hot helium gas 950°C flows in the inner tube and cold helium gas of 400°C in the outer one, is used for the primary and the secondary coolant system of the HTTR.

JAEA performed the demonstration test on the concentric hot gas duct to clarify the structural integrity and thermal insulation performance with the HENDEL (Helium Engineering Demonstration Loop) before the construction of the HTTR.

2.1 Concentric hot gas duct in the primary coolant system of HTTR

The HTTR primary concentric hot gas duct consists of a pressure tube, inner tube and an internal insulation as shown in **Figure 7**. **Table 2** shows the major specification. The helium gas at temperature of 400°C flows in annular path and of 950°C inside the inner tube. The pressure tube can contain high pressure helium gas at 4.0MPa. The inner tube, which separates the high and low temperature helium gas paths, supports the pressure difference between the high and low temperature helium gas. The liner forms a high temperature helium gas boundary and reinforces the ceramic fiber insulation. The internal insulation between the liner and inner tube minimized heat loss from the high to low temperature helium gases and maintains the temperature of the inner tube lower than the temperature limit. The pressure tube and inner tube are made of 2-1/4Cr-1Mo steel, the material of the liner is Hastelloy XR, and the insulation material is a ceramic fiber composed of SiO_2 and Al_2O_3.

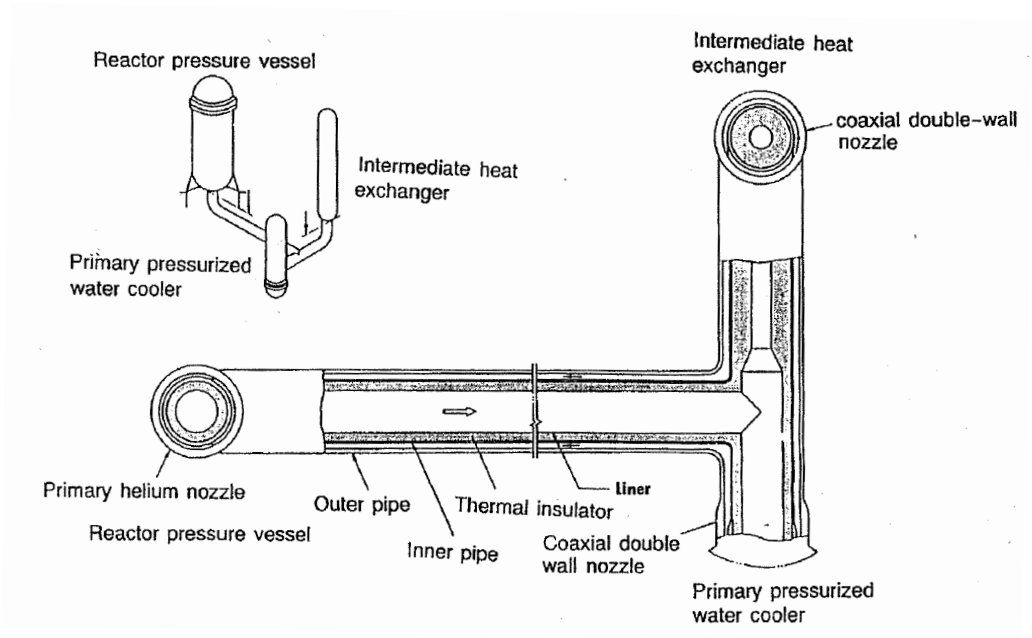


Figure 7: Cross section view of the primary concentric hot gas duct [3]

Table 2: Major specification of the primary concentric hot gas duct [3]

Maximum pressure Outer pipe	 4.8 MPa
Maximum temperature Outer pipe	 430 °C
Dimension of pressure tube Outer diameter Thickness	 860 mm 42 mm
Dimension of inner tube Outer diameter Thickness	 660 mm 15 mm
Thickness of internal insulation	90mm
Material Pressure tube Inner tube Liner	 SCMV4-2NT (2-1/4Cr-1Mo) SFVA F22B (2-1/4Cr-1Mo) SCMV4-2NT (2-1/4Cr-1Mo) STPA 24 (2-1/4Cr-1Mo) Hastelloy XR

2.2 Concentric hot gas duct in the secondary coolant system of HTTR

Secondary helium piping consists of concentric hot gas duct connecting the Intermediate Heat exchanger (IHX) and the Secondary Pressurized Water Cooler (SPWC), single wall pipes connecting the SPWC and the Secondary Gas Circulator (SGC) and so on. **Table 3** shows the major specification of secondary helium piping. Thermal insulation is attached on the inside of inner tube of concentric hot gas duct. The hot helium gas from the IHX flows inside the inner tube. The helium gas, pressurized by the SGC, flows in the annular space between the inner and outer tubes. The 2-1/4Cr-1Mo steel is used in the inner and outer tubes, and Hastelloy XR is used as the liner.

Table 3: Major specification of the primary secondary hot gas duct [3]

Maximum pressure Outer pipe	 5.1 MPa
Maximum temperature Outer pipe	 350 °C
Dimension of pressure tube Outer diameter Thickness	 610 mm 31 mm
Dimension of inner tube Outer diameter Thickness	 460 mm 15 mm
Thickness of thermal insulation	60mm
Material Outer tube Inner tube Liner	 SCMV4-2NT (2-1/4Cr-1Mo) SCMV4-2NT (2-1/4Cr-1Mo) Hastelloy XR

2.3 Demonstration test on the concentric hot gas duct in the HENDEL-loop

An experimental study on the thermal insulation performance of the concentric hot gas duct was carried out with the T_2 test section of the HENDEL-loop[4]. The structural integrity was also investigated on a part where the concentric hot gas duct is separated into two single hot gas ducts for hot and cold helium gases.

The two concentric hot gas ducts, type-A and type-B, are installed in the T_2 test section. The basic configuration of the concentric hot gas duct type-A vertically installed in the test section, as shown **Figure 8**, is the same as that in the HTTR. The concentric hot gas duct type-B shown in **Figure 9** is horizontally installed in the test section. The internal insulation layer is installed between the liner and inner tubes to assure temperature of the inner tube below design value and to prevent heat exchange between hot and cold helium gases. The thermal insulation performance was investigated on the concentric hot gas duct A by measuring temperature distributions of hot and cold helium gases, and the liner and inner tube surfaces with thermocouples in the following conditions: a hot helium temperature of 450-950°C, a flow rate of 2.0-4.0 kg/s, and a pressure of 1.0-4.0 MPa, and a cold helium temperature of 50-400°C, a flow rate of 1.0-4.0 kg/s, and pressure of 1.0-4.0 MPa. The structural integrity of the part where the concentric hot gas duct is separated into two single hot gas ducts was also investigated on the concentric hot gas duct B by measuring the temperature distribution of the inner and outer tube surfaces with thermocouples in the following conditions: a hot helium temperature of 530-730°C, a flow rate of 1.5-3.0 kg/s, and pressure of 3.0MPa, and a cold helium temperature of 170-200°C, a flow rate of 1.5-3.0 kg/s, and a pressure of 3.0 MPa.

A relationship between the mean temperature and the effective thermal conductivity of the thermal insulator in the concentric hot gas duct type-A is shown **Figure 10**. The effective thermal conductivity of the single hot gas duct [6] is also shown in the same figure. Both the effective thermal conductivity of the concentric and the single hot gas ducts are nearly equal. Moreover, there is no difference on the effective thermal conductivity within the helium gas pressure range of 1.0-4.0 MPa. This result verified that the effect of natural convection in the thermal insulator could be safely ignored. The obtained data were fitted by a linear form as follows:

$$\lambda_{eff} = 2.49 \times 10^{-4} T(K)\ 0.34\ (W/mK)$$

Figure 11 shows the temperature distributions of inner and outer tube surfaces on the concentric hot gas duct type-B at the location where the concentric hot gas duct is separated into two single hot gas ducts in the following conditions: a hot helium temperature of 730°C, a flow rate of 3.0 kg/s, and a pressure of 3.0 MPa, and a cold helium temperature of 180°C, a flow rate of 3.0 kg/s, and a pressure of 3.0 MPa. The temperature distributions in both axial and circumferential directions were nearly uniform, and there was no hot spot on the outer tube surface by measurement of temperature profiles with a radiation pyrometer. Overall, it is concluded that the structural integrity is assured.

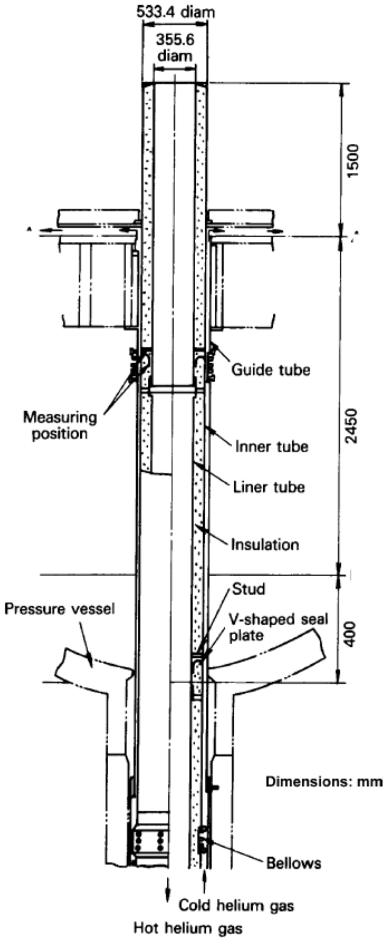


Figure 8: Cross-section of the concentric hot gas duct type-A [5]

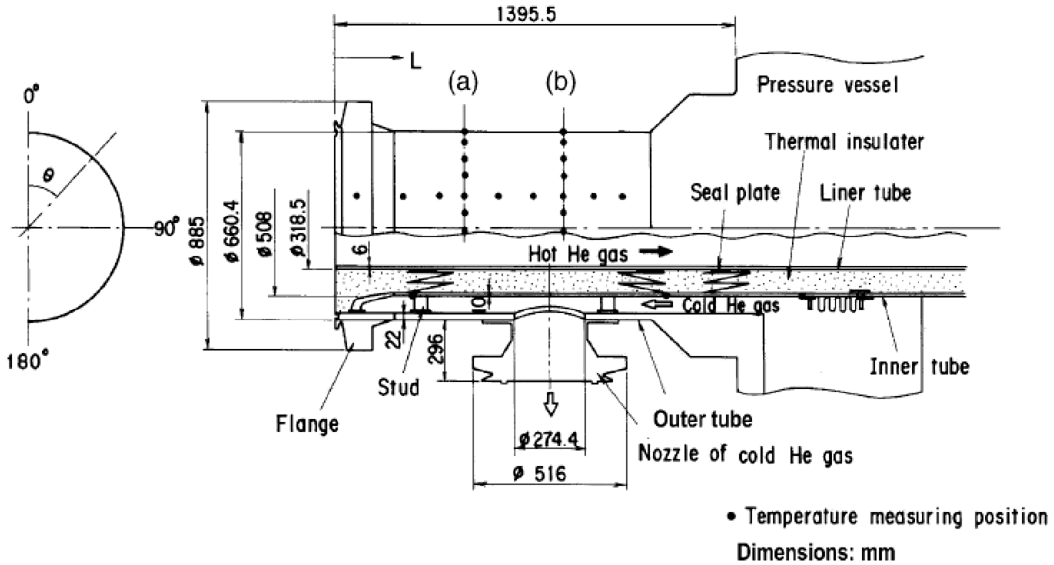


Figure 9: Cross-section of the concentric hot gas duct type-B [5]

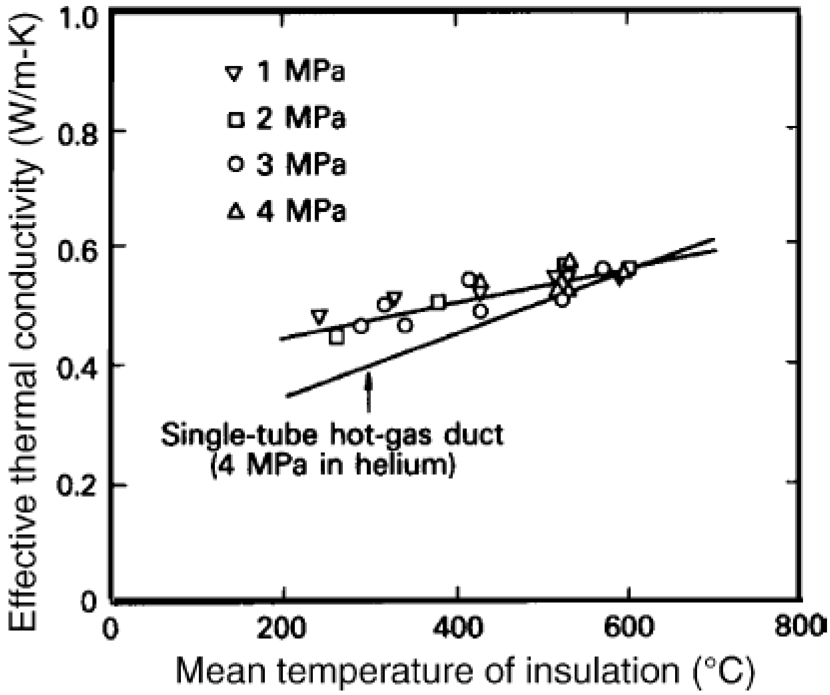


Figure 10: Relation between effective thermal conductivity and mean temperature of thermal insulator of the concentric hot gas duct type-A [5]

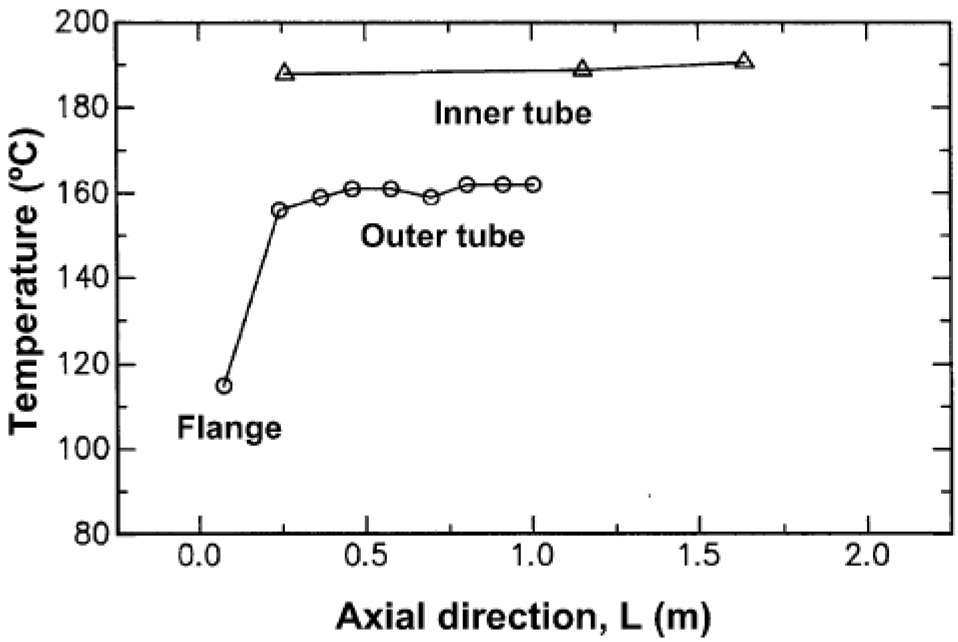


Figure 11: Temperature distributions of the inner and the outer tubes, and the flange of the concentric hot gas duct type-B [5]

3 High temperature isolation valve (HTIV)

The High Temperature Isolation Valve (HTIV) is a key component to ensure safety of the HTGR coupled with a heat application system such as the HTGR hydrogen production system. Its functions are to prevent radioactive materials release to the heat application system in case of a fracture of the IHX and to prevent combustible gas ingress to the nuclear reactor in case of a fracture of the chemical reactor. The HTIV used in the helium gas above 900°C, however, has been not fabricated for practical use yet. JAEA has been conducting design work focusing on prevention of the valve seat deformation caused by thermal expansion, and a new coating material was developed to keep face roughness of the seat within an allowable level against open and close.

An angle valve was selected from the viewpoint of workability of the inner thermal insulator, and the detailed structure was shown by thermal stress analysis to prevent the valve seat deformation. The main specifications of the HTIV for the HTTR hydrogen production system (HTTR-H2) are shown in **Figure 12**. **Table 4** shows the main specifications. The coating material of the valve seat, which can keep hardness and wear resistance at temperatures above 900°C, is necessary to ensure the seal performance. The new coating material was developed by adding 30 wt% Cr_3C_2 to the coating material used for the valve at around 500°C [9].

A component test was carried out with a one-half scale model of the HTIV, as shown in **Figure 13**, for the HTTR-H2 to confirm the structural integrity and the seal performance of the valve seat. The experimental apparatus is composed of the one-half scale model of the HTIV, electric heaters, gas supply systems, an actuator, a concentration measurement system, and so on, as shown in **Figure 14**. Helium gas at 4 MPa was supplied to the one-half scale model, and the helium gas leaking from the closed valve seat was mixed with argon gas. Then the leak amount was measured by a helium gas detector. The pressure difference between the supplied and the leaked helium gases was 4 MPa. Before closing at 900 °C, the helium gas leak rate from the valve seat at room temperature was less than 1 cm^3/s, which satisfied the design target, 4.4 cm^3/s. The leak rate decreased less than 10^{-1} cm^3/s after closing at 900 °C, as shown in **Figure 15**, and then it increased up to around the design target at room temperature after opening at room temperature. However, the leak rate became less than 10^{-1} cm^3/s when closing once again at 900°C. The following possibility is considered from the above results: Slight plastic deformation occurred at the coating material of the valve seat from the decline of the hardness when closing at 900°C, and then the face roughness of the valve seat increased when opening at room temperature. By fitting the valve seat, the leak rate at room temperature became less than 1 cm^3/s again. The current technology can be applied to the HTTR-H2; however, the work to fit the valve seat is necessary after closing at a high temperature. Therefore, the next research item is improvement of durability of the valve seat by refinement of the coating metal and so on.

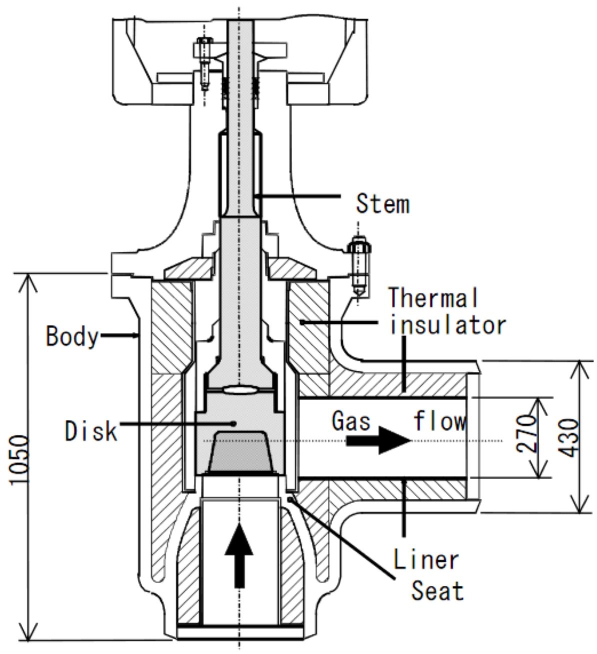


Figure 12: Schematic view of the HTIV for HTTR-H2 [7]

Table 4: Main Specifications of the HTIV for HTTR-H2 [8]

Design Classification	Category III Valve
Fluid	Helium gas
Temperature	905°C
Pressure	4.0 MPa
Flow rate	9070 kg/h
Nominal size	o.d. 558.8 mm (22 in.)
Bore	i.d. 204 mm (8 in.)
Height	～3m
Material	
Body	SCPH32
Seat	Hastelloy X
Thermal insulator	Isowool 1400

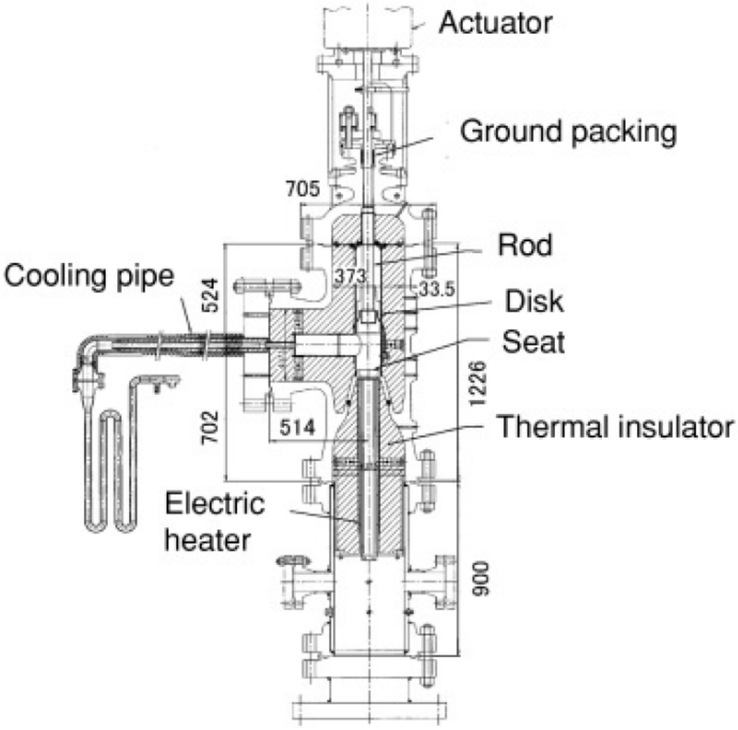


Figure 13: Schematic view of one-half scale model of the HTIV [8]

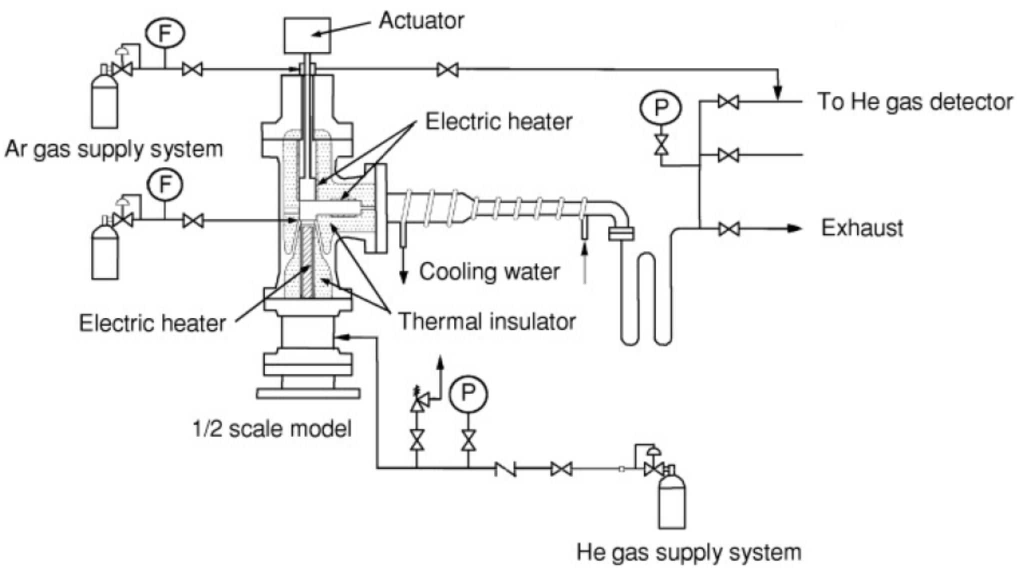


Figure 14: Experimental apparatus for the HTIV [8]

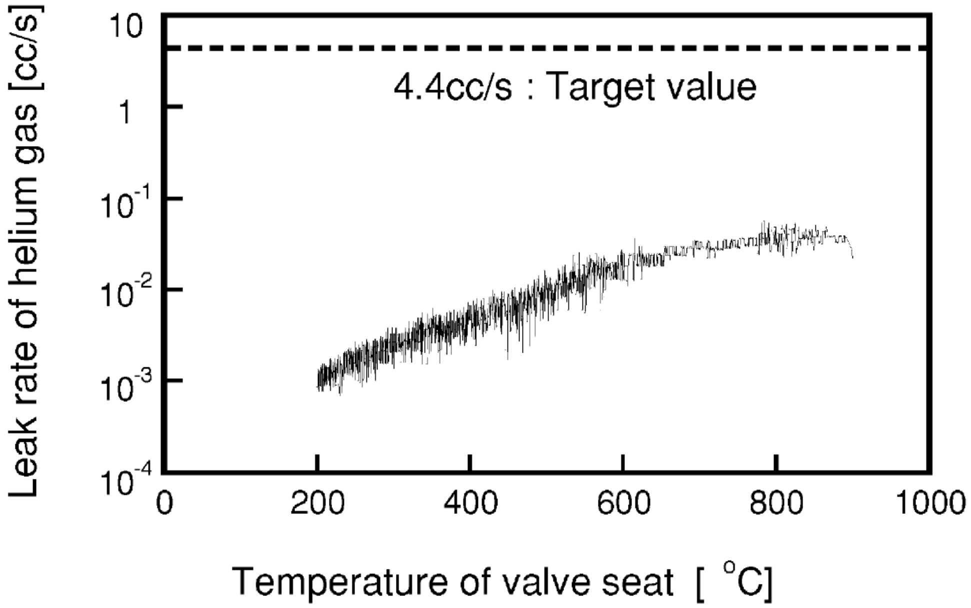


Figure 15: Leak test result of the valve seat with the one-half scale model of the HTIV [8]

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