
**Reactor technology — Nuclear
fusion reactors — Hot helium leak
testing method for high temperature
pressure-bearing components in
nuclear fusion reactors**

*Technologie du réacteur — Réacteurs à fusion nucléaire — Méthode
de contrôle d'étanchéité par détection de fuite d'hélium à chaud pour
les composants sous pression à haute température de réacteurs à
fusion nucléaire*

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Foreword

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Introduction

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.

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

1 Scope

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 at its operating conditions. The minimum detectable leakage rate can be as low as 10^{-10} Pa·m³/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 are referred to in the text in such a way that some or all of their content constitutes requirements of this document. 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 20485:2017, *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.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

background noise

I_n

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 given in [Table 1](#) apply to this document.

Table 1 — Symbols and units

Symbol	Description	Unit
C	The volume fraction of the helium gas when a helium gas mixture is used for the leak test	%
D	Systematic error of the leakage rate measurement	%
I_n	Background noise	Pa·m ³ /s
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
Q_s	The minimum detectable leakage rate of the test facility, named as the minimum detectable leakage rate of the system	Pa·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·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·m ³ /s
q_G	Actual total leakage rate of the component referred to its working pressure and temperature in operation	Pa·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·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·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·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·m ³ /s
T_{test}	The elevated test temperature	°C
T_0	The temperature of the reference leak in its calibration, certified by an authorized metrological verification agency	°C
T_1	The ambient temperature of the reference leak in the calibration of the leak test system	°C
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

5 Principles and techniques of detection

5.1 The vacuum box technique for closed objects B.2.1 in ISO 20485:2017 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 $\pm 20\%$. This is taken as a criterion for validation of the test system:

$$D = \frac{(S_{CL} - R_{CL} - q_{CL})}{q_{CL}} \cdot 100\% \quad (1)$$

where q_{CL} is determined by [Formula \(2\)](#):

$$q_{CL} = Q_0 \cdot [1 + (T_1 - T_0) \cdot \alpha\%] \quad (2)$$

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 \(3\)](#):

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

5.3.2 For calculation of the total leakage rate, q_G , of the component under the working pressure, p_0 , in its operation, [Formulae \(4\)](#) and [\(5\)](#) shall be applied as referring to various testing pressure conditions when the leakage rate is not higher than 10^{-5} Pa·m³/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 $\pm 5\%$, the total leakage rate, q_G , is determined by [Formula \(4\)](#):

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

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 \(5\)](#):

$$q_G = \frac{(S_L - R_L)}{(S_{CL} - R_{CL})} \cdot q_{CL} \cdot \frac{1}{C} \cdot \frac{p_0}{p_{test}} \quad (5)$$

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 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](#).

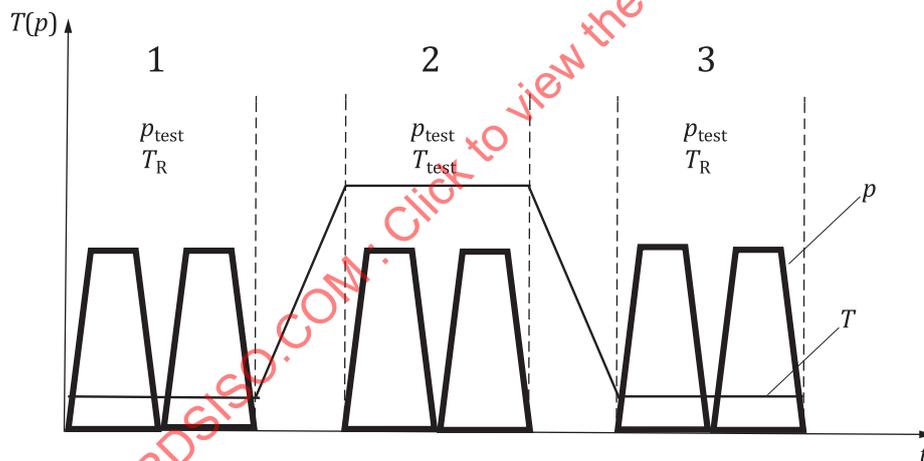
5.5.1 A hot helium leak test goes through a temperature cycle from the ambient temperature to the specific high temperature, T_{test} , and then back to the ambient temperature. The test after cooling could be performed at a fixed temperature lower than 80 °C with the acceptance criteria from the client. 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 Two or more thermal cycles are recommended conducting for components with joints of different materials in a fusion reactor, considering its thermal cycling in operation has higher potential to open leaks in the joints.

5.5.4 The test temperature and pressure should be in the tolerance range of $\pm 10\%$ and $\pm 5\%$ 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 history of the hot helium leak test
- T temperature
- p pressure
- T_R ambient temperature
- 1 initial helium leak testing
- 2 helium leak testing at elevated temperature
- 3 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

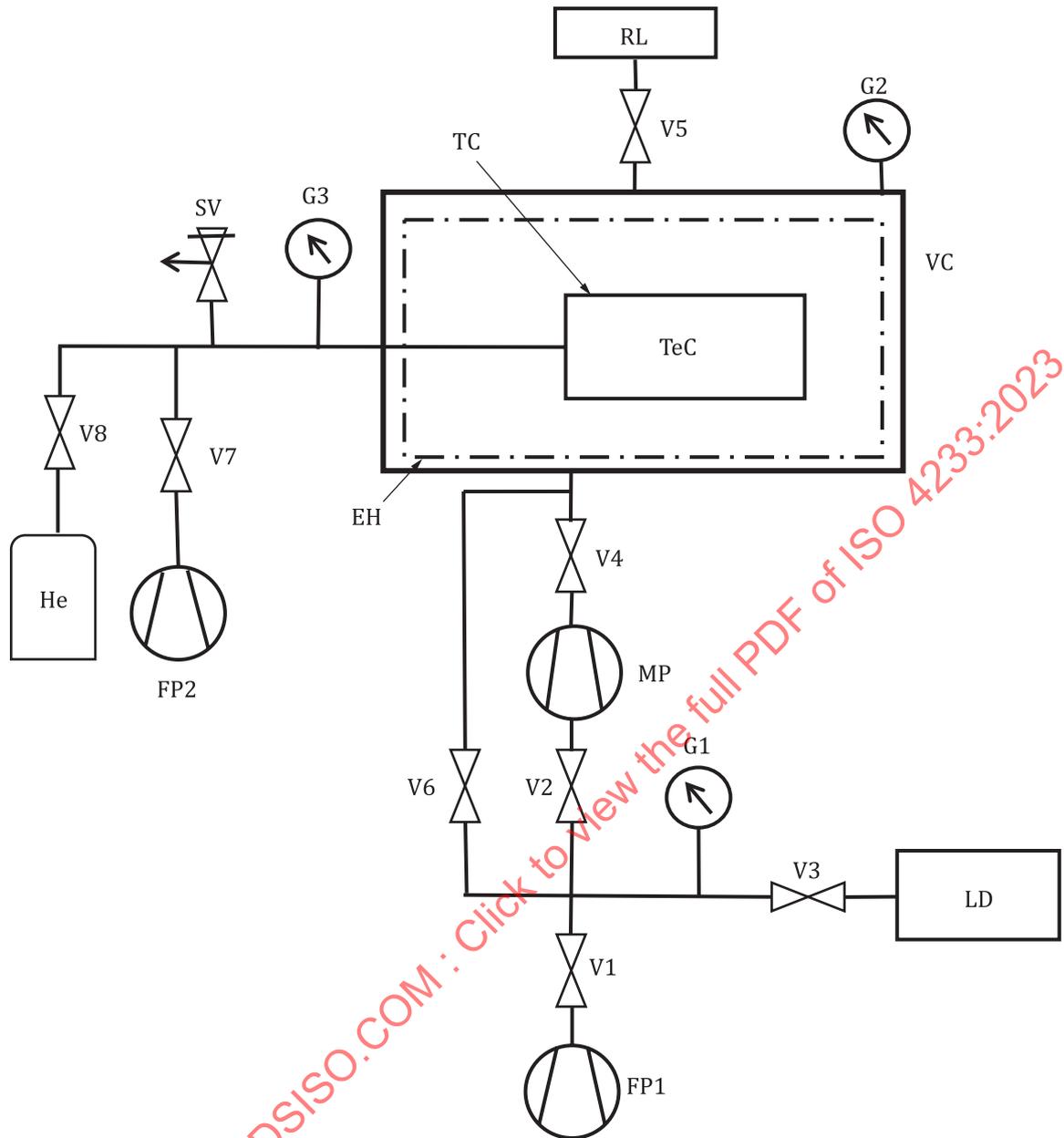
Personnel performing testing in accordance with this standard shall be qualified to an appropriate level in accordance with ISO 9712 or equivalent in the relevant industrial sector.

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](#).

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

7.3 The vacuum pumping system

A vacuum pumping system may consist of turbo-molecular pumps, a fore pump, vacuum gauges and valves, depending on the vacuum level to be reached in the vacuum chamber. It should be designed to achieve at least a pressure level of 10^{-1} Pa at any test temperature. For the in-vessel components of a fusion reactor and other components requiring quite low leakage rate, the pumping system is essential to make the pressure of the vacuum chamber down to lower than 1×10^{-3} Pa so that the test facility can vacuum bake the component at elevated temperature to reduce the minimum detectable leakage rate of the test system.

7.4 Heating and temperature control system

7.4.1 The test component can be heated by an electric heater and/or by circulating high temperature inert gas flowing through the internal cooling passage of the component.

7.4.2 The system shall have the function to monitor, record and control the temperature of the component throughout the leak test procedure. The heating-up and cooling-down rates in temperature shall be controlled within a specific limit to prevent the component from being damaged by unacceptable thermal stresses. The limit can be determined by thermo-mechanical analysis or be decided in accordance with heat treatment requirements. For austenitic stainless-steel components, to speed up the thermal cycling, the rate can be controlled in a way that its maximum temperature difference will not exceed 55 °C. In this case, a number of thermal couples shall be mounted on its surface.

7.5 Temperature uniformity requirement

The test component shall be placed in the uniform temperature zone of the vacuum chamber. The test temperature uniformity in this zone should be compatible with the tolerance range requirement as specified in [5.5.4](#).

7.6 Reference leak

A reference leak is also called as a calibrated leak. It shall be connected to the vacuum chamber and shall be far away from the vacuum pumping sets in order to correctly calibrate the test system and accurately measure the minimum detectable leakage rate of the entire system. The standard leakage value of the reference leak shall commensurate with the maximum allowable leakage rate specified for the test component and shall in any case be chosen in order to demonstrate the minimum detectable leakage rate of the system is in line with the acceptance criteria from the client.

It is suggested to add a fore pump in front of the reference leak. The air in the pipeline shall be evacuated before opening the reference leak to avoid its impact on the test results.

7.7 Tracer gas leak detector

7.7.1 Either a helium leak detector or a mass spectrometer leak detector can be used.

7.7.2 With its minimum detectable leakage rate, the detector shall be able to detect leaks that are an order of magnitude lower than the allowable maximum leakage rate of the component to be tested. To avoid helium accumulation in the ionization chamber of the detector, high pump rate detector should be used.

7.7.3 There shall be no by-pass pumping to the tracer gas leak detector to ensure that all leaking helium can go into and be detected by the detector during leakage rate measurement. Vacuum valves V1 and V4 in [Figure 2](#) shall thus be closed during the measurement.

7.7.4 It is not allowable to use the zero adjustment of the detector during the entire helium leak testing.

7.8 Other equipment

7.8.1 A calibrated helium concentration detector to monitor the "concentration of helium in the air" in the leak testing atmosphere or the tracer gas mixture.

7.8.2 A helium spray gun to locate the leak site of the system or the component to be tested.

7.8.3 A calibrated thermometer to measure the ambient temperature, which is taken as the working temperature of a reference leak that is being used for the calibration of the leak test system.

7.8.4 A calibrated pressure gauge or sensor to measure the pressure of the tracer gas in contacting with the component when measuring its leakage rate.

8 Test component preparation

8.1 Preliminary tests before hot helium leak test

8.1.1 The hot helium leak test shall be performed after a hydro-pressure test and a preliminary cold helium leak test of the component.

8.1.2 The hydro-pressure test shall be conducted in accordance with the design code for the component. Following the hydro-pressure test, the component shall be thoroughly cleaned, drained and dried.

8.1.3 The preliminary cold helium leak test shall be conducted at ambient temperature with a hood test method using Group A technique in ISO 20485:2017, Clause 8. If the leakage rate of the component is higher than the acceptance criterion, the leak site can be located using the same technique but with helium gas applied at the component surface by a spraying gun.

8.1.4 The helium concentration in the hood test shall be at least 50 %.

8.1.5 Only those components which pass preliminary tests can be considered to be used in hot helium leak test.

8.2 Vacuum baking

8.2.1 In any case, if the minimum detectable leakage rate of the system could not meet the requirements due to component outgassing, a baking of the component should be performed till the background leakage rate is reduced to an acceptable level. The components shall be baked at 200 °C to 250 °C for 8 h to 24 h, depending on the material and dimension of the component. The baking shall be performed at a pressure not higher than 1×10^{-3} Pa for in-vessel components of a fusion reactor. The temperature increasing and decreasing rates shall not be so high as to damage the component by unacceptable thermal stress.

8.2.2 This baking process can be integrated with the hot helium leak test process as shown in [Figure 1](#), as part of the first thermal cycle before the test at elevated temperature to shorten the overall test duration.

9 Calibration

9.1 General

The operations and calibrations in [9.2](#) and [9.3](#) shall be performed prior to the helium leakage rate measurement of a test component when all the conditions below are reached.

- a) The test component is installed in and connected to the leak test system and is pumped down to less than 100 Pa.
- b) The vacuum in the leak test system has been set up and the system has been checked to have an acceptable leakage rate as compared to the allowable maximum leakage rate of the test component.
- c) The by-pass pumping to the tracer gas leak detector has been closed.

9.2 Response and cleanup time measurements

The response and cleanup time measurements shall be done for large systems or where there is a long path length involving small bore tubes. It validates the operation duration of the leak test. ISO 20485:2017, 8.2 for determining the response and cleanup time applies for the measurements.

9.3 Leak detector validation and determination of minimum detectable leakage rate

The test system shall be calibrated in accordance with the following procedures. See [Figure 3](#).

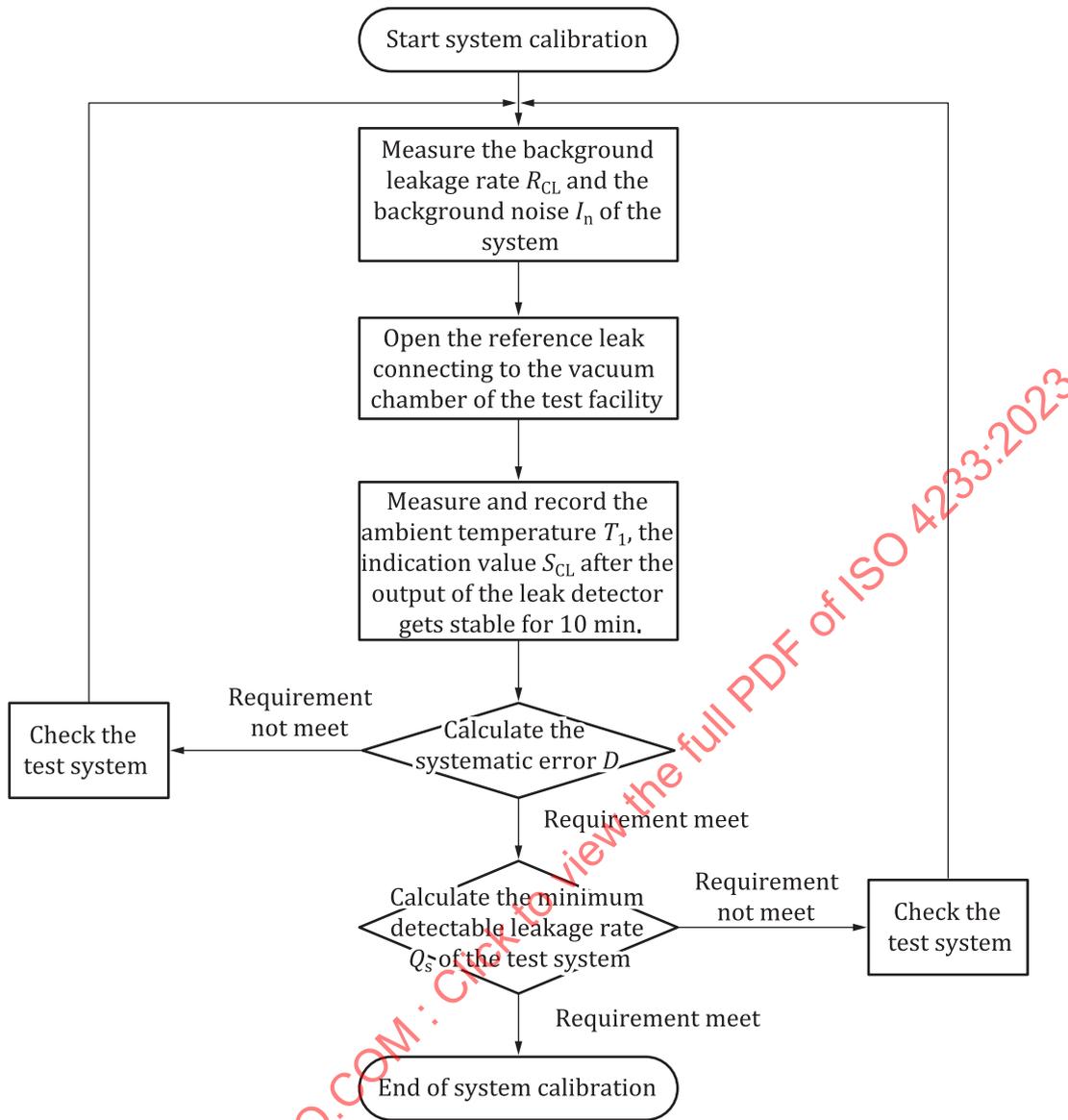


Figure 3 — Process for Calibration of the test system

9.3.1 Measure the background leakage rate, R_{CL} , and the background noise, I_n , of the system and record them in the record of the helium leak detector.

9.3.2 Open the reference leak connecting to the vacuum chamber of the test facility. Measure and record the ambient temperature, T_1 , the indication value, S_{CL} , after the output of the leak detector gets stable for 10 min. Raising signal of the leak detector is not allowed.

9.3.3 Calculate the systematic error, D , by [Formulae \(1\)](#) and [\(2\)](#) according to the recorded T_1 , R_{CL} and S_{CL} .

9.3.4 Calculate the minimum detectable leakage rate, Q_s , of the test system by [Formula \(3\)](#) according to the recorded T_1 , R_{CL} , S_{CL} and I_n .

9.3.5 Whenever there is a change of reference leak, these operations shall be repeated.