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Hot helium leak testing method for high temperature pressure-bearing components in nuclear fusion reactors

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Foreword

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The committee responsible for this document is ISO/TC 85, *Nuclear technology, nuclear technologies, and radiological protection*, Subcommittee SC 6, *Reactor technology*.

Hot helium leak testing method for high temperature pressure-bearing components in nuclear fusion reactors

1 Scope

Hot helium leak testing can realize more reliable leak tightness assessment than the conventional cold helium leak testing for components that run at elevated temperatures. It gives the total leakage rate of a component at its operating temperature and pressure, and could greatly reduce its operational leak risk.

This document specifies the methods and techniques for leak tightness assessment of a metallic component at high temperature by measuring its total leakage rates in a vacuum chamber with a tracer gas leak detector and high-pressure helium gas or the gas mixture flowing out of the component as tracer gas during its thermal and pressure cycles as these at its operating conditions. The minimum detectable leakage rate can be as low as 10^{-10} Pa · m^3/s, depending on the dimension, external configuration complexity and materials of the component, and is strongly related to the test system and the test conditions.

This document is applicable for the hot helium leak test of in-vessel components as per its normal operating conditions in nuclear fusion reactors, which operate at elevated temperatures in an ultra-high vacuum environment down to 10^{-6} Pa and with inner flowing-coolant at operating pressure. It is also applicable to the overall leak tightness test of welds in other metallic components and equipment that could be evacuated and pressurized, such as pressurized tanks, pipes and valves in power plants, aerospace and other nuclear reactors.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 20484, *Non-destructive testing — Leak testing — Vocabulary*

ISO 20485, *Non-destructive testing — Leak testing — Tracer gas method*

EN 1779:1999, *Non-destructive testing-Leak testing -Criteria for method and technique selection*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 20484 and the following apply.

3.1
background noise
maximum vibration value of the background signal in a specified period

Note 1 to entry: The specified period is usually 5 min.

Note 2 to entry: The large pulse signal appearing occasionally during the test process should be ignored.

4 Symbols

The symbols and units in Table 1 apply to this document.

Table 1 — Symbols and units

Symbol	Description	Unit
P_0	The maximum working pressure of a component in operation	MPa
P_{test}	Actual helium pressure applied to the component in a helium leak test	MPa
I_n	Background noise	$Pa \cdot m^3/s$
R_{CL}	Stable background signal in leakage rate measurement, reading from a tracer gas leak detector before opening a reference leak for calibration of a leak test system	$Pa \cdot m^3/s$
S_{CL}	Stable leak signal in leakage rate, reading from the tracer gas leak detector after opening the reference leak for calibration of the leak test system	$Pa \cdot m^3/s$
R_L	Stable background signal in leakage rate measurement, reading from the tracer gas leak detector after closing the reference leak	$Pa \cdot m^3/s$
S_L	Stable leak signal in leakage rate measurement, reading from the tracer gas leak detector during high-pressure helium gas applied to the component in the leak test	$Pa \cdot m^3/s$
Q_0	The standard leakage rate of the reference leak at its calibration conditions, certified by an authorized metrological verification agency	$Pa \cdot m^3/s$
q_{CL}	The standard leakage rate of the reference leak corrected by a temperature coefficient at the conditions to calibrate the leak test system	$Pa \cdot m^3/s$
Q_s	The minimum detectable leakage rate of the test facility, named as the minimum detectable leakage rate of the system	$Pa \cdot m^3/s$
q_G	Actual total leakage rate of the component referred to its working pressure and temperature in operation	$Pa \cdot m^3/s$
α	The temperature coefficient for correcting a reference leak, in the range of 2 % to 7 %, certified by an authorized metrological verification agency	K^{-1} or $°C^{-1}$
D	Systematic error of the leakage rate measurement	%
C	The volume fraction of the helium gas when a helium gas mixture is used for the leak test	%
T	The ambient temperature of the reference leak in the calibration of the leak test system	°C
T_0	The temperature of the reference leak in its calibration, certified by an authorized metrological verification agency	°C
T_{test}	The elevated test temperature	°C

5 Principles and techniques of detection

5.1 The vacuum box technique for closed objects B.2.1 in ISO 20485 partially applies for this hot helium leak test. The test component shall be evacuated until the pressure is down to less than 100 Pa, and is then filled with helium tracer gas to its test pressure through a pipe connection to a tracer gas source. The test pressure should be in the range not higher than its operating pressure when the pressure gets stable. A pressure difference across its wall is obtained by placing it in a vacuum chamber. If there are leaks in the test components, the tracer gas or its mixture will flow out of the component and into the vacuum chamber. All of the leaked and the background tracer gases are collected by a tracer gas leak detector, either a helium leak detector or a mass spectrometer leak detector (MSLD), through a vacuum pumping system, and the reading shall be recorded.

5.2 Prior to any leak test, the test facility shall be calibrated by a reference leak. The systematic error D, calculated by Formula (1), shall be in the range of ±20 %. This is taken as a criterion for validation of the test system.

$$D = \frac{(S_{CL} - R_{CL} - q_{CL})}{q_{CL}} \times 100\,\% \tag{1}$$

Where q_{CL} is determined by Formula (2),

$$q_{CL} = Q_0 \times [1 + (T - T_0) \times \alpha\,\%] \tag{2}$$

5.3 The minimum detectable leakage rate Q_s of the leak test system shall be checked according to the calibration results. It shall be lower than the actual total leakage q_G of the test component, which shall be calculated by Formula (4) in 5.3.2.

5.3.1 Q_s is calculated by Formula (3),

$$Q_s = \frac{I_n}{(S_{CL} - R_{CL})} \times q_{CL} \tag{3}$$

5.3.2 For calculation of the total leakage rate q_G of the component under the working pressure in its operation, Formulas (4) and (5) shall be applied as referring to various testing pressure conditions when the leakage rate is not higher than 10^{-5} Pa · m^3/s. It shall be lower than the allowable maximum leakage rate of the component in operation for acceptance.

When the tracer gas pressure in the leak test is the same as the specified operating pressure of the component or between the two is within a tolerance of ±5 %, the total leakage rate q_G is determined by Formula (4).

$$q_G = \frac{(S_L - R_L)}{(S_{CL} - R_{CL})} \times q_{CL} \times \frac{1}{C} \tag{4}$$

When the tracer gas pressure is more different from the operating pressure of the component, the total leakage rate q_G of the component shall be determined by Formula (5).

$$q_G = \frac{(S_L - R_L)}{(S_{CL} - R_{CL})} \times q_{CL} \times \frac{1}{C} \times \frac{P_0}{P_{test}} \tag{5}$$

Where the effect of the downstream pressure (the vacuum pressure) is ignored as it is quite lower than the upstream pressure (tracer gas pressure P_{test}) in the leak test.

5.4 EN 1779:1999 applies for the selection of the test conditions, which shall be consistent with the operating conditions of the component, including temperature and pressure. The temperature of the component under test should not be lower than the maximum temperature of its inner surface contacting with the working medium or coolant under operation. Otherwise, a temperature correction shall be made to the total leakage rate of the component in accordance with EN 1779:1999, 7.3.2. In addition, the component should go through the operating temperature at least once while the leakage rate reading from the leak detector shall be recorded as reference.

5.5 The high temperature pressure-bearing component will always go from ambient temperature to its operating conditions in its service. A temperature cycle is essential in the hot helium leak test to assess its operational leak tightness. Considering possible foreign materials may block the leak in the test component, pressure cycle at each test temperature is recommended to open the leak. This is especially the case for pulse operation components. The whole hot helium leak test process is schematically shown in Figure 1.

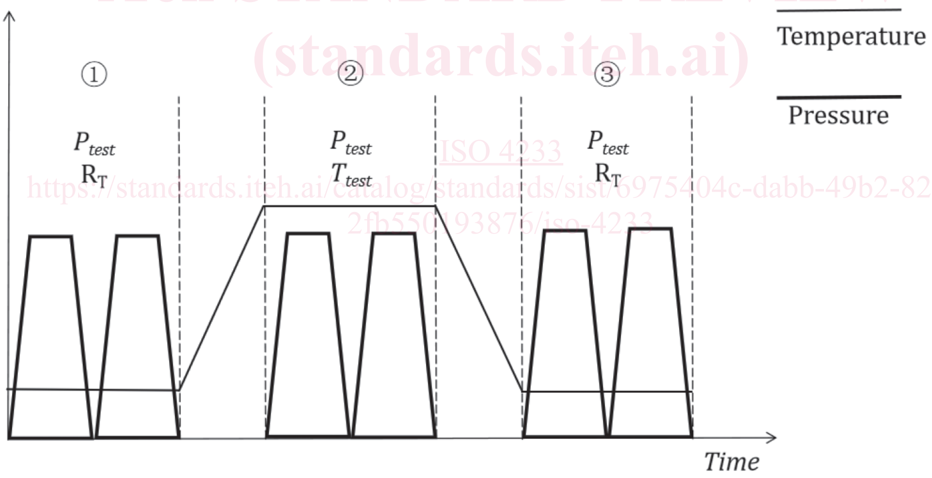
5.5.1 A hot helium leak test goes through a temperature cycle from the ambient temperature to the specific high temperature (T_{test}) and then back to the ambient temperature. The test after cooling could be performed at a fixed temperature lower than 80 °C with the acceptance criteria from the client. The heating and cooling rate shall be recorded. At each test temperature, the leakage rate of the component shall be measured.

5.5.2 Two pressure cycles from atmospheric pressure to the test pressure (P_{test}) shall be performed at each test temperature. The test pressure shall be as close as possible to the operating pressure of the component. The leakage rate shall be measured and recorded in the whole process.

5.5.3 For components with joints of different materials, two or more thermal cycles are recommended conducting so as to open potential leaks by generating thermal stresses repeatedly in the joints.

5.5.4 The test temperature and pressure should be in the tolerance range of ±10 % and ±5 % respectively, but the test pressure should not be higher than the design pressure of the component, unless otherwise specified.

5.5.5 The pressurizing rate shall be no more than 0,2 MPa/min for safety. For each pressure cycle, the test pressure shall be kept for at least 15 min.



Key

T_{test} is the elevated test temperature
R_T is the ambient temperature
Time is the history of the hot helium leak test
① is initial helium leak testing
② is the helium leak testing at elevated temperature
③ is final cold helium leak testing

Figure 1 — Schematic diagram showing the historical hot helium leak test process

5.6 In any leakage rate measurements, the high-pressure helium gas shall be kept in contact with the test component for a duration longer than the response time as specified in 9.2 or 10 min, for whichever is longer. If the leakage rate measurement takes longer time than expected, the minimum detectable leakage rate shall be determined again immediately after the measurement.

5.7 After calibration of the leak test system or when a second leakage rate measurement will be performed, the residual gas outside the component shall be evacuated. The pumping time shall be longer than the helium cleanup time as specified in 9.2. It depends on the pumping rate of the system and should be longer than 10 min.

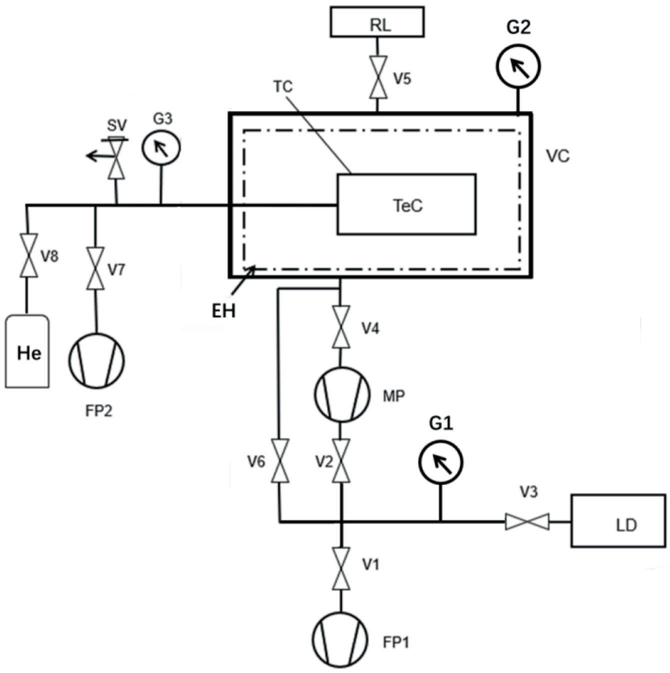
6 Personnel

Personnel performing testing in accordance with this standard shall be qualified to an appropriate level in accordance with ISO 9712 or equivalent in the relevant industrial sector.

7 Apparatus

7.1 General

7.1.1 The hot helium leak testing system consists of at least a vacuum chamber connecting to a vacuum pumping system, a test component connecting to a vacuum pump and a high-pressure tracer gas source, a heating system to heat the test component, a temperature control and measurement system, a reference leak connecting to the vacuum chamber, a gas pressuring system for the pressure cycle, and a tracer gas leak detector. It is schematically shown in Figure 2.



Key

RL, TeC, VC	are reference leak, test component and vacuum chamber, respectively
LD	is tracer gas leak detector, either a helium leak detector or a MSLD
FP, MP	are fore pump set and molecular pump set, respectively
G1, G2, G3	are vacuum gauges to measure the vacuum pressure in the vacuum system
PG	is the pressure gauge to measure the helium gas pressure
V1~V6	are vacuum valves
V7, V8	are two vacuum / pressure valve sets
He	is a high-pressure helium gas or its mixture gas source
EH	is an electric heater set to heat the component
TC	are thermocouples to measure the component and vessel temperatures
SV	is safety valve

Figure 2 — Schematic diagram of hot helium leak testing system

7.1.2 The test system shall show an acceptable leakage rate as checked by the Group A technique in ISO 20485 with a helium spray gun.

7.1.3 The vacuum chamber, pipes and their connections should be made out of materials compatible with high vacuum conditions for those used for the leak test of high-vacuum components, such as stainless steels, various glass, alumina ceramic, Kovar alloy, metal or fluororubber sealing ring.

7.1.4 The high-pressure helium gas applied to the test component shall have a helium concentration C of more than 99 % in volume fraction for the leak test of high-vacuum components to mitigate surface oxidation, such as the in-vessel components for nuclear fusion reactors.

7.2 Test component and vacuum chamber

The test component shall be placed in a vacuum chamber, with its inner channels connecting to a gas pressuring system and a helium source. A pressure gauge shall be used to measure and monitor the