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Safe transport of radioactive materials — Leakage testing on packages

Sûreté des transports de matières radioactives — Contrôle de l'étanchéité des colis

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 5, *Nuclear installations, processes and technologies*.

This second edition cancels and replaces the first edition (ISO 12807:1996), which has been technically revised.

In this document, the word "shall" denotes a requirement; the word "should" denotes a recommendation; and the word "may" denotes permission, neither a requirement nor a recommendation. Imperative statements also denote requirements. To conform with this document, all operations shall be performed in accordance with its requirements, but not necessarily with its recommendations.

The words "can", "could" and "might" denote possibility rather than permission.

The word "will" denotes that an event is certain to occur rather than a requirement.

Introduction

The International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material* specify permitted release of radioactivity under normal and accident conditions of transport, in terms of activity per unit of time, for Type B(U), Type B(M) and Type C packages used to transport radioactive materials. Generally, it is not practical to measure activity release directly. The usual method used is to relate activity release to non-radioactive fluid leakage, for which several leakages test procedures are available. The appropriate procedure will depend on its sensitivity and its application to a specific package.

The regulations specify permissible activity release for normal and accident conditions of transport. These activity release limits can be expressed in maximum permissible activity release rates for the radioactive material carried within a containment system.

In general, it is not feasible to demonstrate that the activity release limits are not exceeded by direct measurement of activity release. In practice, the most common method to prove that a containment system provides adequate containment is to carry out an equivalent gas leakage rate test.

Safe transport of radioactive materials — Leakage testing on packages

1 Scope

This document specifies gas leakage test criteria and test methods for demonstrating that packages used to transport radioactive materials comply with the package containment requirements defined in the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material* for:

— design verification;

— fabrication verification;

— preshipment verification;

— periodic verification;

— maintenance verification.

This document describes a method for relating permissible activity release of the radioactive contents carried within a containment system to equivalent gas leakage rates under specified test conditions. This approach is called gas leakage test methodology. However, in this document it is recognized that other methodologies might be acceptable, provided that they demonstrate that any release of the radioactive contents will not exceed the regulatory requirements, and subject to agreement with the competent authority.

This document provides both overall and detailed guidance on the complex relationships between an equivalent gas leakage test and a permissible activity release rate. Whereas the overall guidance is universally agreed upon, the use of the detailed guidance shall be agreed upon with the competent authority during the Type B(U), Type B(M) or Type C packages certification process.

It should be noted that, for a given package, demonstration of compliance is not limited to a single methodology.

While this document does not require particular gas leakage test procedures, it does present minimum requirements for any test that is to be used. It is the responsibility of the package designer or consignor to estimate or determine the maximum permissible release rate of radioactivity to the environment and to select appropriate leakage test procedures that have adequate sensitivity.

This document pertains specifically to Type B(U), Type B(M) or Type C packages for which the regulatory containment requirements are specified explicitly.

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.

International Atomic Energy Agency (IAEA). *Regulations for the Safe Transport of Radioactive Material*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in the International Atomic Energy Agency (IAEA), *Regulations for the Safe Transport of Radioactive Material* and the following apply.

ISO and IEC maintain terminological 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
activity release rate
loss of radioactive contents per unit time through leaks or permeable walls of a containment system

3.2
blockage mechanism
mechanism by which radioactive material might be retained within a containment system due to blockage of potential leakage paths by solid or liquid material

3.3
competent authority
any national or international authority designated or recognized as such for any purpose in connection with the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material* and other applicable regulations

3.4
containment system
assembly of components of the packaging intended to retain the radioactive material during transport

3.5
gas leakage test methodology
method of specifying a gas leakage test which relates permissible activity release rates of the radioactive contents carried within a containment system to equivalent gas leakage rates under specified test conditions

3.6
leak
any unwanted opening or openings through a containment system that could permit the escape of the contents

3.7
leakage
transfer of a material from the containment system to the environment through a leak or leaks

Note 1 to entry: See also *permeation* (3.14).

3.8
leakage rate
quantity of solid particles, liquids or gases passing through leaks per unit time

Note 1 to entry: The term leakage rate can refer to the radioactive material (gas, liquid, solid or any mixture of these) or to the test fluid.

Note 2 to entry: The dimensions of the rate of solid leakage are mass divided by time. The dimensions of the rate of liquid leakage can be mass divided by time or volume divided by time. The dimensions of the rate of gas leakage are the product of pressure and volume (this is a mass-like unit) divided by time at a known temperature.

3.9
leaktight
general term indicating that a containment system meets the required level of containment for particular contents

Note 1 to entry: See Clause 8 in Annex E.

3.10
medium
any fluid, which might or might not be radioactive itself, which could carry radioactive material through a leak or leaks

3.11
molecular flow
flow of gas through a leak under conditions such that the mean free path is greater that the largest dimension of a transverse section of the leak

Note 1 to entry: The rate of molecular flow depends on the partial pressure gradient.

3.12
package
packaging together with its radioactive contents as presented for transport

3.13
packaging
assembly of components necessary to enclose the radioactive contents completely

3.14
permeation
passage of a fluid through a solid permeable barrier (even if there are no leaks) by adsorption-diffusion-desorption mechanisms

Note 1 to entry: Permeation should not be considered as a release of activity unless the fluid itself is radioactive. In this document, permeation is applied only to gases.

3.15
permeation rate
quantity of gases passing through permeable walls per unit time

Note 1 to entry: The permeation rate depends on the partial pressure gradient.

3.16
qualitative
refers to leakage test procedures which detect the presence of a leak but do not measure leakage rate or total leakage

3.17
quantitative
leakage test procedures which measure total leakage rate(s) from a containment system or from parts of it

3.18 Sensitivity

3.18.1
sensitivity of a leakage detector
minimum usable response of the detector to tracer fluid leakage, that is, the leakage rate that will produce a repeatable change in the detector reading

3.18.2
sensitivity of a leakage test procedure
minimum detectable leakage rate that the test procedure is capable of detecting

3.19
standardized leakage rate
SLR
leakage rate, evaluated under known conditions, normalized to the flow of dry air at reference conditions of upstream pressure $1{,}013 \times 10^5$ Pa, downstream pressure 0,0 Pa and temperature of 298 K (25 °C)

Note 1 to entry: The units for standardized leakage rate are written as $Pa \cdot m^3 \cdot s^{-1}$ SLR.

3.20
standardized helium leakage rate
SHeLR
helium leakage rate, evaluated under known conditions, normalized to the flow of dry helium at reference conditions of upstream pressure $1{,}013 \times 10^5$ Pa, downstream pressure 0,0 Pa and temperature of 298 K (25 °C)

Note 1 to entry: The units for standardized helium leakage rate are written as $Pa \cdot m^3 \cdot s^{-1}$ (SHeLR).

3.21
test gas or tracer gas
gas that is used to detect leakage or measure leakage rates

3.22
viscous flow
continuous flow of gas through a leak under conditions such that the mean free path is very small in comparison with the smallest dimension of a transverse section of the leak

Note 1 to entry: This flow may be either laminar or turbulent. Viscous flow depends upon total pressure gradient.

4 Symbols and units

The following symbols and units are used in this document.

Symbol	Definition	Unit
A_i	Activity of radionuclide *i*	Bq
A_2	Quantity (activity) of radioactive material, other than special-form radioactive material, as defined in the applicable documents listed in the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material*	Bq
A_{2i}	A_2 value of radionuclide *i*	Bq
a	Capillary length/leakage hole length	m
C	Average activity per unit volume; the symbol is used to simplify Figure 1 and represents the use of either C_A or C_N	$Bq \cdot m^{-3}$
C_A	Average activity per unit volume of the medium that could escape from the containment system under accident conditions of transport	$Bq \cdot m^{-3}$
C_N	Average activity per unit volume of the medium that could escape from the containment system under normal conditions of transport	$Bq \cdot m^{-3}$
D	Capillary diameter/leakage hole diameter	m
D	Maximum permissible diameter; the symbol is used to simplify Figure 1 and represents the use of either D_A or D_N	m
D_A	Maximum permissible equivalent capillary leak diameter under accident conditions of transport	m
D_B	Bubble diameter	m
D_N	Maximum permissible equivalent capillary leak diameter under normal conditions of transport	m
FC_{iA}	Release fraction of radionuclide *i* from the radioactive contents into the containment system under accident conditions of transport	—

Symbol	Definition	Unit
FC_{iN}	Release fraction of radionuclide *i* from the radioactive contents into the containment system under normal conditions of transport	—
FE_{iA}	Fraction of radionuclide *i* which is available for release from the containment system into the environment under accident conditions of transport	—
FE_{iN}	Fraction of radionuclide *i* which is available for release from the containment system into the environment under normal conditions of transport	—
g	Acceleration due to gravity	g = 9,81 m·s^{-2}
g_0	Constant	g_0 = 1 kg m N^{-1}·s^{-2}
H	Test duration	s
h	Liquid height	m
L	Volumetric leakage rate	m^3·s^{-1}
L	Maximum permissible volumetric leakage rate; the symbol is used to simplify Figure 1 and represents the use of either L_A or L_N	m^3·s^{-1}
L_A	Maximum permissible volumetric leakage rate of the medium at pressure p_A, under accident conditions of transport	m^3·s^{-1}
L_N	Maximum permissible volumetric leakage rate of the medium at pressure p_N, under normal conditions of transport	m^3·s^{-1}
M	Relative molecular mass	kg·mol^{-1}
M_i	Relative molecular mass of component *i*	kg·mol^{-1}
M_{mix}	Relative molecular mass of mixture	kg·mol^{-1}
p_A	Containment system pressure under accident conditions of transport	Pa
p_N	Containment system pressure under normal conditions of transport	Pa
p_d	Downstream pressure	Pa
p_i	Partial pressure of one component *i* of gas mixture	Pa
p_{mix}	Total pressure of gas mixture	Pa
p_s	Reference pressure	p_s = 1,013 × 10^5 Pa
p_t	Partial pressure of tracer gas	Pa
p_u	Upstream pressure	Pa
p_1	Gas pressure at start of test	Pa
p_2	Gas pressure at end of test	Pa
Q	Leakage rate	Pa·m^3·s^{-1}
Q_{SLR}	Standardized leakage rate; the symbol is used to simplify Figure 1 and represents the use of either $Q_{A(SLR)}$ or $Q_{N(SLR)}$	Pa·m^3·s^{-1}
Q_A	The permissible leakage rate of the medium under accident conditions of transport and is calculated from L_A	Pa·m^3·s^{-1}
$Q_{A(SLR)}$	The permissible standardized leakage rate (SLR) under accident conditions of transport	Pa·m^3·s^{-1}
Q_m	Leakage rate for molecular flow	Pa·m^3·s^{-1}
Q_{mix}	Leakage rate for gas mixture	Pa·m^3·s^{-1}
Q_N	The permissible leakage rate of the medium under normal conditions of transport and is calculated from L_N	Pa·m^3·s^{-1}
$Q_{N(SLR)}$	The permissible standardized leakage rate (SLR) under normal conditions of transport	Pa·m^3·s^{-1}
Q_p	Permeation rate	Pa·m^3·s^{-1}
Q_{TDA}	The permissible test leakage rate of the tracer or test gas that is related to accident conditions of transport at the design verification stage and is determined from $Q_{A(SLR)}$	Pa·m^3·s^{-1}

Symbol	Definition	Unit
Q_{TDN}	The permissible test leakage rate of the tracer or test gas that is related to normal conditions of transport at the design verification stage and is determined from $Q_{N(SLR)}$	$Pa \cdot m^3 \cdot s^{-1}$
Q_{TF}	The permissible test leakage rate of the tracer gas at the fabrication verification stage	$Pa \cdot m^3 \cdot s^{-1}$
Q_{TM}	The permissible test leakage rate of the tracer gas at the maintenance verification stage	$Pa \cdot m^3 \cdot s^{-1}$
Q_{TP}	The permissible test leakage rate of the tracer gas at the periodic verification stage	$Pa \cdot m^3 \cdot s^{-1}$
Q_{TS}	The permissible test leakage rate of the tracer gas at the preshipment vérification stage	$Pa \cdot m^3 \cdot s^{-1}$
Q_v	Leakage rate for viscous flow	$Pa \cdot m^3 \cdot s^{-1}$
R	Universal gas constant	$R = 8{,}31\ J\ mol^{-1}\ K^{-1}$
R	Maximum permissible activity release rate; the symbol is used to simplify Figure 1 and represents the use of either R_A or R_N	$Bq \cdot s^{-1}$
R_A	Maximum permissible activity release rate of the contents under accident conditions of transport	$Bq \cdot s^{-1}$
R_N	Maximum permissible activity release rate of the contents under normal conditions of transport	$Bq \cdot s^{-1}$
RG	Maximum permissible activity release rate of the gas contents; the symbol is used to simplify Figure 1 and represents the use of either RG_A or RG_N	$Bq \cdot s^{-1}$
RG_A	Maximum permissible activity release rate of the gas contents under accident conditions of transport after allowing for permeation	$Bq \cdot s^{-1}$
RG_N	Maximum permissible activity release rate of the gas contents under normal conditions of transport after allowing for permeation	$Bq \cdot s^{-1}$
RI_{iA}	Releasable activity of radionuclide i under accident conditions of transport	Bq
RI_{iN}	Releasable activity of radionuclide i under normal conditions of transport	Bq
RI_T	Total releasable activity for all radionuclides; the symbol is used to simplify Figure 1 and represents the use of either RI_{TA} or RI_{TN}	Bq
RI_{TA}	Total releasable activity for all radionuclides under accident conditions of transport	Bq
RI_{TN}	Total releasable activity for all radionuclides under normal conditions of transport	Bq
RP	Activity release rate due to permeation; the symbol is used to simplify Figure 1 and represents the use of either RP_A or RP_N	$Bq \cdot s^{-1}$
RP_A	Activity release rate due to permeation under accident conditions of transport	$Bq \cdot s^{-1}$
RP_N	Activity release rate due to permeation under normal conditions of transport	$Bq \cdot s^{-1}$
S	Leakage rate sensitivity	$Pa \cdot m^3 \cdot s^{-1}$
SHeLR	Standardized helium leakage rate	$Pa \cdot m^3 \cdot s^{-1}$ SHeLR
SLR	Standardized leakage rate	$Pa \cdot m^3 \cdot s^{-1}$ SLR
T	Fluid absolute temperature	K
T_0	Reference temperature	$T_0 = 298$ K
T_1	Gas temperature at start of test	K
T_2	Gas temperature at end of test	K
u	Velocity	$m \cdot s^{-1}$
V	Gas volume	m^3
V_A	Volume of medium under accident conditions of transport	m^3
V_N	Volume of medium under normal conditions of transport	m^3
μ	Dynamic viscosity of fluid	Pa·s

Symbol	Definition	Unit
μ_i	Viscosity of component *i*	Pa·s
μ_{mix}	Viscosity of mixture	Pa·s
v	Bubble-generation rate	s^{-1}
ρ	Density	kg m^{-3}
ρ_g	Gas density	kg m^{-3}
ρ_l	Liquid density	kg m^{-3}
σ	Liquid surface tension	N m^{-1}

5 Regulatory requirements

5.1 Relevant regulations

See 5.1 in Annex E for further information on relevant regulations.

5.2 Regulatory containment requirements

See 5.2 in Annex E for further information on the Type B(U), Type B(M) or Type C packages containment requirements.

6 Procedure for meeting the requirements of this document

6.1 General

Compliance with package containment requirements may be demonstrated either by measurement of the radioactive-contents release rate or by other methods. This document shows how the package containment requirements can be demonstrated by an equivalent gas leakage test. All measured test leakage rates shall be correlated to the potential release of the contained material by performance of tests on prototypes or models, reference to previous demonstrations, calculations or reasoned arguments.

This document is based on the following premises.

a) The radioactive material which could be released from the package could be in any one or any combination of the following forms:

   — liquid;

   — gas;

   — solid;

   — liquids with solids in suspension;

   — particulate solids in a gas (aerosols).

   The maximum permissible activity release rate can be expressed in terms of a maximum permissible leak diameter when the physical form and properties of the radioactive contents are taken into account.

b) The assumption of steady-state condition is an appropriate approximation.

c) Gas leakage test procedure can be used to measure gas flow rates. These rates can be related mathematically to the diameter of a single straight capillary which in most cases is considered to conservatively represent a leak or leaks.

d) Gas leakage test procedures can be used to demonstrate compliance with regulatory containment requirements when the diameter of the single straight capillary associated with the leakage test from 6.1 c) is equal to or smaller than the maximum permissible leak diameter from 6.1 a).

For activity release, or retention considerations, according to this document, the phenomena of viscous flow, molecular flow, permeation and blockage should be considered.

6.2 Quality management system

A management system, based on international, national or other standards, shall be established and implemented. To ensure the consistent quality of the activities described in this document, the implementation of ISO 9001:2015 is advised.

See 6.2 in Annex E for further information on the regulatory requirements on the management system.

6.3 Procedure

6.3.1 General

Using the flow chart in Figure 1 as a guide, the procedure below shall be used. The text within each box in the flow chart indicates the result of the particular step.

Steps 1 to 8 in Figure 1 pertain to containment of the radioactive contents, while Steps 10 to 12 pertain to leakage of a test gas. Step 9 is a reference step which links containment of the radioactive contents to the leakage of a test gas.

Because the releasable radioactive material might be in the form of gas, liquid or solid, or a combination of these, it is necessary to follow the appropriate part of the procedure below, as applicable to the form of the radioactive material, to obtain the permissible standardized leakage rates.

Figure 1 has been prepared for the general case. In some cases, it is not necessary to complete all the steps, for example, in the case of a single radionuclide in liquid form. In other cases, such as a mixture of radioactive materials that are in different forms, it might be necessary to repeat some steps in a reiterative fashion. However, for any of these cases it will be necessary to complete the appropriate steps in Figure 1 for both normal and accident conditions of transport.

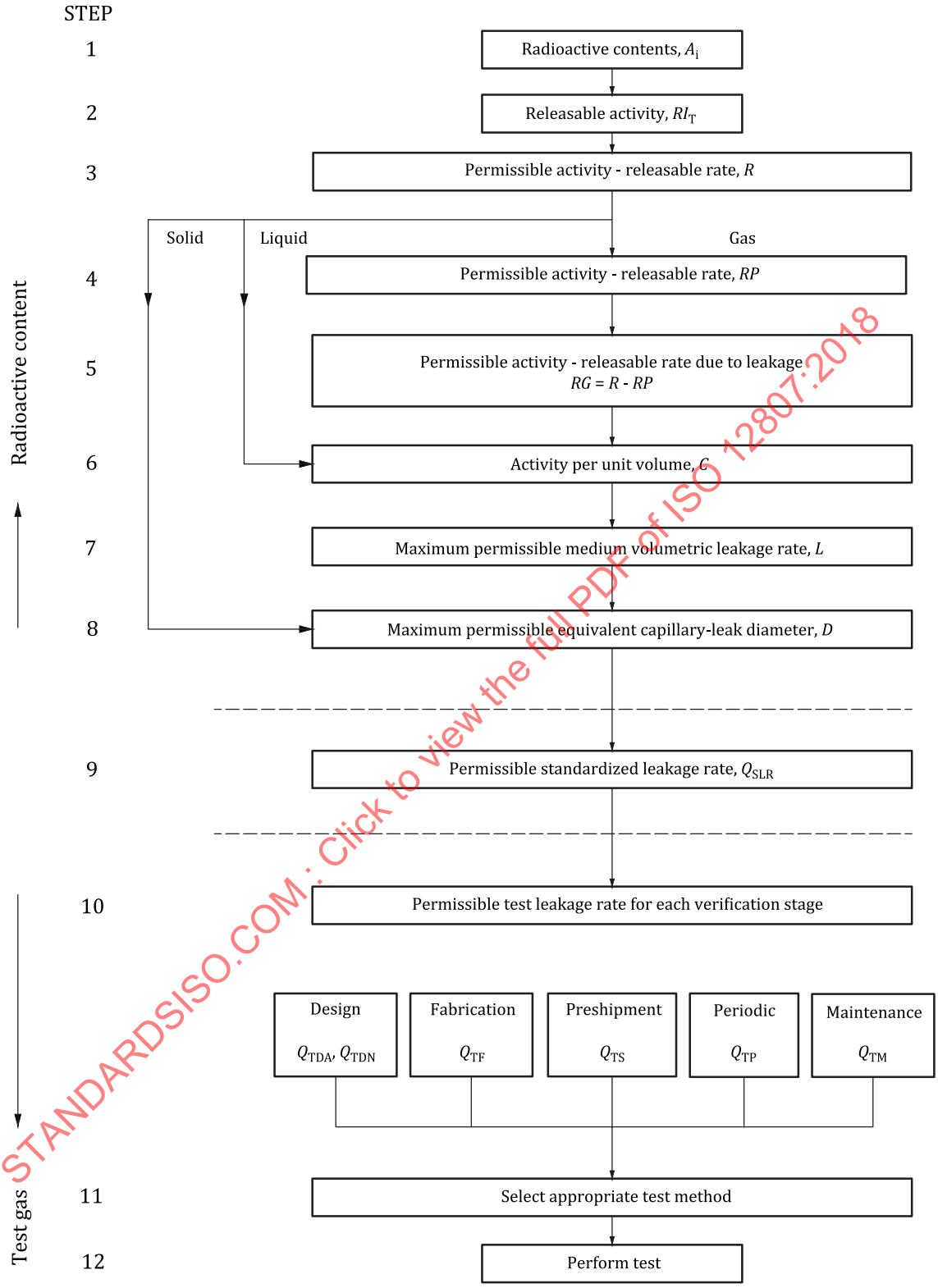


Figure 1 — Flow chart for gas leakage test methodology

6.3.2 Determination of permissible activity release rates

The inventory of the releasable radioactive contents shall be identified and the releasable contents shall be compared to the regulatory containment requirements. See Steps 1 to 3 in Figure 1 and Clause 7.

6.3.3 Determination of standardized leakage rates

The permissible activity release rates shall be converted to equivalent standardized leakage rates. See Steps 4 to 9 in Figure 1 and Clause 8.

6.3.4 Determination of permissible test leakage rates for each verification stage

The appropriate gas leakage rates shall be determined for the design, fabrication, preshipment, periodic and maintenance verification stages. See Step 10 in Figure 1 and 9.2.

6.3.5 Selection of appropriate test methods

The appropriate gas leakage test methods shall be selected for the design, fabrication, preshipment, periodic and maintenance verification stages. See Step 11 in Figure 1 and 9.2.

6.3.6 Performance of test and record of results

The required tests shall be performed and the results shall be recorded. See Step 12 in Figure 1 and Clause 10.

7 Determination of permissible activity release rates

Permissible activity release rates shall be determined by following Steps 1 to 3 for both normal and accident conditions of transport.

7.1 Step 1: List the radioactive contents, A_i

This gives an inventory of the radioactive contents and includes the activity and physical characteristics for each radionuclide. It could be necessary to consider the contents as separate phases, i.e. liquids, gases and solids. Aerosols can be considered as gases. Fine particles in solution can be considered as a liquid.

When it is impractical to determine actual radioactive contents, the bounding radioactive contents shall be estimated by the user and shall be acceptable to the competent authority.

7.2 Step 2: Determine the total releasable activity, RI_T

In some cases, the radioactive contents might be contained by more than one container in the containment system. An irradiated fuel rod assembly in a transport packaging is an example of this situation. Then, for either normal or accident conditions of transport, only a fraction of the radioactive contents might be released from the innermost container into the containment system FC_{iN}, FC_{iA} and, of this fraction, only another fraction may be available for release from the containment system to the environment, FE_{iN}, FE_{iA}. The numerical value of any release fraction will depend on the specific radionuclide and, if the radioactive contents consist of a mixture of radionuclides, many release fraction values could result. Also, release fraction values for normal conditions of transport might differ from those for accident conditions of transport, even for the same radionuclide.

The releasable fractions depend upon such factors as:

a) the chemical and physical forms of the materials within the containment system, for normal and accident conditions of transport;

b) the possible release modes, such as permeation of gases, mobility of aerosols or particulates, reactions with water or other materials present in the system, and solubility;

c) the maximum temperature, pressure, vibration, mechanical strains or distortions, and the like, to which the contained material would be subjected for normal and accident conditions of transport. These shall be determined by the performance of tests on prototypes or models, by reference to previous demonstrations, calculations, or a reasoned argument.

Where a release fraction cannot be quantified, a value of 1,0 shall be assumed. The values of the release fractions normally require agreement with the competent authority.

For normal conditions of transport, the releasable activity of radionuclide *i*, RI_{iN}, in becquerels, is:

$$RI_{iN} = FC_{iN} \times FE_{iN} \times A_i$$

and for the total inventory

$$RI_{TN} = \Sigma_i RI_{iN}$$

Similarly, for accident conditions of transport, the releasable activity of radionuclide *i*, RI_{iA}, in becquerels is:

$$RI_{iA} = FC_{iA} \times FE_{iA} \times A_i$$

and for the total inventory

$$RI_{TA} = \Sigma_i RI_{iA}$$

7.3 Step 3: Determine the maximum permissible activity release rates, *R*

The data from Steps 1 and 2 identify the radionuclides that could be released from the package and their physical form. Then, for any radionuclide, the A_2 value shall be established or, in the case of mixtures, an equivalent A_2 value shall be used (see paragraph 405 in the 2012 Edition of the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material*). Next, the regulatory containment requirements shall be calculated as indicated in E.5.2. At this stage, the containment requirements will be given in units of activity per hour or activity in a period of one week. Because gas leakage test rates are normally given in units of flow per second, it is necessary to convert the time units of the regulatory containment requirements to seconds for compatibility reasons. In this document it is assumed that leakage occurs at a uniform rate over the regulatory time period (1 h for normal conditions of transport/1 week for accident conditions of transport). Other time-averaging methods may be used, provided they are accepted by the competent authority. When all the above factors have been taken into account, the permissible activity release rates will have been determined.

8 Determination of standardized leakage rates

8.1 General

Standardized leakage rates shall be determined by following Steps 4 to 9 for both normal and accident conditions of transport.

In some cases, where the standardized leakage rates are relatively low, the relevant competent authority may permit the use of a specified rather than a calculated value for the standardized leakage rate. Also, where the standardized leakage rates are relatively high, the relevant competent authority may agree that leakage tests are inappropriate and unnecessary or may permit the use of a specified rather than a calculated value for the standardized leakage rate. See Clause 8 in Annex E.

In this clause, the method for determining the standardized leakage rate (from which the test leakage rate can be determined) is detailed for all the leakage mechanisms. The procedure followed in Steps 4 to 9 shall establish maximum permissible standardized leakage rates which are numerically equivalent to the appropriate regulatory containment requirements.

A knowledge of the radioactive contents, their properties and of the containment system of the packaging is essential in order to carry out the requirements of Steps 4 to 9.

8.2 Step 4: Determine the activity release rate due to permeation, *RP*

For a radioactive gas, determine the release rate of activity due to permeation. See B.13.

8.3 Step 5: Determine the maximum permissible activity release rate due to leakage, *RG*

When the contents include a radioactive gas, deduct the release rate due to permeation, as determined in Step 4, from the regulatory containment requirement which was determined in Step 3.

If RG < 0, the package does not meet the regulatory requirement.

If the pressure inside the containment system remains lower than the external one during the whole transport, activity can only be released by permeation and molecular flow (if predominant compared to laminar flow) driven by the partial pressures of radioactive substances.

8.4 Step 6: Determine the activity per unit volume of the containment system medium, *C*

The activity per unit volume in the medium that could escape from the containment system to the environment shall be designated as C_N and C_A for normal and accident conditions of transport respectively. Values of C_N and C_A depend upon the activity of each radionuclide and the fraction of inventory that is available for release to the containment cavity and then available for release to the environment.

For a medium volume of V_N, C_N, in becquerels per cubic metre ($Bq \cdot m^{-3}$), is determined as follows:

$$C_N = \frac{RI_{TN}}{V_N}$$

For a medium volume of V_A, C_A, in becquerels per cubic metre ($Bq \cdot m^{-3}$), is determined as follows:

$$C_A = \frac{RI_{TA}}{V_A}$$

8.5 Step 7: Determine the maximum permissible volumetric leakage rate of the medium, *L*

When the data from Step 3, or Step 5 if permeation shall be taken into account, are divided by the data from Step 6, the data for Step 7 results. This gives the maximum permissible volumetric flow rate of the medium that could escape from the package due to a leak. At this stage, the medium will be at its operating pressure and temperature conditions.

For normal conditions of transport, the maximum permissible volumetric leakage rate for the medium, L_N, in cubic metres per second ($m^3 \cdot s^{-1}$), shall be determined from the following equation:

$$L_N = \frac{R_N}{C_N}$$

For accident conditions of transport, the maximum permissible volumetric leakage rate for the medium, L_A, in cubic metres per second ($m^3 \cdot s^{-1}$), shall be determined from the following equation:

$$L_A = \frac{R_A}{C_A}$$

8.6 Step 8: Determine the maximum permissible equivalent capillary leak diameter, *D*

For liquids, the volumetric flow rate from Step 7 can be converted to a diameter for a single leak using the Poiseuille's law [Formula (B.7)].

For gases and aerosols, the volumetric leakage rates, L_N and L_A, from Step 7 shall be converted to permissible leakage rates, Q_N and Q_A, in pascals cubic metres per second ($Pa \cdot m^3 \cdot s^{-1}$), by using the following equations:

$$Q_N = L_N \times p_N$$

$$Q_A = L_A \times p_A$$

For gas and aerosol leakage rates, a diameter for a single leak may be calculated using the Knudsen'law [Formula (B.1)].

For solids, including particulates, and some liquids, it might be possible, by assessing the characteristics of the radioactive material, such as particle size or fluid viscosity, to establish a limiting diameter through which the radioactive material will not flow and hence, by this blockage mechanism [see 6.1 C b) in Annex E], there will be no activity release. The use of this blockage mechanism shall be accepted by the competent authority.

8.7 Step 9: Determine the permissible standardized leakage rate, Q_{SLR}

Where the maximum permissible equivalent capillary leak diameter has been determined in Step 8, the value of this diameter may be used in Formula (B.1) to determine the permissible standardized leakage rate (see examples in D.3, D.10, D.11 and D.13).

If the total pressure in the containment system is lower than the external one (for instance, if the initial pressure in the containment system is lower than the external one, and if Q_{SLR} is such that the internal pressure remains lower than the external one during the whole transport (see example in D.15) and if molecular flow is the predominant mode, only molecular flow driven by the partial pressures of radioactive substances needs to be regarded. For this, the first summand of Formula (B.1) should be set to zero. In the second summand, the properties of the radioactive substances (molecular mass, partial pressure) shall be used. This assessment shall be performed for each relevant radioactive substance and the results shall be combined.

Standardized leakage rates shall be determined for both normal and accident conditions of transport, D_A shall be used to determine $Q_{A(SLR)}$ and D_N shall be used to determine $Q_{N(SLR)}$. Where the radioactive material is in more than one form, values of D_A, $Q_{A(SLR)}$, D_N and $Q_{N(SLR)}$ shall be determined for each form.

The most restrictive value of $Q_{A(SLR)}$ shall be assessed to determine if this value needs to be made more restrictive to account for the activity releases in the other forms.

Similarly, the most restrictive value of $Q_{N(SLR)}$ shall be assessed to determine if this value needs to be made more restrictive to account for the activity releases in the other forms.

The above determinations and assessments will result in the values of $Q_{A(SLR)}$ and $Q_{N(SLR)}$ that shall be used in Step 10.

9 Containment-system verification requirements

9.1 Containment-system verification stages

9.1.1 General

Compliance with package containment requirements shall be demonstrated by verification procedures at the design, fabrication, preshipment, periodic and maintenance stages. It is necessary to establish a set of test requirements for each test stage.

Verification procedures shall demonstrate that all the regulatory containment requirements will be satisfied for both normal and accident conditions of transport. Therefore, leakage tests are only part

of the verification procedures. It will be necessary to establish a set of procedures acceptable to the competent authority for the different verification stages.

Assembly shall be performed in accordance with a written quality assurance procedure that includes a checklist for verifying that all parts of the containment system comply with the applicable requirements, are in place, and are properly secured.

9.1.2 Design verification

Design verification procedures shall demonstrate that the package design meets all the regulatory containment requirements for both normal and accident conditions of transport.

The packaging shall be tested to show that it has a leakage rate less than or equal to the maximum permissible test leakage rates Q_{TDN} and Q_{TDA}.

The maximum permissible test leakage rates shall be Q_{TDN} and Q_{TDA} for tests relating to normal and accident conditions, respectively. When tests are carried out at conditions (such as temperature and pressure) which are different from the normal and accident conditions, it will be necessary to show that the measured leakage rates are relevant and representative.

See 9.1.2 in Annex E for further information on regulatory references.

9.1.3 Fabrication verification

Fabrication verification procedures shall demonstrate that each packaging of a given design is fabricated in such a way that the regulatory containment requirements will be satisfied for both normal and accident conditions of transport, assuming the package is correctly assembled before shipment and the packaging is correctly maintained.

The packaging shall be tested to show that it has a leakage rate less than or equal to the maximum permissible test leakage rate Q_{TF}. The entire containment boundary, including base material, welds, seals, closures, valves, rupture disks, or other boundary elements shall be tested, except those for which evidence can be given that the leakage rate is negligible.

The maximum permissible test leakage rate, Q_{TF}, shall be the more restrictive of Q_{TDN} and Q_{TDA}. Where the test conditions differ from the worst case conditions for normal and accident conditions as appropriate, test leakage rates shall be chosen such that the tests demonstrate that the package would not leak more than the maximum permissible leakage rates for normal and accident conditions of transport.

See 9.1.3 in Annex E for further information on regulatory references.

9.1.4 Preshipment verification

Preshipment verification procedures shall demonstrate that, before each shipment, and after the contents are loaded, the package is assembled and the packaging is maintained so that, during transport and in any conditions (normal and accident), regulatory containment requirements will be fulfilled. For this purpose, the procedures shall verify that the package has been properly assembled and the packaging is correctly maintained, and that the containment function has been established.

Preshipment verification shall show that the packaging has a leakage rate less than or equal to the maximum permissible test leakage rate, Q_{TS}.

The maximum permissible test leakage rate, Q_{TS}, shall be the more restrictive of Q_{TDN} and Q_{TDA}. Where the test conditions differ from the worst case conditions for normal and accident conditions as appropriate, test leakage rates shall be chosen such that the tests demonstrate that the package would not leak more than the maximum permissible leakage rates for normal and accident conditions of transport.

See Clause 8 in Annex E for further information on exception.

See 9.1.4 in Annex E for further information on regulatory references.

9.1.5 Periodic verification

Periodic verification procedures shall demonstrate that all packaging built to an approved design shall continue to comply with the regulatory containment requirement, even after repeated use.

The packaging shall be tested to show that it has a leakage rate less than or equal to the maximum permissible test leakage rate, Q_{TP}. Because of the possible difficulties with disassembly of component parts, the extent of the containment and the number of seals to be tested, the numerical value for Q_{TP} shall be accepted by the competent authority.

The time between periodic tests shall be acceptable to the competent authority.

See 9.1.5 in Annex E for further information on regulatory references.

9.1.6 Maintenance verification

Maintenance verification procedures shall demonstrate that any maintenance, repair, or replacement of components has not degraded the containment system.

Maintenance verification shall be performed prior to returning a package to service to show that it has a leakage rate less than or equal to the maximum permissible rate Q_{TM}.

Maintenance verification tests need only to be performed for the affected area or joint, and can be combined with the preshipment verification.

See 9.1.6 in Annex E for further information on regulatory references.

9.2 Verification requirements

9.2.1 General

The appropriate permissible test leakage rate for each verification stage, as described in 9.1, shall be determined in order to demonstrate that the containment system satisfies the regulatory containment requirements and appropriate test methods shall be selected.

9.2.2 Step 10: Determine permissible test leakage rate for each verification stage, Q_{TDA}, Q_{TDN}, Q_{TF}, Q_{TS}, Q_{TP} and Q_{TM}

The results from Step 9, as appropriate, shall be taken into account in specifying the permissible test leakage rates.

$Q_{A(SLR)}$ should be considered to determine Q_{TDA} and $Q_{N(SLR)}$ should be considered to determine Q_{TDN}. For Q_{TF}, Q_{TS}, Q_{TP} and Q_{TM}, the more restrictive value of $Q_{A(SLR)}$ and $Q_{N(SLR)}$ should be considered.

Similarly, the more restrictive value of the permissible standardized leakage rates, calculated for both normal and accident conditions of transport, shall be established for determining the appropriate permissible test leakage rate in Step 10.

See B.2 and Clause 8 in Annex E for further information on the determination of standardized leakage rates and on the consideration of various test conditions (i.e. different tracer gases, operating temperatures and pressures during measurement).

9.2.3 Step 11: Select appropriate test methods

For each permissible test leakage rate established in Step 10 (design, fabrication, preshipment, periodic or maintenance), select an appropriate test method and specify suitable test procedures.

Table A.1 lists some suitable test procedures.

10 Leakage test procedure requirements

10.1 General

All leakage tests shall be performed in accordance with a written quality-assurance program. Tests shall be performed in order to ensure that the leakage test requirements are met. If, during any fabrication, preshipment or verification test, it is found that the actual leakage rate is greater than the maximum permissible, actions shall be taken to reduce the leakage rate to the acceptable level.

10.2 Step 12: Perform tests and record results

The successful completion of this step will demonstrate compliance with the regulatory containment requirements. Minimum requirements for any gas leakage test procedure that is to be used are specified in 10.3 and 10.4.

10.3 Test sensitivity

The sensitivity of each leakage test procedure, as determined by reference to applicable literature or performance of tests, shall be considered adequate when it is less than or equal to one-half of the permissible test leakage rate for the tracer gas, as determined in Step 10 in 9.2.2.

Consideration shall be given to the leakage test procedures as they are applied to the test item. For example, the gas pressure drop test (test A.3.1, Table A.2) and gas pressure rise test (test A.3.2, Table A.2) are dependent on the gas volume under test, and therefore the sensitivity of these tests shall be adjusted (for volume as well as time). In many cases, the sensitivity of a leakage test procedure can be varied extensively by changing volume, pressure, temperature, mixture composition, or time. Leakage test procedures performed under well-controlled laboratory conditions will normally be more sensitive than the same procedures under field conditions.

10.4 Test procedure requirements

10.4.1 General

Leakage test procedures shall be compatible with the test item, and, when applied to the containment system, shall have sufficient sensitivity to demonstrate compliance with test requirements for containment-system verification.

Allowable test leakage rates and test sensitivities shall be determined from activity release rates to satisfy the requirements for containment-system verification.

The tests shall be designed to preclude false acceptance. This might include assuring the presence of a tracer gas and a driving force (pressure difference).

Any necessary safety precautions shall be implemented.

Leakage test procedures shall be established and reviewed by personnel qualified according to ISO 9712 or equivalent standard. All leakage tests shall be performed by qualified operators. Operators should be qualified according to ISO 9712 or equivalent standard.

10.4.2 Testing

The user shall be responsible for verifying that the selected procedure is relevant to particular situations and that the test is applied correctly.

Testing shall be performed in accordance with 10.4.1, as applicable, and shall be documented.

Annex A
(informative)

Preferred leakage test methods

A.1 General

There are numerous text books and submitted papers related to the complex subject of leakage testing methods. Some of these are listed in the Bibliography. The purpose of this annex is to assist the user in the selection of appropriate test procedures. Consequently, this annex gives a concise description of suitable leakage test methods, their range of sensitivity, their advantages and limitations and information about safety-related considerations.

It is the user's responsibility to specify a detailed test procedure that is appropriate to the particular situation. Often, this annex will not provide enough detail and therefore the user should obtain additional information from other sources. It is also the user's responsibility to ensure that the test procedure is applied correctly.

Leakage test procedures that are not listed in this document may be used if they meet the minimum requirements of this document and are acceptable to the competent authority.

Practical leakage testing techniques for measuring the leaktightness of packages have been reviewed, and tests appropriate to packages for radioactive materials identified and recommended for use.

Detailed procedures have been developed for the recommended methods, with emphasis on the factors relevant to particular types of container.

These methods and their nominal sensitivity are listed in Table A.1. For most, the actual sensitivity shall be calculated for each application since it is a function of pressure, time, volume, temperature: and gas properties. The methods have been classified in Table A.1 and in the text under quantitative and qualitative methods. The quantitative methods provide measurements of total leakage. The qualitative methods locate discrete leaks. If possible, the qualitative methods should be checked using calibrated leaks.

The recommended methods of leakage testing are listed, with diagrammatic representation, in Table A.2. The table summarizes the test method, nominal sensitivity and applicability of each method, it is intended to be used as a guide when choosing a test method for a particular container.

A.2 Comments and precautions

A.2.1 Risks of explosion

For test items with high design pressure or large gas volumes, or both, take precautions against risks of explosion. For large gas volumes, even modest gas pressures can be hazardous. Either reduce the pressure to a known safe value or fill the test item with a liquid or solid, so that only a small gas volume remains for testing. It might be better to hydrostatically proof-test the item to help ensure safety. When a liquid is used, be certain that it cannot interfere with the leakage test.

Tests may be conducted at pressures and temperatures other than those used during operation, if the effects of the difference on containment system geometry and performance are negligible, or if operating conditions do not give sufficient pressure difference for meaningful results. Leakage flow direction during testing should be the same as during operation; flow in the reverse direction shall be justified.

Table A.1 — Leakage test sensitivities

Subclause	Test method	Nominal test sensitivity $Pa \cdot m^3 \cdot s^{-1}$ SLR
	Quantitative methods	
A.3.1	Gas pressure drop	10^{-2} to 10^{-6} [a]
A.3.2	Gas pressure rise	10^{-2} to 10^{-6} [a]
A.3.3	Gas filled envelope (gas detector)	10^{-4} to 10^{-10}
A.3.4	Evacuated envelope (gas detector)	10^{-4} to 10^{-9}
A.3.5	Evacuated envelope (with back pressurization)	10^{-4} to 10^{-9}
	Qualitative methods	
A.4.1	Gas bubble techniques	10^{-4} [b,c]
A.4.2	Bubble test	10^{-4} [b]
A.4.3	Tracer gas (sniffer technique)	10^{-4} to 10^{-7}
A.4.4	Tracer gas (spray method)	10^{-4} to 10^{-7}

[a] Sensitivity depends upon volume, pressure, time, gas properties and temperature stability.

[b] Higher reliable sensitivities can be achieved by the use of calibrated leaks to check the test equipment and the technique used.

[c] Gas bubble techniques include hot water bubble, vacuum bubble and pressurized cavity bubble methods.

Table A.2 — Summary of leakage tests

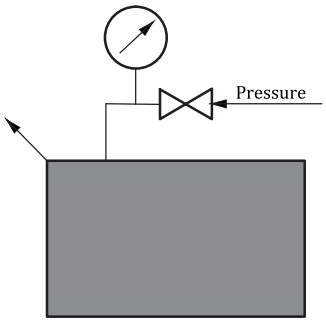
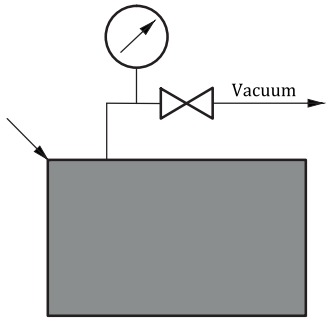
Corresponding subclause	Illustration
A.3 Quantitative methods	
A.3.1 Gas pressure drop The method involves pressurizing the test item, or interspace, and measuring the pressure drop. The sensitivity of the method is inversely proportional to the test volume. The method is particularly useful for testing double O-ring seals, where the small interspace volume makes the method most sensitive and the primary seal of the cavity shall not be broken. Nominal test sensitivity: 10^{-2} $Pa \cdot m^3 \cdot s^{-1}$ to 10^{-6} $Pa \cdot m^3 \cdot s^{-1}$ SLR.	
A.3.2 Gas pressure rise The method involves evacuating the test cavity to 10^3 Pa, or less, and measuring a pressure rise during a specified test period. The method applies to test items with pressure tap connections, but can also be used for testing double O-ring seals. Test sensitivity is inversely proportional to the test volume. Nominal test sensitivity: 10^{-2} $Pa \cdot m^3 \cdot s^{-1}$ to 10^{-6} $Pa \cdot m^3 \cdot s^{-1}$ SLR.	

Table A.2 *(continued)*

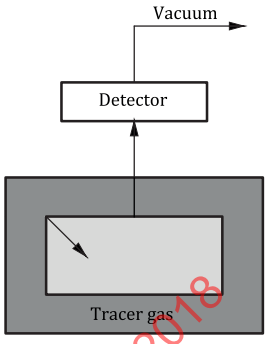
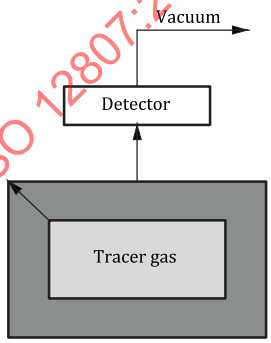
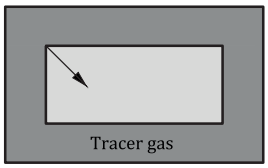
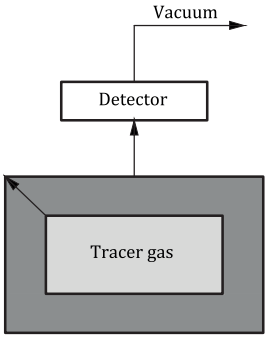
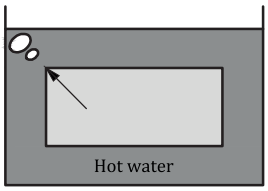
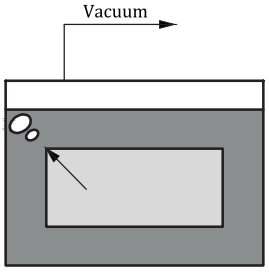
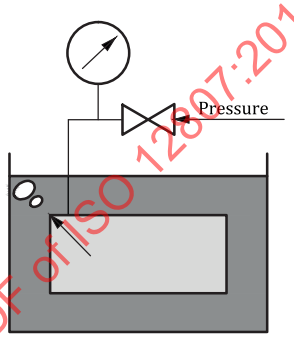
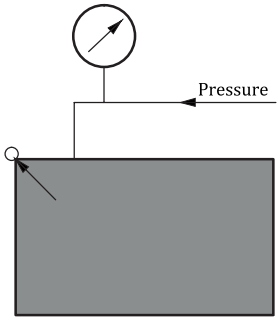
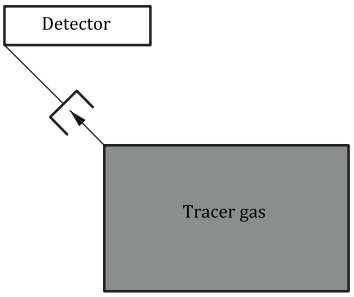
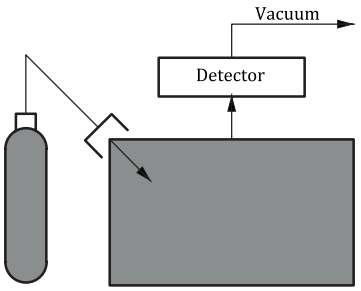
Corresponding subclause	Illustration
A.3.3 Gas filled envelope (gas detector) The method involves evacuating the test item connected to a gas detector and placing the item in an envelope filled with a test gas (usually helium or halogen compound). The method is suitable for large test items which have a replaceable seal. Where several seals are used (e.g. a double O-ring closure), the procedure can be applied to each seal in turn. Nominal test sensitivity: 10^{-4} Pa·m³·s^{-1} to 10^{-10} Pa·m³·s^{-1} SLR.	
A.3.4 Evacuated envelope (gas detector) The method involves pressurizing the test item with test gas (usually helium or halogen) while placed in a vacuum chamber connected to a gas detector. The method is ideal for small test items which have a replaceable seal. Where several seals are used (e.g. a double O-ring closure), the procedure can be applied to each seal in turn. Nominal test sensitivity: 10^{-4} Pa·m³·s^{-1} to 10^{-9} Pa·m³·s^{-1} SLR.	
A.3.5 Evacuated envelope (with back pressurization) The method involves externally pressurizing the test item in an envelope of the test gas (usually helium) for a certain time, and subsequently transferring the test item to an evacuated envelope connected to a gas detector. The method is ideal for welded capsules from the very small up to the limit of the pressurizing chamber. The internal void volume of the test item should be at least 10 mm³. This method can be used in laboratory or in manufacturing. The procedure should be carefully validated and carried out. Nominal test sensitivity: 10^{-4} Pa·m³·s^{-1} to 10^{-9} Pa·m³·s^{-1} SLR.	 
A.4 Qualitative methods	
A.4.1.4.1 Hot water bubble The method involves submerging the test item in hot water, which raises the internal pressure. A leak is indicated by a stream of bubbles. This method applies to welded capsules and small test items, usually without pressure tap connections. It can be used in the field without sophisticated equipment. Nominal maximum test sensitivity: 10^{-4} Pa·m³·s^{-1} SLR. NOTE This method is also a quantitative method but should not be used as such.	

Table A.2 *(continued)*

Corresponding subclause	Illustration
A.4.1.4.2 Vacuum bubble The method involves producing a vacuum above the liquid in which the test item is submerged. A leak is indicated by a stream of bubbles. The method is suitable for welded capsules and small resealable items. The method can be used for sources or containers with void volumes greater than 10 mm^3. The size of the test item is limited only by the size of vacuum vessel. Nominal test sensitivity: 10^{-4} $Pa \cdot m^3 \cdot s^{-1}$ SLR.	
A.4.1.4.3 Pressurized cavity bubble The method involves pressurizing the test item, and immersing it in water, glycol or isopropyl alcohol. A leak is indicated by a stream of bubbles. This method applies to welded capsules, containers with pressure tap connections, or where the pressure required within the cavity can be obtained by the vaporization of solid carbon dioxide. Nominal test sensitivity: 10^{-4} $Pa \cdot m^3 \cdot s^{-1}$ SLR. NOTE This method is also a quantitative method but should not be used as such.	
A.4.2 Bubble test The method involves pressurizing the test item, and coating the surface with a leak detection liquid film. A leak is indicated by a bubble on the surface. This method applies to containers with pressure tap connections. The required pressure within the cavity can be obtained by the vaporization of solid carbon dioxide crystals. Nominal test sensitivity: 10^{-4} $Pa \cdot m^3 \cdot s^{-1}$ SLR.	
A.4.3 Tracer gas (sniffer technique) The method involves pressurizing the test item with the test gas (usually helium or halogen compound). A leak is detected by moving a probe (connected to gas detector) across areas that are likely to leak. The method is best used on large test items where the area of potential leak (e.g. a weld or seal) is clearly visible. Some facility shall be available for pressurizing (with gas) the inside of the weld or seal. Nominal test sensitivity: 10^{-4} $Pa \cdot m^3 \cdot s^{-1}$ to 10^{-7} $Pa \cdot m^3 \cdot s^{-1}$ SLR.	
A.4.4 Tracer gas (spray method) The method involves evacuating a test item connected to a gas detector and spraying the test gas (usually helium or halogen compound) over the surface. The method can be used for testing partially finished vessels provided that one side of a potential leak can be evacuated and the other side is easily accessible with a supply of test gas. Nominal test sensitivity: 10^{-4} $Pa \cdot m^3 \cdot s^{-1}$ to 10^{-7} $Pa \cdot m^3 \cdot s^{-1}$ SLR.	

A.2.2 Tracer materials

Tracer materials shall be clean and free of contaminants that might affect test results. Care shall be taken to ensure that a known representative tracer mixture reaches the boundary being tested. Ensure

that there are no adverse reactions that would affect either the containment system contents or the leakage testing properties of the tracer.

A.2.3 Leakage rates

For some of the bubble tests, individual leakage rates as small as 10^{-7} Pa·m^3·s^{-1} SLR can be detected under favourable laboratory conditions at a pressure difference of 10^5 Pa. However, test capabilities are reduced by problems such as poor visibility due to inadequate lighting, test object configuration, bath turbulence, gas solubility, operator inattention, leak clogging by liquids, limited time of application, and the possibility that there could be a multitude of leaks too small to be detected that collectively exceed the maximum allowable leakage rate. Tracer gas pressure shall overcome the hydrostatic head of the liquid bath and surface tension effects.

The bubble test has additional problems, such as ensuring simultaneous coverage over the complete area to be tested and recognizing the effects of ambient relative humidity and temperature. Bubble tests should not be used for quantitative measurements.

For these reasons, the total leakage rate is considered to be 10^{-4} Pa·m^3·s^{-1} SLR when no bubbles are observed, unless the particular situation can be verified to have a higher sensitivity.

A.2.4 Avoid wetting the test item

For leaks expected to be smaller than 10^{-7} Pa·m^3·s^{-1} SLR, wetting of the test item before the leakage test should be avoided whenever possible. When wetting cannot be avoided, the test item shall be dried thoroughly before the test.

A.2.5 Partial pressure

The partial pressure of tracer gas in the test mixture should be at least 10 % of the total pressure and shall be known. A correction factor for the partial pressure percentage shall be used. See Formula (B.13).

A.2.6 Vacuum conditions

When normal operations are with positive pressure, consideration shall be given to the behaviour of the containment boundary, closure, and seal while testing under vacuum conditions.

A.2.7 Performing leakage test

All leakage tests shall be performed by qualified operators.

A.3 Quantitative methods

A.3.1 Gas pressure drop

A.3.1.1 Applicability of the method

This procedure is used with items having pressure tap connections. The test volume can be the container volume or the small interspace volume associated with a double O-ring seal.

A.3.1.2 Leakage rate indication

The total leakage rate is indicated by a pressure drop from a known initial pressure, over a given period of time. If the test duration is long, corrections may be required to take into account changes in ambient temperature and pressure.

A.3.1.3 Test sensitivity

The sensitivity depends mainly upon the test volume, test duration, and the accuracy to which the pressure and temperature can be measured. With large volumes, the technique is relatively insensitive, but with small interspace volumes and accurate instrumentation, sensitivities of 10^{-6} Pa·m^3·s^{-1} SLR can be achieved. It should be noted that the total volume includes the volume associated with the container plus the volume associated with the measuring instrumentation.

The actual test procedure sensitivity should be calculated taking into consideration Formula (B.12).

A.3.1.4 Test method

Pressurize the test volume to its specified test pressure and measure the change of pressure and temperature within the test volume during a specified time period. To calculate the total leakage rate, the maximum test volume shall be established accurately, including the volume of the test equipment and the extreme positions of the seals in their groove.

Pressure measurements should be accurate within 1 %, or less, of full scale of the measuring devices. These devices shall have a range between 1,5 and 4 times the specified test pressure. Test objects should be at or near thermal equilibrium before the measurement is taken, otherwise errors in determining the average temperatures might hide leakage effects.

A.3.1.5 Advantages and disadvantages

The equipment used to carry out the test could also have demountable seals, therefore the results of the test give the leakage rate across all the seals (test equipment plus vessel). Hence, the procedure could give an overestimate of the vessel leakage. If the test sensitivity required is in the order of 10^{-6} Pa·m^3·s^{-1} SLR, the leaktightness of the seals and connections of the test equipment could have an influence on the sensitivity of the test.

If the procedure is used in test work (e.g. testing before and after drop tests), at least one of the connections of the test equipment shall be broken and later resealed.

High pressure will increase the test sensitivity, but there are disadvantages. The O-rings could move during the test thus giving unreliable results. High pressure could bypass the seals and create a hazard.

Tests should take place at isothermal conditions, if at all possible, as temperature changes lead to corresponding pressure changes.

A.3.1.6 Hazards

As the test volume is pressurized, care shall be taken to ensure that the vessel will not be dangerously stressed, as failure due to gas pressurization can be “explosive” and extremely hazardous.

A.3.2 Gas pressure rise

A.3.2.1 Applicability of the method

This procedure is similar to the gas pressure-drop test and applies to test items with pressure tap connections. It has the advantage of being less affected by temperature changes than the pressure drop method.

A.3.2.2 Leakage rate indication

The total leakage rate is indicated by a pressure rise from a known initial pressure, over a given period of time. If the test duration is long, corrections may be required to take into account changes in ambient temperature and pressure.

A.3.2.3 Test sensitivity

The sensitivity depends mainly upon the test volume, test duration, and the accuracy to which pressure and temperature can be measured. The method can be used to measure leakage rates down to 10^{-6} Pa·m^3·s^{-1} SLR.

The actual test procedure sensitivity may be calculated taking into account Formula (B.12). However, it should be noted that subscripts 1 and 2 shall be interchanged.

A.3.2.4 Test method

Evacuate the test item to a suitable pressure, 10^3 Pa or less (typically 10^2 Pa), and measure the change of pressure and temperature within the test volume during a specified time period. Special care should be taken to avoid the risk of ice formation at low pressure leading to clogging of the pressure device. To calculate the total leakage rate, the maximum test volume shall be established accurately, including the volume of the test equipment and the extreme positions of the seals in their groove.

Pressure measurements should be accurate within 1 %, or less, of full scale of the measuring devices. These devices shall have a range between 1,5 and 4 times the specified test pressure. Tests should be carried out where possible in isothermal conditions. Small temperature variations can lead to large pressure variations.

A.3.2.5 Advantages and disadvantages

One problem with this method is outgassing (the release of gases from the surfaces of the test item when the item is evacuated). Keeping the test item clean and dry will minimize outgassing, which obscures leakage rate measurements.

The equipment used to carry out the test normally requires further seals apart from the seals being tested. The results of the test give the leakage rate across all the seals. Hence, the procedure could give an overestimate of the leakage rate of the vessel seals. At higher sensitivities, the leaktightness of test equipment seals could have an influence on the sensitivity of the test.

A.3.2.6 Hazards

The hazards are those associated with vacuum equipment.

A.3.3 Gas filled envelope (gas detector)

A.3.3.1 Applicability of the method

The procedure is carried out in containers which can be surrounded by an envelope filled with tracer gas. Where only a single flange joint is being tested, it might be possible to reduce the envelope size to just enclose the flange area. Common tracer gases used are helium and halogen compound gas.

A.3.3.2 Leakage rate indication

The total leakage rate is measured by a gas detector which measures the concentration of gas in the container.

A.3.3.3 Test sensitivity

The sensitivity depends upon the gas used, the pressure difference, and the method of detection. For halogen gas systems, using gases such as sulfur hexafluoride (SF_6), sensitivities of 10^{-4} Pa·m^3·s^{-1} to 10^{-7} Pa·m^3·s^{-1} SLR are achievable. With helium, a mass spectrometer could typically detect leaks with a leakage rate of 10^{-4} Pa·m^3·s^{-1} to 10^{-10} Pa·m^3·s^{-1} SLR.

A.3.3.4 Test method

Attach a vacuum system equipped with a detector head to the vessel or interspace connection. Determine response time using a calibrated leak or by allowing a small amount of the tracer into the loosened fitting or valve.

Fill the envelope with the tracer gas and monitor the response of the detector.

A.3.3.5 Advantages and disadvantages

The partial pressure of the tracer gas in the envelope should be at least 10 % of the total gas pressure and should be known.

Halogen compound gas should only be used with stainless steel systems after it has been determined that the selected halogen will not cause detrimental corrosion in the stainless steel by intergranular attack.

Halogen leakage testing requires a work space that is free from smoke (such as tobacco smoke) and other possible sources of halogen vapour (such as a leak in a building refrigeration system).

A.3.3.6 Hazards

Do not use positive ions in halogen-leak detectors in a combustible or explosive atmosphere.

Halogen compound gas in the proximity of high temperatures could break down into highly toxic compounds. Some halogen compound gases themselves could be toxic so that test areas shall be well ventilated.

Particular care shall be exercised when operating high-pressure gas cylinders.

A.3.4 Evacuated envelope (gas detector)

A.3.4.1 Applicability of the method

This method involves pressurizing the container with tracer gas, and subsequently placing the container in an evacuated envelope connected to a tracer-gas detection system. Where only a flange joint is being tested, it might be possible to reduce the envelope size to just enclose the flange area. Again, if a double O-ring seal joint is used, the tracer gas detector can be fitted into a vacuum system connected to the space between the two O-rings.

Common tracer gases used are helium and halogen compound gas.

A.3.4.2 Leakage rate indication

The leakage rate is measured by a gas detector which measures the concentration of gas in the evacuated envelope or interspace.

A.3.4.3 Test sensitivity

The sensitivity depends upon the gas used, the pressure difference and the method of detection. For halogen gas systems, using gases such as sulfur hexafluoride (SF_6), sensitivities of 10^{-4} Pa·m^3·s^{-1} to 10^{-7} Pa·m^3·s^{-1} SLR are achievable. With helium, a mass spectrometer could typically detect leaks with a leakage rate of 10^{-4} Pa·m^3·s^{-1} to 10^{-9} Pa·m^3·s^{-1} SLR are possible.

A.3.4.4 Test method

Pressurize the container with the tracer gas to the test pressure. Evacuate the envelope surrounding the container or, if testing a flange with double O-rings, evacuate the interspace, and monitor the response of the monitor fitted in the vacuum systems.

If the container cannot be filled with tracer gas, the test item can be placed in a suitable chamber and externally pressurized with the tracer gas for a certain time. The external pressure should then be reduced and the item transferred to the envelope prior to evacuation.

NOTE 1 This method is only used with items which are able to withstand the high external pressure.

A.3.4.5 Advantages and disadvantages

The partial pressure of the tracer gas in the container should be at least 10 % of the total pressure.

Halogen compround gas should only be used with stainless steel systems after it has been determined that the selected halogen will not cause detrimental corrosion in the stainless steel by intergranular attack.

Halogen leakage testing requires a work space that is free from smoke (such as tobacco smoke) and other possible sources of halogen vapour (such as leak in a building refrigeration system).

Permeation can affect the results and should be considered in their subsequent analysis.

A.3.4.6 Hazards

Do not use positive ions in halogen-leak detectors in a combustible or explosive atmosphere.

Halogen compound gas in the proximity of high temperatures could break down into highly toxic compounds. Some halogen compound gases themselves could be toxic so that test areas shall be well ventilated.

Particular care shall be exercised when operating high-pressure gas cylinders.

A.3.5 Evacuated envelope with helium back pressurization

A.3.5.1 Applicability of the method

This procedure applies to test items without pressure taps and sealed sources that cannot be filled with helium during final closure. The items shall be able to withstand the selected external pressure without damage. When sophisticated mass spectrometers are used, gases other than helium can be used.

A.3.5.2 Leakage rate indication

A mass-spectrometer leak detector (MSLD) measures leakage rates.

A.3.5.3 Test sensitivity

The sensitivity (10^{-7} Pa·m^3·s^{-1} to 10^{-9} Pa·m^3·s^{-1} SLR) depends upon the machine. It also depends upon the rate of outgassing of helium from the outer surface of the test item.

A.3.5.4 Test method

The test item is placed in a suitable chamber and externally pressurized with helium for a certain time. A typical value is 3×10^6 Pa for 1 h. Relieve the pressure and immediately transfer the item to a vacuum chamber connected to an MSLD, then evacuate to operating pressure. Operate the MSLD according to the manufacturer's instructions. In this procedure, the helium enters the test item through any existing leak and is detected subsequently when the test item is placed in a vacuum and the helium flows from the leak.

A.3.5.5 Advantages and disadvantages

This procedure is very useful for testing several small samples at a time, provided they can all be tested for leakage quickly in the evacuation chamber.

When the samples are delicate, it is possible to use a lower gas pressure for a longer period of time.

Permeation can affect the results and should be considered in their subsequent analysis.

A.3.5.6 Hazards

As the back pressure chamber is under very high pressure, it is necessary to use specially designed equipment. Operators shall be fully trained and made aware of the hazards involved.

A.4 Qualitative methods

A.4.1 Gas bubble techniques

A.4.1.1 Applicability of the method

This procedure applies to small items usually without pressure tap connections, which shall be of a size allowing them to be conveniently lifted in and out of a tank permitting close observation of the liquid.

The method can be used with test items having pressure tap connections, or where the required pressure difference can be obtained by:

a) vaporization of solid CO_2 crystals, liquid N_2 or refrigerant liquid;

b) use of a vacuum over the liquid in the tank;

c) use of hot liquid in the tank.

A.4.1.2 Leak indication

Individual leaks are indicated by gas bubble streams through the test liquid.

A.4.1.3 Test sensitivity

The test gives a qualitative result, with an absence of bubbles through the test liquid indicating a leakage rate in the range of 10^{-4} Pa·m^3·s^{-1} SLR.

Various liquids, such as water, various alcohols, mineral oil, silicone oil, glycol can be used in conjunction with various tracer gases to obtain improved sensitivity.

A.4.1.4 Test method

A.4.1.4.1 Hot water bubble

Immerse the test item at room temperature in water at 90 °C. Submerge the test item, or feature to be tested, in a suitable tank such that it is covered by at least 50 mm of water and search for bubble streams.

The duration of the test shall be long enough for the test item and its gas volume to be heated by the water. The time that the item should remain in the water shall be determined by a calculation or test.

Air bubbles could stream for a few seconds and then cease. Such streams could be caused by gas trapped on the exterior of the test item and do not necessarily indicate a leak.

A.4.1.4.2 Vacuum bubble

Immerse the test item in a bath of liquid. Evacuate the space above the liquid to a suitable pressure, typically 10^4 Pa and search for bubble streams. The immersion liquid should possess a low surface tension and a low vapour pressure and should be easily removable from the test item after the test.

Atmospheric air adheres to the surface of the test item, and could, under evacuation, form air bubbles which could stream for a few seconds and then cease. Such streams do not necessary indicate a leak.

A.4.1.4.3 Pressurized cavity bubble method

Pressurize the test item with tracer gas to its specified test pressure for at least 15 min. This pressure can be provided by a pressure tap connection or by the use of solid CO_2 crystals. When an internal pressure is to be generated, the vaporization of, for example, 2 kg of solid CO_2 crystals per cubic metre of cavity volume will produce an increase in pressure of 10^5 Pa.

With the item still pressurized, immerse the potential leaking area in a liquid bath and search for bubble streams. Air bubbles could stream for a few seconds, and then cease. Such streams could be caused by gas trapped on the exterior of the test item and do not necessarily indicate a leak.

A.4.1.5 Advantages and disadvantages

This method applies generally to small containers and welded capsules that can be conveniently lifted in and out of a suitable tank.

Air could be trapped in seals and on surfaces and could give rise to spurious bubbles which could be confused with true leakage.

With the vacuum bubble technique, air could be entrained in the test liquid and it might be necessary to evacuate the liquid for some time before leakage testing. The evacuation time depends upon the liquid volume.

If the test is repeated, there is a possibility that the leakage holes could have become clogged with liquid.

A.4.1.6 Hazards

Consideration shall be given to the risk of pressurization causing rupture of the test item.

When generating pressure by means of CO_2 crystals, care shall be taken not to exceed the correct amount of CO_2 needed to produce the required internal pressure.

Care shall be taken when handling CO_2 crystals which could cause “cold” burns.

If alcohols are used there is a danger of fire.

Safety spectacles or a shield shall be used to protect the operator and others from the possible rupture of the liquid container.

A.4.2 Bubble test

A.4.2.1 Applicability of the method

This method applies to containers with pressure tap connections, or where the pressure required within the cavity could be obtained by the vaporization of solid CO_2 crystals.

A.4.2.2 Leak indication

Individual leaks are indicated by gas bubbles forming in a leak detection liquid that has been brushed over the outer surface of the test item.

A.4.2.3 Test sensitivity

The test gives a qualitative result, with an absence of bubbles through the leak detection liquid film indicating a leakage rate of less than 10^{-4} Pa·m^3·s^{-1} SLR. Sensitivity could be increased by increasing

the test pressure. If possible, the method should be checked by using a calibrated leak corresponding to the sensitivity required for the containment.

A.4.2.4 Test method

Pressurize the test item to its specified test pressure for at least 15 min. Then, with the test item still pressurized, coat or brush all possible leakage areas with a leak detection liquid solution, and search for bubbles.

To be effective, the solution shall bridge all potential leakage areas or joints. Commercial leak detection solutions with low surface tensions are available. The affected areas should be cleaned after the test.

When an internal pressure is to be generated, the vaporization of, for example, 2 kg of solid CO_2 crystals per cubic metre of cavity volume will produce an increase in pressure of 10^5 Pa.

A.4.2.5 Advantages and disadvantages

This method is similar to the pressurized cavity bubble test but is not restricted by the size or mass of the container.

Where seals are not readily accessible, or joint gaps are such that they cannot be bridged or flooded, this method becomes unreliable.

A.4.2.6 Hazards

Consideration shall be given to the risk of pressurization causing rupture of the test item.

When generating pressure by means of CO_2 crystals, care shall be taken not to exceed the correct amount of CO_2 crystals needed to produce the required internal pressure.

Care shall be taken when handling CO_2 crystals which could cause “cold” burns.

A.4.3 Tracer gas (sniffer technique)

A.4.3.1 Applicability of the method

This procedure is best used on large containers or sources where the area of potential leak, for example a weld or seal, is clearly visible. A facility shall be available for supplying tracer gas to the open sides of the seal and a detector device shall be placed on the other side.

Typical tracer gases are helium and halogen gases.

A.4.3.2 Leak indication

A leak is indicated by a detector which measures the concentration of any released tracer gas.

A.4.3.3 Test sensitivity

The sensitivity depends upon the tracer gas used, the pressure difference, and the particular detector. For halogen compound gas systems, using gas such as sulfur hexafluoride (SF_6), sensitivities of 10^{-4} Pa·m^3·s^{-1} to 10^{-7} Pa·m^3·s^{-1} SLR are achievable. With helium, a mass spectrometer could typically detect leaks with a leakage rate of 10^{-4} Pa·m^3·s^{-1} to 10^{-9} Pa·m^3·s^{-1} SLR.

A.4.3.4 Test method

Operate the detector according to the manufacturer's instructions. Pressurize the test item or flange with tracer gas up to the test pressure and “sniff” the potential leakage areas. The “sniffer” should be held close to the surface (<1 mm away) and moved not faster than 20 mm·s^{-1}.

Prior to starting, the “sniffer” should be checked with a calibrated leak.

A.4.3.5 Advantages and disadvantages

Because the “sniffer” detects individual leaks, it cannot be used to quantify the total leakage rate of a container.

Halogen compound gas should only be used with stainless steel systems, after it has been determined that the selected halogen will not cause detrimental corrosion in the stainless steel by intergranular attack.

Halogen-leakage testing requires a work space that is free from smoke (such as tobacco smoke) and other sources of halogen vapour (such as a leak in a building refrigeration system).

The partial pressure of the tracer gas in the test mixture should be at least 10 % of the total pressure and shall be known.

A.4.3.6 Hazards

Do not use positive ions in halide-torch-leak detectors in a combustible or explosive atmosphere.

Halogen compound gas in the proximity of high temperatures could break down into highly toxic compounds. Some halogen compound gases themselves could be toxic so that test areas shall be well ventilated.

Particular care shall be exercised when operating high-pressure gas cylinders.

A.4.4 Tracer gas (spray method)

A.4.4.1 Applicability of the method

This procedure is most suitable for large containers where the area of a potential leak, for example a weld or seal, is clearly visible. Some facilities shall be available for supplying tracer gas to the area and a detector device to the remote side of the weld or flange.

Typical tracer gases are helium and halogen gases.

A.4.4.2 Leakage-rate indications

The leakage rate is measured by a gas detector which measures the concentration of tracer gas.

A.4.4.3 Test sensitivity

The sensitivity depends upon the tracer gas used, the pressure difference, and the particular detector. With halogen compound gas such as sulfur hexafluoride (SF_6), sensitivities of 10^{-4} Pa·m^3·s^{-1} to 10^{-7} Pa·m^3·s^{-1} SLR can be measured. With helium, a mass spectrometer could typically detect leaks with a leakage rate of 10^{-4} Pa·m^3·s^{-1} to 10^{-9} Pa·m^3·s^{-1} SLR.

A.4.4.4 Test method

Evacuate the test item or joint interspace with a vacuum pump and operate the gas detector according to the manufacturer's instructions. Determine the response time by spraying a small quantity of tracer gas into a known leak, such as a partially opened valve or loosened fitting, or by using a calibrated leak, and note the time required for the detector to respond.

Isolate the known leak and spray potential leakage areas with tracer gas. Spray each area for a period longer than the response time and monitor the gas detector response.

A.4.4.5 Advantages and disadvantages

Because the spray method detects individual leaks, it cannot be used to quantify the total leakage rate of a container.

Halogen compound gas should only be used with stainless steel systems, after it has been determined that the selected halogen will not cause detrimental corrosion in the stainless steel by intergranular attack.

Halogen-leakage testing requires a work space that is free from smoke (such as tobacco smoke) and other sources of halogen vapour (such as a leak in a building refrigeration system).

A.4.4.6 Hazards

Particular care shall be exercised when operating high-pressure gas cylinders.

Annex B
(informative)

Methods of calculation

B.1 General

This annex summarizes basic data and equations concerning methods of calculation.

Worked examples are given in Annex D to illustrate how the calculation methods can be applied to this document.

B.2 Gas leakage

Gas leakage may occur by gas flow, which is described in this clause, or by permeation, which is described in B.13.

The gas flow rate through small leaks depends on the fluid and thermodynamic properties of the gas, characteristics of the leakage path and flow regime. Pressure is a fluid property; pressure difference is the driving force for leakage. For this annex, a single straight circular tube (a capillary) will be used to model the leakage path or paths. For the range of leakage referred to in this document (i.e. 10^{-8} Pa·m^3·s^{-1} to 1 Pa·m^3·s^{-1}) the modified Knudsen equation for transitional flow [Formula (B.1)] adequately calculates the flow rate, Q, in pascals cubic metres per second (Pa·m^3·s^{-1}).

$$Q = \frac{\pi}{128}\frac{D^4}{\mu \cdot a}\frac{\left(p_u^2 - p_d^2\right)}{2} + \frac{\sqrt{2\pi}}{6}\sqrt{\frac{RT}{M}}\frac{D^3}{a}\left(p_u - p_d\right) \tag{B.1}$$

Formula (B.1) is valid for a single gas. Equivalent properties are required for a mixture of gases, see B.4.

The first part of this equation represents the viscous laminar flow component, Q_V which is derived from Poiseuille's law for laminar flow and the second part represents the molecular flow component, Q_m which is derived from Knudsen's law for free molecular flow.

Formula (B.1) may be applied to the viscous laminar flow regime only, the molecular flow regime only or the transition flow regime. For predominating laminar flow, the calculated contribution for molecular flow becomes negligible, and similarly for predominating molecular flow, the calculated contribution for laminar flow becomes negligible.

E.Annex B gives the derivation of Formula (B.1), the justification for its use and the limitations of its use.

B.3 Correlation between gas leakage rates in different conditions

Correlations between various conditions can be made using Formula (B.1). The capillary diameter can be calculated from the known conditions. The leakage rate in other conditions is found by using the calculated diameter.

For the special case where the different conditions are both in the pure laminar flow regime, the relationship between the leakage rates, Q_x and Q_y, in pascals cubic metres per second ($Pa \cdot m^3 \cdot s^{-1}$), of gases x and y, respectively, is the following:

$$Q_x = Q_y \frac{\mu_y}{\mu_x} \times \frac{\left(p_u^2 - p_d^2\right)_x}{\left(p_u^2 - p_d^2\right)_y} \tag{B.2}$$

Similarly, for the pure molecular flow regime:

$$Q_x = Q_y \frac{\sqrt{T_x M_y}}{\sqrt{T_y M_x}} \times \frac{\left(p_u - p_d\right)_x}{\left(p_u - p_d\right)_y} \tag{B.3}$$

B.4 Mixture of gases

For a perfect gas mixture of n components, mixture properties for total pressure p, in pascals (Pa), and viscosity μ, in pascals seconds (Pa·s), [in the first part of Formula (B.1)] can be derived as follows:

$$p_{mix} = \sum_{i=1}^{n} p_i \tag{B.4}$$

$$\mu_{mix} = \sum_{i=1}^{n} \frac{p_i \mu_i}{p_{mix}} \tag{B.5}$$

The term $\frac{p}{\sqrt{M}}$ [in the second part of Equation (B.1)], in pascals kilograms to the power −0,5 moles to the power 0,5 ($Pa \cdot kg^{-0,5} \cdot mol^{0,5}$) can be as follows:

$$\left(\frac{p}{\sqrt{M}}\right)_{mix} = \sum_{i=1}^{n} \frac{p_i}{\sqrt{M_i}} \tag{B.6}$$

B.5 Correlation to standard conditions

To allow leakage rates measured at various conditions to be compared, it is useful to refer to the leakage rates at standard conditions.

Usual standard conditions are dry air at 298 K (25 °C) with an upstream pressure of $1,013 \times 10^5$ Pa and a down stream pressure of 0,0 Pa. The standard unit of leakage rate is $Pa \cdot m^3 \cdot s^{-1}$ SLR. Any given leakage can be stated in terms of the standard conditions by using Formula (B.2) or (B.3). The leakage rate at these standard conditions is defined in this document as the standardized leak rate (SLR).

B.6 Liquid leakage

Liquid leakage will be laminar at low flow rates and turbulent at high flow rates. Because of the hole sizes involved, only laminar flow is considered. Liquid-leakage rate, L, in cubic metres per second ($m^3 \cdot s^{-1}$) is derived from Poiseuille's law and is given by the following equation:

$$L = \frac{\pi}{128} \times \frac{D^4}{\mu \cdot a} \left(p_u - p_d\right) \tag{B.7}$$

B.7 Correlation between liquid-leakage rates at different conditions

The correlation between a measured leakage rate, L_y, and an equivalent leakage rate, L_x, in cubic metres per second ($m^{3}\cdot s^{-1}$), is given by the following equation:

$$L_x = L_y \left(\frac{\mu_y}{\mu_x} \right) \frac{(p_u - p_d)_x}{(p_u - p_d)_y} \tag{B.8}$$

B.8 Correlation between gas and liquid leakage rates

For a system containing radioactive liquid, the maximum permissible equivalent capillary leak diameter, *D*, in metres (m), is determined from Formula (B.7). This value of *D* is then substituted in Formula (B.1) to determine the equivalent gas leakage rate.

B.9 Aerosol leakage

An aerosol is a suspension of particles such as solid powder in a gaseous medium. The nature of an aerosol formed in a package is likely to be non-uniform in both space and time. Particle suspension is a result of forces randomly applied to the system; settling is a continuous process that removes particles from the aerosol and reduces the quantity available for release. Release (removal) of the suspended particles is caused by particle entrainment in the escaping fluid. Analytical prediction of aerosol release is difficult because of uncertainty in aerosol characteristics, entrainment and settling, both in the system and in escape through a leakage path. Consequently, an equation that describes an aerosol leakage rate cannot be provided.

B.10 Correlation between gas and aerosol leakage rates

The use of the following correlation requires that the partial distribution as mass fraction versus geometric particle diameter be known.

The correlation equates a maximum permissible equivalent capillary diameter, *D*, in metres (m), to a limiting geometric diameter for the particles. A limiting geometric diameter shall be determined so that the total activity of all the particles that could be released will be restricted to permissible levels.

The value of the limiting geometric diameter is then substituted in Formula (B.1) to determine the equivalent gas leakage rate.

B.11 Precautions in the use of correlations

The correlations in B.3, B.5, B.7, B.8 and B.10 shall be used with caution. Firstly, the correlations are valid provided the flow regime effects are properly considered. Secondly, they account for effects of temperature and pressure on leaking fluids but not on leakage path geometry. For example, if a system normally operates at pressure *p*, the result of an air-leakage test at 0,1*p* would be doubtful because, at test conditions, the system would be subject to less strain.

B.12 Surface tension

In bubble test methods, bubbles will not be emitted unless the internal pressure of the bubble exceeds the sum of the atmospheric pressure above the liquid, the gravitational pressure level of the liquid, and

the pressure level due to surface tension. The internal pressure of the bubble, p_u, in pascals (Pa), that is required to overcome surface tension can be estimated from the following Formula (B.9):

$$p_u > p_d + \frac{2\sigma}{D} \tag{B.9}$$

Two other parameters shall be considered in bubble testing: bubble diameter, D_B, in metres (m), and bubble generation rate, v, in seconds to the power minus one (s^{-1}). These parameters can be estimated as follows:

$$D_B = \left[\frac{6D\sigma g_0}{g\left(\rho_l - \rho_g\right)}\right]^{1/3} \tag{B.10}$$

$$v = \frac{6L}{\pi D_B^3} \tag{B.11}$$

B.13 Permeation

Permeation is the passage of a fluid through a solid barrier (which has no leaks) by adsorption-diffusion-desorption processes. It should not be considered as a leakage or a release unless the fluid itself is radioactive. If this is the case, the container boundary shall reduce the permeation to an acceptable level. In this document, permeation is applied only to gases.

If a containment system includes organic material, such as elastomeric O-rings, permeation can be a problem when a leakage test procedure is being used to demonstrate that the system is leaktight. Typically, helium has a nominal permeation coefficient of 5×10^{-7} $m^3 \cdot s^{-1}$ per cm of O-ring exposed, for every $1{,}0 \times 10^5$ Pa of pressure difference. Some methods for reducing the effects of permeability as a factor in leakage rates are:

a) complete the leakage test before permeation reaches a significant level;

b) use a tracer/seal material combination that either reduces or delays permeation;

c) if the nominal steady-state permeation rate (obtainable from the manufacturer) for the tracer/material com-bination, temperature, and pressure difference is 50 % or less of the maximum permissible leakage rate, the nominal value may be subtracted from the measured leakage rate if sufficient time was allowed for the value to reach steady-state before the measurements were made.

The examples in D.8 provides further guidance in the calculation of gas permeation.

B.14 Leakage test for pressure drop and pressure rise

The leakage rate Q, in pascals cubic metres per second ($Pa \cdot m^3 \cdot s^{-1}$), for the pressure-drop test is derived from the perfect gas law relationships.

When the temperature of the gas volume V changes from temperature T_1 to T_2 during a leakage test, the leakage rate, Q, normalized to the gas reference temperature, T_0, is the following:

$$Q = \frac{VT_0}{H}\left(\frac{p_1}{T_1} - \frac{p_2}{T_2}\right) \tag{B.12}$$

Formula (B.12) applies when the laminar flow is assumed to be predominant.

Formula (B.12) is applicable to the pressure rise test when subscripts 1 and 2 are interchanged.

B.15 Correction for tracer-gas partial pressure

If a tracer gas is contained in a mixture, the measured leakage rate, Q, in pascals cubic metres per second ($Pa \cdot m^3 \cdot s^{-1}$) resulting from a procedure that measures only the tracer (such as using a mass spectrometer leak detector) shall be corrected:

$$Q = Q_{mix}\left(\frac{P_{mix}}{P_t}\right) \tag{B.13}$$

B.16 Sensitivity of leakage test procedure

In accordance with 10.3, the sensitivity of the leakage test procedure to be used shall be equal to or less than one-half the maximum permissible leakage rate for the tracer fluid.

Annex C
(informative)

Conversion tables

The coefficients of conversion for diverse units are given in Tables C.1 to C.3.

Table C.1 — Pressure units

		bar[a]	Pa $N \cdot m^{-2}$	atm (standard)	torr[b]	inH_2O	$lbf \cdot in^{-2}$	$kgf \cdot cm^{-2}$
1 bar	=	1	$1{,}00 \times 10^{5}$	$9{,}87 \times 10^{-1}$	$7{,}50 \times 10^{2}$	$4{,}01 \times 10^{2}$	$1{,}45 \times 10^{1}$	1,02
1 Pa	=	$1{,}00 \times 10^{-5}$	1	$9{,}87 \times 10^{-6}$	$7{,}50 \times 10^{-6}$	$4{,}01 \times 10^{-3}$	$1{,}45 \times 10^{-5}$	$1{,}02 \times 10^{-5}$
1 atm	=	1,01	$1{,}01 \times 10^{5}$	1	$7{,}60 \times 10^{2}$	$4{,}07 \times 10^{2}$	$1{,}47 \times 10^{1}$	1,03
1 torr	=	$1{,}33 \times 10^{-3}$	$1{,}33 \times 10^{2}$	$1{,}32 \times 10^{-3}$	1	$5{,}35 \times 10^{-1}$	$1{,}93 \times 10^{-2}$	$1{,}36 \times 10^{-3}$
1 inH_20	=	$2{,}49 \times 1\ 0^{-3}$	$2{,}49 \times 10^{2}$	$2{,}46 \times 10^{-3}$	1,87	1	$3{,}61 \times 10^{-2}$	$2{,}54 \times 10^{-3}$
1 $lbf \cdot in^{-2}$	=	$6{,}89 \times 10^{-2}$	$6{,}89 \times 10^{3}$	$6{,}80 \times 10^{-2}$	$5{,}17 \times 10^{1}$	$2{,}77 \times 10^{1}$	1	$7{,}03 \times 10^{-2}$
1 $kgf \cdot cm^{-2}$	=	$9{,}81 \times 10^{-1}$	$9{,}81 \times 10^{4}$	$9{,}68 \times 10^{-1}$	$7{,}36 \times 10^{2}$	$3{,}94 \times 10^{2}$	$1{,}42 \times 10^{1}$	1

[a] 1 $dyne \cdot cm^{-2} = 10^{-6}$ bar.

[b] 1 mmHg = 1 torr.

Table C.2 — Volumetric flow units

		$cm^3 \cdot s^{-1}$	$m^3 \cdot s^{-1}$	$m^3 \cdot min^{-1}$	$m^3 \cdot h^{-1}$	$litre \cdot s^{-1}$	$ft^3 \cdot min^{-1}$
1 $cm^3 \cdot s^{-1}$	=	1	$1{,}00 \times 10^{-6}$	$6{,}00 \times 10^{-5}$	$3{,}60 \times 10^{-3}$	$1{,}00 \times 10^{-3}$	$2{,}12 \times 10^{-3}$
1 $m^3 \cdot s^{-1}$	=	$1{,}00 \times 10^{6}$	1	$6{,}00 \times 10^{1}$	$3{,}60 \times 10^{3}$	$1{,}00 \times 10^{3}$	$2{,}12 \times 10^{3}$
1 $m^3 \cdot min^{-1}$	=	$1{,}67 \times 10^{4}$	$1{,}67 \times 10^{-2}$	1	$6{,}00 \times 10^{1}$	$1{,}67 \times 10^{1}$	$3{,}53 \times 10^{1}$
1 $m^3 \cdot h^{-1}$	=	$2{,}78 \times 10^{2}$	$2{,}78 \times 10^{-4}$	$1{,}67 \times 10^{-2}$	1	$2{,}78 \times 10^{-1}$	$5{,}89 \times 10^{-1}$
1 $l \cdot s^{-1}$	=	$1{,}00 \times 10^{3}$	$1{,}00 \times 10^{3}$	$6{,}00 \times 10^{-2}$	3,60	1	2,12
1 $ft^3 \cdot min^{-1}$	=	$4{,}72 \times 10^{2}$	$4{,}72 \times 10^{-4}$	$2{,}83 \times 10^{-2}$	1,60	$4{,}72 \times 10^{-1}$	1

Table C.3 — Flow-rate units

		$bar \cdot cm^3 \cdot s^{-1}$	$Pa \cdot m^3 \cdot s^{-1}$	$torr \cdot litre \cdot s^{-1}$	Lusec	$atm \cdot cm^3 \cdot s^{-1}$	$atm \cdot ft^3 \cdot h^{-1}$
1 $bar \cdot cm^3 \cdot s^{-1}$	=	1	$1{,}00 \times 10^{-1}$	$7{,}50 \times 10^{-1}$	$7{,}50 \times 10^{2}$	$9{,}87 \times 10^{-1}$	$1{,}25 \times 10^{-1}$
1 $Pa \cdot m^3 \cdot s^{-1}$ (watt)	=	$1{,}00 \times 10^{1}$	1	7,50	$7{,}50 \times 10^{3}$	9,87	1,25
1 $torr \cdot litre \cdot s^{-1}$	=	1,33	$1{,}33 \times 10^{-1}$	1	$1{,}00 \times 10^{3}$	1,32	$1{,}67 \times 10^{-1}$
1 Lusec	=	$1{,}33 \times 10^{-3}$	$1{,}33 \times 10^{-4}$	$1{,}00 \times 10^{-3}$	1	$1{,}32 \times 10^{-3}$	$1{,}67 \times 10^{-4}$
1 $atm \cdot cm^3 \cdot s^{-1}$	=	1,01	$1{,}01 \times 10^{-1}$	$7{,}60 \times 10^{-1}$	$7{,}60 \times 10^{2}$	1	$1{,}27 \times 10^{-1}$
1 $atm \cdot ft^3 \cdot h^{-1}$	=	7,97	$7{,}97 \times 10^{-1}$	5,98	$5{,}98 \times 10^{3}$	7,87	1

Annex D
(informative)

Worked examples

D.1 General

The examples given in this annex are hypothetical: their purpose is to illustrate the principles that are contained in this document. Their applicability to actual shipments should be subjected to review.

The symbols used in this annex are the same as those used in Clause 4, unless otherwise mentioned.

List of worked examples:

D.2 Test leakage rates for dry spent fuel flask

D.2.1 General

This example illustrates the use of the gas leakage test methodology for normal conditions of transport of spent fuel, to determine the maximum permissible volumetric leakage rate for normal conditions. The spent fuel package carries 7 PWR fuel bundles and has a cavity with a free volume of 2,32 m^3.

The following considerations are exemplary and the hypotheses taken on the inventory behaviour should not be considered as binding.

The steps and their sequence are defined in Figure 1.

D.2.2 Step 1

The spent fuel has 35 MWd/kgU burnup and has been cooled for five years prior to shipment. There are nine radionuclides of concern for release, as listed in Table D.1 with their activities for a single fuel assembly.

D.2.3 Step 2

It is assumed that 3 % of the spent fuel rods fail under normal conditions of transport. The release fractions listed in Table D.1 are based on measured release fractions from tests for each radionuclide of concern for the 3 % failed fuel rods. The release fraction for the crud is assumed to be one. For solids, only airborne fraction is considered to be releasable from the cavity and into the environment. The releasable inventory for each radionuclide is listed in Table D.1.

D.2.4 Step 3

The regulatory containment requirements are determined by calculating an equivalent A_2 for the releasable radionuclides. The equivalent A_2 is determined from Table D.1 as follows:

$$A_{2eq} = \frac{1}{\sum \frac{FC_{IN}}{A_{2i}}}$$

$$= \frac{1}{0,376} = 2,66 \text{TBq}$$

Table D.1 — Dominant radionuclides and their limits for a single PWR fuel assembly cooled for five years, under normal conditions of transport

Radionuclide	Activity TBq	Release fraction to cavity	Airborne fraction	Releasable activity TBq	Activity fraction F_i	A_2 A_{2i} TBq	F_i/A_{2i} TBq^{-1}
^{60}Co	$7,81 \times 10^{-1}$	1,0	1×10^{-1}	$7,81 \times 10^{-2}$	$9,93 \times 10^{-2}$	4×10^{-1}	$2,48 \times 10^{-1}$
^{85}Kr	$7,70 \times 10$	$3 \times 10^{-1} \times 0,03$	1,0	$6,93 \times 10^{-1}$	$8,81 \times 10^{-1}$	1×10^{1}	$8,81 \times 10^{-2}$
^{106}Ru	$2,88 \times 10^{2}$	$2 \times 10^{-5} \times 0,03$	1,0	$1,73 \times 10^{-4}$	$2,20 \times 10^{-4}$	2×10^{-1}	$1,10 \times 10^{-3}$
^{134}Cs	$9,62 \times 10^{2}$	$2 \times 10^{-4} \times 0,03$	1,0	$5,77 \times 10^{-3}$	$7,34 \times 10^{-3}$	7×10^{-1}	$1,05 \times 10^{-2}$
^{137}Cs	$1,60 \times 10^{3}$	$2 \times 10^{-4} \times 0,03$	1,0	$9,60 \times 10^{-3}$	$1,22 \times 10^{-2}$	6×10^{-1}	$2,03 \times 10^{-2}$
^{238}Pu	$5,22 \times 10$	$2 \times 10^{-5} \times 0,03$	1×10^{-1}	$3,13 \times 10^{-6}$	$4,0 \times 10^{-6}$	1×10^{-3}	$3,98 \times 10^{-3}$
^{239}Pu	6,18	$2 \times 10^{-5} \times 0,03$	1×10^{-1}	$3,71 \times 10^{-7}$	$4,7 \times 10^{-7}$	1×10^{-3}	$4,71 \times 10^{-4}$
^{240}Pu	7,62	$2 \times 10^{-5} \times 0,03$	1×10^{-1}	$4,57 \times 10^{-7}$	$5,8 \times 10^{-7}$	1×10^{-3}	$5,81 \times 10^{-4}$
^{241}Pu	$2,03 \times 10^{3}$	$2 \times 10^{-5} \times 0,03$	1×10^{-1}	$1,22 \times 10^{-4}$	$1,5 \times 10^{-4}$	6×10^{-2}	$2,58 \times 10^{-3}$
			Total	0,787			0,376

NOTE For the sake of simplicity, the factor 10 which is considered regarding the A_2 value for ^{85}Kr (see E.5.2) is not taken into account: it is conservative not to use it and does not significantly modify the results of the calculations.

The maximum permissible activity release rate, R_N, under normal conditions of transport, is therefore:

$$R_N = A_{2eq} \times 10^{-6} \times \frac{1}{3600}$$

$$= 7,39 \times 10^{-10} \text{TBq} \cdot \text{s}^{-1}$$

D.2.5 Steps 4 and 5

These steps do not apply because permeation is not considered in this example.

D.2.6 Step 6

The average activity per unit volume under normal conditions of transport, C_N, is determined from the free volume of the cavity and contents (7 PWR assemblies) to be:

$$C_N = \frac{7 \times RI_{TN}}{V_N}$$

$$= \frac{7 \times 0{,}787}{2{,}32} = 2{,}37 \text{TBq} \cdot \text{m}^{-3}$$

where V_N = 2,32 m^3.

D.2.7 Step 7

The maximum permissible volumetric leakage rate L_N, is therefore:

$$L_N = \frac{R_N}{C_N} = 3{,}11 \times 10^{-10} \text{m}^3 \cdot \text{s}^{-1}$$

D.3 Test leakage rates for wet spent fuel flask

D.3.1 General

In this example, a water-cooled spent fuel package is considered and the maximum permissible release rates that are required are determined. The example includes calculations to determine the standardized leakage rate (SLR) for the required leakage test.

Spent fuels are transported in a large package. Prior to shipment, the package shall be tested for leakage to ensure that the radioactive release is not greater than the regulatory limits, not only under normal conditions of transport but also under accident conditions of transport.

The steps and their sequence are defined in Figure 1.

D.3.2 Steps 1 and 6

The package cavity will contain the spent fuel and be filled with water from the storage pool in which radioactive materials have been dissolved.

This package is assumed to have no fuel failures, not only under normal conditions of transport but also under accident conditions of transport.

Any radioactive material leakage during transportation is assumed to have the following composition, which is based on that of the fission products in the spent fuel.

Radionuclide	Activity per unit volume C_i TBq·m^{-3}	A_{2i} TBq	C_i/A_{2i}
Sr-90	1,39 × 10^{-3}	0,3	4,63 × 10^{-3}
Ru-106	4,67 × 10^{-3}	0,2	2,34 × 10^{-3}
Cs-134	1,81 × 10^{-3}	0,7	2,59 × 10^{-3}
Cs-137	1,96 × 10^{-3}	0,6	3,25 × 10^{-3}
Ce-144	7,85 × 10^{-3}	0,2	3,93 × 10^{-3}
Total	1,77 × 10^{-2}	—	7,31 × 10^{-2}

D.3.3 Step 2

Here, the release fractions FE_{iA} and FE_{iN} are assumed to be 1,0. The release fractions FC_{iA} and FC_{iN} have been taken into account in the determination of the activities per unit volume that are given in Step 1.

D.3.4 Step 3

The A_2 equivalent, A_{2eq}, of the package cavity water is found as follows:

$$A_{2eq} = \frac{\sum C_i}{\sum (C_i / A_{2i})}$$

For the radionuclides listed in Step 1:

$$A_{2eq} = \frac{1{,}77 \times 10^{-2}}{7{,}31 \times 10^{-2}}$$

$$= 0{,}24 \text{ TBq}$$

Accordingly, the values of R_N under normal conditions of transport and of R_A under accident conditions of transport are as follows:

$$R_N = \frac{A_{2eq} \times 10^{-6}}{3\,600}$$

$$= 6{,}7 \times 10^{-11} \text{ TBq} \cdot \text{s}^{-1}$$

$$R_A = \frac{A_{2eq}}{7 \times 24 \times 3\,600}$$

$$= 4{,}0 \times 10^{-7} \text{ TBq} \cdot \text{s}^{-1}$$

D.3.5 Step 6

Proceed vertically downward under "Liquid" in Figure 1. The activity per unit volume is that given in Step 1 above.

$$C_A = C_N = 1{,}77 \times 10^{-2} \text{ TBq} \cdot \text{m}^{-3}$$

D.3.6 Step 7

$$L_N = \frac{R_N}{C_N}$$

$$L_N = \frac{6{,}7 \times 10^{-11}}{1{,}77 \times 10^{-2}}$$

$$= 3{,}80 \times 10^{-9} \text{ m}^3 \cdot \text{s}^{-1}$$

$$L_A = \frac{R_A}{C_A}$$

$$L_A = \frac{4{,}0 \times 10^{-7}}{1{,}77 \times 10^{-2}}$$

$$= 2{,}26 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$$

D.3.7 Step 8

See B.6 to calculate the leak diameter:

$$L = \frac{\pi}{128} \times \frac{D^4}{\mu \cdot a} \left(p_u - p_d\right)$$

The conditions of temperature and pressure and the physical properties of the package under normal and accident conditions of transport are as follows:

Conditions of temperatures and pressure and the physical properties	Normal conditions	Accident conditions
Temperature, T (K)	380	480
Inside pressure of the package, p_u (Pa)	$4{,}32 \times 10^5$	$2{,}99 \times 10^6$
Outside pressure of the package, p_d (Pa)	$2{,}50 \times 10^4$	$1{,}013 \times 10^5$
Viscosity of the water, μ (Pa·s)	$2{,}66 \times 10^{-4}$	$1{,}27 \times 10^{-4}$
Leakage hole length, a (m)	$1{,}2 \times 10^{-2}$	$1{,}2 \times 10^{-2}$

For:

$L_N = 3{,}80 \times 10^{-9}$ m^3·s^{-1}

$D_N = 3{,}32 \times 10^{-5}$ m

For:

$L_A = 2{,}26 \times 10^{-5}$ m^3·s^{-1}

$D_A = 1{,}48 \times 10^{-4}$ m

D.3.8 Step 9

D_N is smaller than D_A; therefore, Q is determined from D_N. Use Formula (B.1) to determine Q_{SLR}. For air, determine Q_V:

$p_u = 1{,}013 \times 10^5$ Pa

$p_d = 0{,}0$ Pa

$\mu = 1{,}85 \times 10^{-5}$ Pa·s

$a = 1{,}2 \times 10^{-2}$ m

$D_N = 3{,}3 \times 10^{-5}$ m

Substituting:

$Q_V = 6{,}9 \times 10^{-4}$ Pa·m^3·s^{-1}

For air, determine Q_m:

$R = 8{,}31$ J·mol^{-1}·K^{-1}

T = 298 K

M_{air} = 0,029 kg·mol^{-1}

p_u = 1,013 × 10^5 Pa

p_d = 0,0 Pa

a = 1,2 × 10^{-2} m

D_N = 3,8 × 10^{-5} m

Substituting:

Q_m = 2,2 × 10^{-5} Pa·m^3·s^{-1}

Therefore:

Q_{SLR} = 7,3 × 10^{-4} Pa·m^3·s^{-1} SLR

D.3.9 Step 10

On the basis of the result of Step 9, test leakage rates at respective stages, Q_{TD}, Q_{TF}, Q_{TS} and Q_{TP} are set so as to meet the following standardized conditions:

Q = 7,3 × 10^{-4} Pa·m^3·s^{-1} SLR

D.4 Pressure rise test on closure fitted with double O-ring seals

D.4.1 General

The purpose of this example is to illustrate how the double O-ring seal concept can provide a simple go/no-go preshipment leakage test method. The advantage of the double O-ring seal concept is that the gas volume under test can be small. This minimizes the test duration and eliminates the need for highly sensitive detection equipment. If a test procedure for gas pressure rise is used, rather than a test procedure for gas pressure drop, the effects of test gas temperature changes can be minimized. Also, the overall simplicity of the test procedure means that little training is required to qualify the leakage test operator.

A package is closed using a flanged connection. This connection incorporates two elastomeric O-rings with a leakage test port between the two O-rings. For this example, assume that the required sensitivity of the preshipment leakage test is 10^{-4} Pa·m^3·s^{-1} SLR and that the gas volume under test is 1,5 × 10^{-5} m^3.

The steps and their sequence are defined in Figure 1.

D.4.2 Step 11

Select the test procedure for gas pressure rise from Table A.1.

Test leakage rate: $Q_{TS} = 10^{-4}$ Pa·m³·s⁻¹

Test volume: $1{,}5 \times 10^{-5}$ m³

Specify initial pressure: 25 000 Pa

Specify maximum pressure rise: 10 000 Pa

Specify test duration: 1 800 s

It is necessary to use Formula (B.12) to check that the specified conditions will satisfy the required test leakage rate for the given test volume.

Substitute:

$V = 1{,}5 \times 10^{-5}$ m³

$H = 1\,800$ s

$p_2 = 25\,000$ Pa

$p_1 = 35\,000$ Pa

Assume: $T_0 = 298$ K

Assume: $T_1 = T_2 = T_0$

$$Q = \frac{1{,}5 \times 10^{-5}}{1\,800}(35\,000 - 25\,000)$$

$$= 8{,}3 \times 10^{-5}\ \text{Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$$

The standardized leakage rate is determined using Formula (B.2).

For the reference conditions:

$p_{uSLR} = 1{,}013 \times 10^5$ Pa

$p_{dSLR} = 0{,}0$ Pa

For the test conditions

$p_u = 1{,}013 \times 10^5$ Pa

$p_d = 30\,000$ Pa (average value between the values at the beginning and at the end of the test)

The viscosity μ of the gas is the same for the reference conditions (μ_{SLR}) and the test conditions (μ) as the temperature is the same.

$$Q_{SLR} = Q\frac{\mu}{\mu_{SLR}} \times \frac{\left(p_{uSLR}^2 - p_{dSLR}^2\right)}{p_u^2 - p_d^2}$$

$$Q_{SLR} = 9{,}1 \times 10^{-5}\ \text{Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}\ \text{SLR}$$

This result shows that the specified test conditions satisfy the required test leakage rate.

In order to illustrate the effect of test gas temperature changes, assume that:

$T_0 = T_2 = 298$ K

$T_1 = 293$ K

$$Q = \frac{1{,}5\times 10^{-5}\times 298}{1\,800}\left(\frac{35\,000}{293}-\frac{25\,000}{298}\right)$$

$$= 8{,}8\times 10^{-5}\,\mathrm{Pa\cdot m^3\cdot s^{-1}}$$

The standardized leakage rate is determined using Formula (B.2).

$Q_{SLR} = 9{,}7 \times 10^{-5}$ Pa·m^3·s^{-1} SLR

This result shows that gas temperature changes during the test will have little effect on test sensitivity.

Caution: this result is not always true, see worked example in D.6. If the gas test volume were $1{,}5 \times 10^{-3}$ m^3 rather than $1{,}5 \times 10^{-5}$ m^3, either the test duration shall be increased to 50 h or the permissible pressure rise shall be decreased to 100 Pa in order to maintain the same test procedure sensitivity. However, if the permissible pressure rise is to be decreased, any temperature changes of the test gas may be significant, as indicated below.

$$Q = \frac{1{,}5 \times 10^{-3} \times 298}{1\,800}\left(\frac{25\,100}{298}-\frac{25\,000}{298}\right)$$

$$= 8{,}3\times 10^{-5}\,\mathrm{Pa\cdot m^3\cdot s^{-1}}$$

The standardized leakage rate is determined using Formula (B.2).

$Q_{SLR} = 8{,}9 \times 10^{-5}$ Pa·m^3·s^{-1} SLR

But for $T_0 = T_2 = 298$ K and $T_1 = 293$ K:

$$Q = \frac{1{,}5 \times 10^{-3} \times 298}{1\,800}\left(\frac{25\,100}{293}-\frac{25\,000}{298}\right)$$

$$= 4{,}4\times 10^{-4}\,\mathrm{Pa\cdot m^3\cdot s^{-1}}$$

The standardized leakage rate is determined using Formula (B.2).

$Q_{SLR} = 4{,}7 \times 10^{-4}$ Pa·m^3·s^{-1} SLR

D.5 Pressure drop test on closure fitted with double O-ring seals

D.5.1 General

This example illustrates the use of the pressure drop method for leakage testing of a containment vessel closure fitted with a double O-ring seal having a relatively small interspace volume.

The example also indicates the sensitivity of the pressure drop method to temperature changes.

The test method is simple and can use any pressure indicator, but it benefits from the use of pressure transducers and associated electronics which are more sensitive than other pressure indicators and give a digital read-out of pressure. Such transducers can also be incorporated in automated (computerized) data acquisition equipment which can be programmed to calculate leakage rates including compensation for temperature effects and calculation of standardized leakage rate.

This example is based on leakage testing of the containment vessel of an actual package which has a flange-type lid closure fitted with a double O-ring seal (⌀200 mm) and a pressure sensor capable of measuring pressure with an accuracy of 0,1 %.

The pass criterion for the test is that the leakage rate should be less than $1{,}0 \times 10^{-5}$ Pa·m^3·s^{-1} SLR.

D.5.2 Test data

Interspace volume: $V = 5{,}0 \times 10^{-6}$ m^3

Ambient pressure: $p_a = 1{,}013 \times 10^5$ Pa

Internal pressure of containment vessel: $p_a = 1{,}013 \times 10^5$ Pa

Initial pressure: $p_1 = 2{,}0 \times 10^5$ Pa

Test duration: $H = 10$ min

Temperature of containment vessel and test gas: $T_1 = 36$ °C (309 K, assumed to be constant during the test)

NOTE 3 In this example, the cavity of the containment vessel is at ambient pressure and therefore the downstream pressure is ambient pressure.

D.5.3 Test results

Pressure at end of test: $p_2 = 1{,}996 \times 10^5$ Pa

Pressure drop: $p_1 - p_2 = 0{,}004 \times 10^5$ Pa

D.5.4 Determination of leakage rate

The leakage rate is determined using Formula (B.12).

$$Q = 3{,}3 \times 10^{-6} \text{ Pa·m}^3\text{·s}^{-1}$$

D.5.5 Determination of standardized leakage rate

The standardized leakage rate (SLR) is determined using Formula (B.2) which is applicable to laminar flow leakage (which is applicable in most practical situations).

The subscript y refers to the test conditions:

$p_{uy} = 1{,}998 \times 10^5$ Pa (mean)

$p_{dy} = 1{,}013 \times 10^5$ Pa

$\mu_y = 1{,}89 \times 10^{-5}$ Pa·s (for air at 309 K)

The subscript x refers to the SLR conditions:

$p_{ux} = 1{,}013 \times 10^5$ Pa

$p_{dx} = 0{,}0$ Pa

μ_X = 1,85 × 10^{-5} Pa·s (for air at 298 K)

The standardized leakage rate for the above test is determined using Formula (B.2).

Q_{SLR} = 1,1 × 10^{-6} Pa·m^3·s^{-1} SLR

This leakage rate is lower than the pass criteria by an order of magnitude 10.

D.5.6 Effect of temperature change

The effect of temperature change can be seen by repeating the above calculations, assuming that there is no leakage and that the pressure of the air, in the interspace volume of the double O-ring seal, changes solely due to an undetected temperature drop of 0,5 °C (from 309 K) which would cause a pressure change from p_1 to p_2 = 308,5/309 × p_1 = 1,996 76 × 10^5 Pa (a pressure change of 324 Pa).

For the calculation of the leakage rate, the temperature of the containment vessel and test gas T_1 = 36 °C (309 K) is assumed to be constant during the test (i.e. T_2 = 309 K).

Q_{SLR} = 0,95 × 10^{-6} Pa·m^3·s^{-1} SLR

From this, it is seen that a 0,5 °C change in the temperature of the air in the interspace of the double O-ring seal would indicate an apparent leakage of 0,95 × 10^{-6} Pa·m^3·s^{-1} SLR. This "apparent" leakage rate is insignificant for this example, for which the pass criteria is 1,0 × 10^{-5} Pa·m^3·s^{-1} SLR. It should be noted that, for a test carried out over a short period of time, it is likely that the temperature will change by less than 0,5 °C because of the thermal inertia of the containment vessel: this applies even if the ambient temperature were to change by a few degrees.

D.6 Comparison between pressure rise and pressure drop tests

The purpose of this example is to illustrate the advantage of the gas pressure rise test compared to the gas pressure drop test when uncertainties in measurement are taken into account. The analysis is based on the use of Formula (B.12).

$$Q = \frac{VT_0}{H}\left(\frac{p_1}{T_1} - \frac{p_2}{T_2}\right) \text{Pa·m}^3\text{·s}^{-1}$$

Conditions for the gas pressure drop test:

V = 1 m^3

H = 1,728 × 10^5 s

T_0 = 298 K

p_1 = 1,0 × 10^6 Pa E_p = ±5 Pa

p_2 = 0,999 5 × 10^6 Pa E_p = ±5 Pa

T_1 = 293 K E_T = ±0,1 K

T_2 = 293 K E_T = ±0,1 K

E_P and E_T represent the uncertainty measurements for pressure and temperature, respectively (E_P represents an accuracy of 0,000 5 %).

Conditions for the gas pressure rise test:

$V = 1\ m^3$

$H = 1{,}728 \times 10^5\ s$

$T_0 = 298\ K$

$p_1 = 10\ Pa$ $\quad E_p = \pm 5\ Pa$

$p_2 = 510\ Pa$ $\quad E_p = \pm 5\ Pa$

$T_1 = 293\ K$ $\quad E_T = \pm 0{,}1\ K$

$T_2 = 293\ K$ $\quad E_T = \pm 0{,}1\ K$

The uncertainty E_P represents an accuracy of 1 %.

For the purposes of this example, V, T_0 and H are assumed to be constant for either the pressure drop or pressure rise tests. Formula (B.12) can then be simplified to:

$$Q = C\left(\frac{p_2}{T_2} - \frac{p_1}{T_1}\right)$$

$$C = \frac{VT_0}{H}$$

First, solve for Q without considering the measurement uncertainty. Substituting:

$$Q = 1{,}706 \times C$$

Next, rewrite the equation to include the uncertainty measurements:

$$Q_D = C\left(\frac{p_1 + E_p}{T_1 - E_T} - \frac{p_2 - E_p}{T_2 + E_T}\right)$$

where Q_D refers to the pressure drop test.

Also, by interchanging the subscripts 1 and 2:

$$Q_R = C\left(\frac{p_2 + E_p}{T_2 - E_T} - \frac{p_1 - E_p}{T_1 + E_T}\right)$$

Where Q_R refers to the pressure drop test.

Substituting the given test conditions:

$$Q_D = 4{,}070 \times C$$

$$Q_R = -1{,}741 \times C$$

The overall percentage uncertainty due to E_p and E_T would be as follows.

For the pressure drop test:

$$E_D = \left|(Q - Q_D)/Q\right|$$

approximately 140 %.

For the pressure rise test:

$$E_R = \left|(Q - Q_R)/Q\right|$$

approximately 2 %.

It can be concluded that, although the pressure drop test is carried out with a pressure gauge with a very high accuracy (0,000 5 %), the pressure rise test gives a better result.

D.7 Determination of an unknown test volume for the pressure rise or pressure drop test

D.7.1 General

The purpose of this example is to illustrate how the test equipment that is used for the pressure rise or pressure drop test can be used to determine the magnitude of an unknown test volume. The principle is based on Boyle's Law for gases. This example is applicable for constant temperature conditions only.

Prepare the measurement as shown in Figure D.1.

D.7.2 Procedure

Open valve 1 and determine pressure p_0.

Close valve 1 and open valve 2.

Evacuate volume 1 or pressurize it by injecting gas.

Close valve 2 and determine pressure p_1.

Open valve 1 and determine pressure p_2.

Determine V_2 by using the following equations.

$$p \times V = \text{constant}$$

$$(p_1 - p_0) \times V_1 = (p_2 - p_0) \times (V_1 + V_2)$$

$$(p_1 - p_0) \times V_1 = (p_2 - p_0) \times V_1 + (p_2 - p_0) \times V_2$$

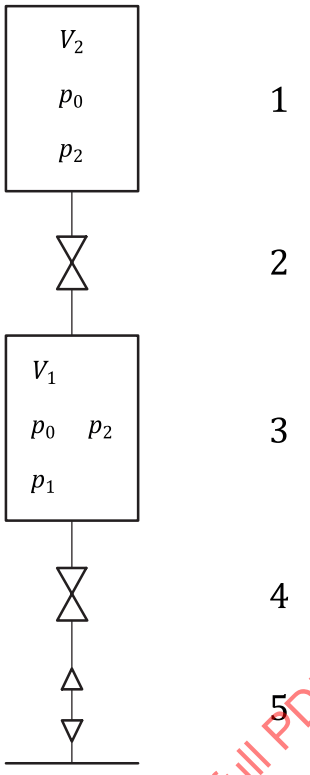
$$(p_1 - p_0) \times V_1 - (p_2 - p_0) \times V_1 = (p_2 - p_0) \times V_2$$

$$V_1 \times [(p_1 - p_0) - (p_2 - p_0)] = (p_2 - p_0) \times V_2$$

$$V_1 \times (p_1 - p_0 - p_2 + p_0) = (p_2 - p_0) \times V_2$$

$$V_1 \times (p_1 - p_2) = (p_2 - p_0) \times V_2$$

$$V_2 = \frac{V_1 \times (p_1 - p_2)}{(p_2 - p_0)}$$



Key

1 unknown volume
2 valve 1
3 known volume
4 valve 2
5 gas in/out
V_1 known volume
V_2 volume to be determined
p_0 initial pressure in V_1 and V_2 (valve 1 open, valve 2 closed)
p_1 pressure in V_1 after V_1 has been pressurized or evacuated (valves 1 and 2 closed)
p_2 final pressure in V_1 and V_2 (valve 1 open, valve 2 closed)

Figure D.1 — Diagram for the calculation of an unknown test volume

D.8 Gas permeation

D.8.1 General

These examples illustrate the analytical methods for determining gas permeation rates through elastomeric materials. Permeation implies solubility of a gas in a permeable material and diffusion of this gas through this material.

The coefficient of permeation, P, in square metres per second ($m^2 \cdot s^{-1}$), is determined from the following equation:

$$P = S \times DC$$

where

S is the coefficient of solubility, in cubic metres of gas per cubic metre of material, at reference pressure and temperature;

DC is the diffusion coefficient, in square metres per second ($m^2 \cdot s^{-1}$).

Any steady-state permeation rate of a gas, Q_P, in pascals cubic metres per second ($Pa \cdot m^3 \cdot s^{-1}$), through an elastomeric material can be described by the following equation:

$$Q_P = P \times \frac{A}{l} \times \Delta p$$

where

P is the coefficient of permeation, in square metres per second ($m^2 \cdot s^{-1}$);

A is the area of the permeable material normal to the gas flow, in square metres (m^2);

l is the thickness of the permeable material, in metres;

Δp is the partial pressure difference of the gas across l, in pascals.

For O-rings, because $A = L \times l$ (where L is the O-ring length and l is the cord diameter) and taking into account two counter-acting simplifications:

a) compression of the O-ring reduces the area and extends the thickness of the permeable material;

b) the non-square cross-section reduces the effective thickness of the permeable material, this equation approximately can be reduced to:

$$Q_P = P \times L \times \Delta p$$

Permeation and diffusion coefficients depend on thermal activation energies described by the following equations:

$$P = C_p \times e^{-\frac{E_p}{RT}}$$

$$DC = C_D \times e^{-\frac{E_D}{RT}}$$

where

C_p and C_D are constant factors, in square metres per second ($m^2 \cdot s^{-1}$);

E_p and E_D are thermal activation energies for permeation and diffusion, respectively in joules per mole ($J \cdot mol^{-1}$);

R is the universal gas constant, in joules per mole per kelvin ($J \cdot mol^{-1} \cdot K^{-1}$);

T is the absolute temperature of the permeable material, in kelvins.

D.8.2 Example 1: activity release by permeation (Krypton)

A significant radioactive fission gas in irradiated fuel which could be released from defective fuel pins into the flask void and then permeate through elastomeric seals to the environment is ^{85}Kr.

Typical examples of permeation coefficients for krypton (see Reference [5]) are:

	P (23 °C = 296 K) $m^2 \cdot s^{-1}$	E_p $kJ \cdot mol^{-1}$	$P(T)$ $m^2 \cdot s^{-1}$
Silicone rubber	$9,5 \times 10^{-10}$	8,8	$3,4 \times 10^{-8} \times e^{-\frac{1\,060}{T}}$
Fluorocarbon rubber	$5,0 \times 10^{-13}$	55,7	$3,4 \times 10^{-3} \times e^{-\frac{6\,700}{T}}$

NOTE The effect of ageing of elastomer on the permeation characteristics needs to be taken into account.

The partial pressure of ^{85}Kr in the flask void is estimated to become 100 Pa at the gas temperature 373 K (100 °C).

A silicone rubber O-ring at a temperature of 373 K (100 °C) with dimensions 1 000 mm × 10 mm and therefore a sealing length of $L = \pi\,(1\,000 + 10)$ mm = 3,2 m at 100 °C would allow a steady-state krypton permeation rate of:

$$Q_P = P \times L \times \Delta p$$

$$= 2,0 \times 10^{-9}\ m^2 \cdot s^{-1} \times 3,2\ m \times 100\ Pa$$

$$= 6,4 \times 10^{-7}\ Pa \cdot m^3 \cdot s^{-1}\ (\text{at } 373\ K)$$

The activity per mole of ^{85}Kr is $1,234 \times 10^{15}\ Bq \cdot mol^{-1}$. Using the ideal gas law, at 273 K and $1,013 \times 10^5$ Pa, the activity per unit volume of ^{85}Kr is $5,51 \times 10^{16}\ Bq \cdot m^{-3}$.

At 373 K and $1,013 \times 10^5$ Pa, it is: $4,03 \times 10^{16}\ Bq \cdot m^{-3}$ or $3,98 \times 10^{11}\ Bq \cdot m^{-3} \cdot Pa^{-1}$.

In this example, ^{85}Kr is considered as the dominant part of a mixture with other radioactive fission gases. Consequently, under normal conditions of transport, an activity release limit of $10^{-6} \times 10\ A_2 \times h^{-1}$ or $2,8 \times 10^4\ Bq \cdot s^{-1}$ shall be applied (see paragraph 659 in the 2012 Edition of the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material*).

The krypton permeation rate is therefore:

$$Q_P = 6,4 \times 10^{-7}\ Pa \cdot m^3 \cdot s^{-1} \times 3,98 \times 10^{11}\ Bq \cdot m^{-3} \cdot Pa^{-1}$$

$$= 2,55 \times 10^5\ Bq \cdot s^{-1} > 10^{-6} \times 10\ A_2 \times h^{-1}$$

which is not acceptable.

Changing to a fluorocarbon rubber (e.g. Viton) with the same dimensions and with P (373 K) = $5,4 \times 10^{-11}\ m^2 \cdot s^{-1}$ (see data above) leads to a krypton permeation rate of:

$$Q_P = 5,4 \times 10^{-11}\ m^2 \cdot s^{-1} \times 3,2\ m \times 100\ Pa \times 3,98 \times 10^{11}\ Bq \cdot m^{-3} \cdot Pa^{-1}$$

$$= 6,88 \times 10^3\ Bq \cdot s^{-1} < 10^{-6} \times 10\ A_2 \times h^{-1}$$

which is acceptable.

D.8.3 Example 2: Test gas permeation (helium)

Typical examples of diffusion and permeation coefficients for helium (see Reference [5] in the Bibliography) are:

	$DC(T)$ $m^2 \cdot s^{-1}$	$P(T)$ $m^2 \cdot s^{-1}$
Silicone rubber	$3{,}3\times10^{-7}\times e^{-\frac{1\,160}{T}}$	$1{,}9\times10^{-7}\times e^{-\frac{1\,965}{T}}$
Fluorocarbon rubber	$6{,}6\times10^{-6}\times e^{-\frac{2\,770}{T}}$	$3{,}5\times10^{-6}\times e^{-\frac{3\,625}{T}}$

Firstly, considering steady-state permeation through an O-ring of which the dimensions are again 1 000 mm × 10 mm, but with ΔP = 1,013 × 10^5 Pa.

Q_P (He, silicone rubber, 23 °C) = 2,5 × 10^{-10} $m^2 \cdot s^{-1}$ × 3,2 m × 10^5 Pa = 8,0 × 10^{-5} $Pa \cdot m^3 \cdot s^{-1}$

Q_P (He, fluorocarbon rubber, 23 °C) = 1,7 × 10^{-11} $m^2 \cdot s^{-1}$ × 3,2 m × 10^5 Pa = 5,4 × 10^{-6} $Pa \cdot m^3 \cdot s^{-1}$

Q_P (He, fluorocarbon rubber, 107 °C) = 2,5 × 10^{-10} $m^2 \cdot s^{-1}$ × 3,2 m × 10^5 Pa = 8,0 × 10^{-5} $Pa \cdot m^3 \cdot s^{-1}$

All these calculations give only rough orders of magnitude but may prove to be helpful for any estimates. For any exact design assessment, measured values of P for each gas through each individual elastomer compound for the full range of temperatures of interest shall be available.

In the case of helium-leakage testing, with a time of application of pressure t = 0, a certain helium pressure is applied to one side of a test region and, if there are no leak paths, no helium would be detected at the other side. In the case of any permeable barriers, such as elastomeric O-rings, the permeation rate rises with time, starting with infinitely small values, according to the equation:

$$Q'_P(t) = Q_P \times \frac{2l}{\sqrt{\pi DCt}} \times e^{-\frac{l^2}{4DCt}}$$

where

t is the time after application of helium pressure, in seconds;

Q_P is the steady-state permeation rate, in pascals cubic metres per second ($Pa \cdot m^3 \cdot s^{-1}$);

l is the thickness of the barrier (equal to the O-ring cord diameter), in metres;

DC is the diffusion coefficient, in square metres per second ($m^2 \cdot s^{-1}$).

This equation is valid up to $DC \times t \times l^{-2} \leq 0{,}3$ when $Q'_P(t)$ approximately 0,9 × Q_P and then $Q'_P(t)$ approaches Q_P continuously with time.

Using the O-rings mentioned above and performing a helium leakage test at ambient temperature, we can make the following estimates:

With DC (He, silicone rubber, 23 °C) = 6,6 × 10^{-9} $m^2 \cdot s^{-1}$, l = 10^{-2} m and after t = 15 min:

$DC \times t \times l^{-2}$ approximately 0,06

Q'_P (silicone, 15 min) approximately 0,07 Q_P (silicone)

approximately $5{,}5 \times 10^{-6}$ Pa·m³·s^{-1}

that is, about the steady-state helium permeation rate through a fluorocarbon O-ring with the same dimensions.

With DC (He, fluorocarbon rubber, 23 °C) = $5{,}7 \times 10^{-10}$ m²·s^{-1}, $l = 10^{-2}$ m and after t = 1,5 h:

Q'_P (fluorocarbon, 1,5 h) approximately 0,002 Q_P (fluorocarbon)

approximately 1×10^{-8} Pa·m³·s^{-1}

which is the level of technical leaktightness (See Clause 8 in Annex E).

This typical example shows that helium leakage test results will not be affected by overlapping permeation effects if the term $DC \times t \times l^{-2}$ is kept small, using elastomeric materials with low diffusion coefficients and thick seals, and by performing speedy measurements. For practical helium-leakage testing, precautions are mainly necessary if silicone O-rings have been installed. Permeation and diffusion rates of helium through other commonly used elastomeric seal materials like ethylene-propylene (EPDM), polychloroprene or nitrile rubbers are similar to those for fluorocarbon rubber.

For further information on permeation, see Reference [5].

D.9 Aerosol leakage

The purpose of this example is to compare the release of particulate solids in a gas with test-gas leakage rates.

The regulations state that a package subjected to specific tests shall restrict the loss of radioactive materials to a value of $10^{-6} \times A_2$ per hour for normal conditions of transport.

The A_2 value for ^{240}Pu is 1×10^{-3} TBq, so its release from any container shall be less than 1×10^{-9} TBq per hour. The activity per unit mass of ^{240}Pu is about 8,4 TBq·kg^{-1}, which is equivalent to 7,4 TBq·kg^{-1} of PuO_2 (atomic mass of oxygen is 16). So the mass leakage rate of PuO_2 shall be less than about $1{,}35 \times 10^{-10}$ kg per hour.

In this example, let a container have a suspended aerosol concentration of 10^8 particles per cubic metre of $^{240}PuO_2$ with a mass median diameter of 2×10^{-6} m and a density of $1{,}15 \times 10^4$ kg.m^{-3}. The average mass of each particle, assuming they are non-porous spheres, is about $4{,}8 \times 10^{-14}$ kg.

D.9.1 Case No 1

If there is a single breach of the seal having a leakage rate of 10^{-6} Pa·m³·s^{-1} SLR with a driving overpressure of 10^5 Pa, and there is negligible attenuation of aerosol within the leakage path, then the volumetric leakage rate will be 10^{-11} m³·s^{-1} which, assuming unbiased sampling of the aerosol in the leak, corresponds to about 4 particles per hour or a mass leakage rate of 2×10^{-13} kg·h^{-1} (i.e. three orders of magnitude below the limit allowed).

D.9.2 Case No 2

If the above conditions and assumptions are retained, but for a single breach of the seal with a leakage rate 10^{-3} Pa·m³·s^{-1} SLR, then the volumetric leakage rate will be 10^{-8} m³·s^{-1} or about 3 600 particles per hour. This corresponds to a mass leakage rate of 2×10^{-10} kg·h^{-1} (i.e. approximately twice the limit allowed).

However, if aerosol particles with a mass median diameter of 7×10^{-6} m are generated within the container (the same number concentration as before), the mass of each particle, assuming they are non-porous spheres, will be about $2{,}1 \times 10^{-12}$ kg.

Applying this criterion to Case No. 1 above, with a leakage rate of 10^{-6} Pa·m^3·s^{-1} SLR, the expected aerosol leakage rate of 4 particles per hour is equivalent to a mass leakage rate of about 8×10^{-12} kg·h^{-1} (i.e. one order of magnitude below the limit allowed).

Applying the same criterion to Case No. 2, with a leakage rate of 10^{-3} Pa·m^3·s^{-1} SLR, the expected aerosol leakage rate of 3 600 particles per hour is equivalent to a mass leakage rate of about 8×10^{-9} kg·h^{-1} (i.e. two orders of magnitude over the limit allowed).

D.10 Correlation between gas and liquid leakage rates

D.10.1 General

The purpose of this example is to show that the determination of the inventory of radioactive contents may require careful consideration. The example also shows how the standardized leakage rate (SLR) can help to select leakage test procedures.

The containment system is a vessel that contains 200 ml of solution containing 555 TBq of molybdenum-99 (half-life 66 h) and 35 TBq of iodine-132 (half-life 2,3 h). Molybdenum-99 decays to technitium-99m (half-life 6,0 h). Determine the standardized leakage rate under accident conditions of transport.

The steps and their sequence are defined in Figure 1.

D.10.2 Step 1

Figure D.2 shows the inventory of the radionuclides as a function of time. This information is significant because the radionuclides have relatively short half-life values.

D.10.3 Step 2

Assume that the release fractions, FC_i and FE_i, have values of 1,0.

D.10.4 Step 3

In this example, consider that the time is equal to 5 h.

The activities are the following:

Mo-99:	527 TBq	A_2 = 0,6 TBq
Tc-99 m:	207 TBq	A_2 = 4,0 TBq
I-132:	8 TBq	A_2 = 0,4 TBq
	742 TBq	

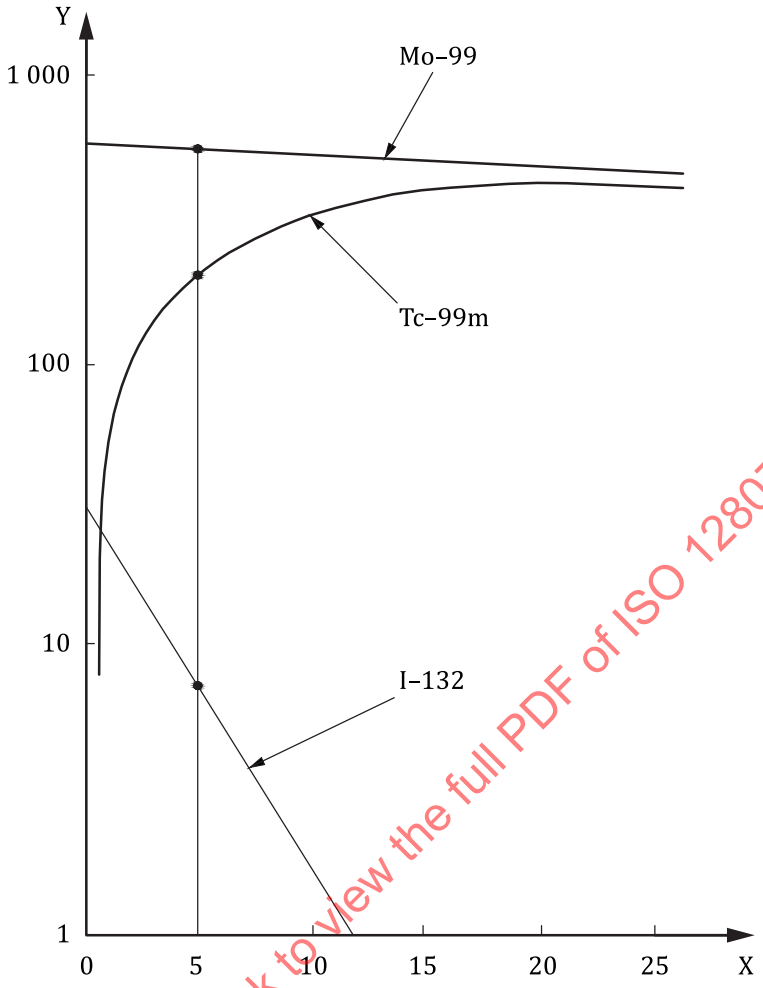
The equivalent value of A_2 for the mixture is:

$$A_{2\text{eq}} = \frac{\sum A_i}{\sum \left(A_i / A_{2i} \right)}$$

$$= \frac{527 + 207 + 8}{527/0{,}6 + 207/4{,}0 + 8/0{,}4}$$

$$= 0{,}781 \text{ Tbq}$$

$R_A = A_{2\text{eq}}$ (in one week) = $1{,}29 \times 10^{-6}$ TBq·s^{-1}



Key

X time, h

Y activity, TBq

Figure D.2 — Time activity histories for Mo-99, Tc-99 m and I-132

D.10.5 Step 6

Because the total activity of the contents is 742 TBq and the volume is 200 ml, or $2{,}0 \times 10^{-4}$ m^3:

$C_A = 3{,}71 \times 10^6$ TBq·m^{-3}

D.10.6 Step 7

$L_A = 3{,}48 \times 10^{-13}$ $m^3 \cdot s^{-1}$

D.10.7 Step 8

To determine an equivalent air-flow rate, see B.8 to determine the hole diameter D_A.

Assume:

$p_u = 2{,}026 \times 10^5$ Pa

$p_d = 1{,}013 \times 10^5$ Pa

$a = 5 \times 10^{-3}$ m

$\mu = 5 \times 10^{-4}$ Pa·s

$L_A = 3{,}48 \times 10^{-13}$ m^3·s^{-1}

Thus,

$D_A = 4{,}33 \times 10^{-6}$ m

D.10.8 Step 9

Determine the standardized leakage rate from Formula (B.1).

Assume:

$D_A = 4{,}33 \times 10^{-6}$ m

$p_u = 1{,}013 \times 10^5$ Pa (SLR conditions for air)

$p_d = 0{,}0$ Pa absolute (SLR conditions for air)

$a = 5 \times 10^{-3}$ m

$\mu = 1{,}85 \times 10^{-5}$ Pa·s (for air at 298K)

$T = 298$ K (SLR conditions for air)

$M = 0{,}029$ kg·mol^{-1}

Then

$$Q_{A(SLR)} = 4{,}8 \times 10^{-7} + 2{,}0 \times 10^{-7}$$

(viscous) (molecular)

$$= 6{,}8 \times 10^{-7} \text{ Pa·m}^3\text{·s}^{-1} \text{ SLR}$$

NOTE This result indicates that a transition flow regime exists, i.e. a combination of viscous and molecular flow modes.

D.10.9 Step 10

If the gas leakage test methodology is used, the result from Step 9 indicates that a quantitative helium-leakage test procedure would be suitable, see Table A.1. This approach would be acceptable to demonstrate design verification.

However, to demonstrate preshipment verification, the blockage of any leaks by the liquid contents should be considered. There are two reasons for this. Firstly, it is impractical to conduct a helium-leakage test on the containment system after it has been filled with the liquid radioactive contents. Secondly, it can be demonstrated (this will not be done in this example) that the viscosity of the liquid contents will block a single leak for which Q has a value of about 10^{-6} Pa·m^3·s^{-1} SLR. Therefore, for

preshipment verification, it would be possible and practical to complete a gas pressure rise test on the containment system closure.

D.11 Correlation between leakage rates for different gases

D.11.1 General

The purpose of this example is to illustrate how the leakage rates of different gases, including mixtures of gases, can be correlated.

The containment system is a vessel that contains $1{,}85 \times 10^{15}$ Bq of tritium gas at $2{,}026 \times 10^{5}$ Pa. The tracer gas will be a mixture of 50 % helium and 50 % air and the test method will be the evacuated envelope (gas detector), see Table A.2. Determine the permissible leakage rate of the tracer gas for normal conditions of transport. Assume that all gas flows are purely molecular. Assume that the activity per unit volume of the tritium gas is $8{,}772 \times 10^{4}$ TBq·m^{-3} at standard conditions.

The vessel is sealed with metallic O-rings. Thus, permeation of tritium through the vessel walls has been determined to be negligible.

The steps and their sequence are defined in Figure 1.

D.11.2 Step 1

The radioactive content is tritium gas and the total activity is $1{,}85 \times 10^{15}$ Bq.

D.11.3 Step 2

Assume that the release fractions, FC_i and FE_i, have values of 1,0.

D.11.4 Step 3

$A_2 = 40$ TBq

$R_N = 1{,}11 \times 10^{-8}$ TBq·s^{-1}

D.11.5 Steps 4 and 5

These steps may be omitted because permeation of tritium through the vessel walls has been considered to be negligible.

D.11.6 Step 6

The activity per unit volume of the medium is:

$$C_N = 8{,}772 \times 10^{4} \left(\frac{2{,}026 \times 10^{5}}{1{,}013 \times 10^{5}} \right)$$

$$= 1{,}754 \times 10^{5}\ \text{TBq} \cdot \text{m}^{-3} \quad \text{(at operating conditions)}$$

D.11.7 Step 7

$$L_N = \frac{R_N}{C_N}$$

$$= 6{,}33 \times 10^{-14}\ \text{m}\cdot^{-3}\cdot\text{s}^{-1}\ \text{(at operating conditions)}$$

For gases, leakage is the product of pressure times volume divided by time. Therefore, L_N may be converted to Q_N as follows:

$$Q_N = (2{,}026 \times 10^5)\ (6{,}33 \times 10^{-14})$$

$$= 1{,}28 \times 10^{-8}\ \text{Pa}\cdot\text{m}^3\cdot\text{s}^{-1}\ \text{(for tritium at operating conditions)}$$

D.11.8 Step 8

D_N could be determined by using Formula (B.1), but in this case the calculation is unnecessary.

D.11.9 Step 9

Because only molecular flow is to be considered, $Q_{N(SLR)}$ can be correlated directly to Q_N by Formula(B.3)

To convert to air at standard conditions, let x represent any gas such as air and let y represent the tritium gas.

Since $T_x = T_y$, Formula (B.3) reduces to:

$$Q_x = Q_y \sqrt{\frac{M_y}{M_x}} \times \frac{(p_u - p_d)_x}{(p_u - p_d)_y}$$

For tritium:

$$M_y = 0{,}006\ \text{kg}\cdot\text{mol}^{-1}$$

$$Q_y = Q_N$$

For air

$$M_x = 0{,}029\ \text{kg}\cdot\text{mol}^{-1}$$

$$Q_x = Q_{N(SLR)}$$

Then:

$$Q_{N(SLR)} = 0{,}455 \times Q_N \times \frac{(p_u - p_d)_x}{(p_u - p_d)_y}$$

In this formula, p_u and p_d actually refer to the partial pressures of gases x and y.

For air:

$$(p_u - p_d)_x = 1{,}013 \times 10^5 - 0{,}0$$

$= 1{,}013 \times 10^5$ Pa

For tritium:

$(p_u - p_d)_y = 2{,}026 \times 10^5 - 0$

$= 2{,}026 \times 10^5$ Pa

Then:

$Q_{N(SLR)} = 2{,}9 \times 10^{-9}$ Pa·m^3·s^{-1} SLR

However, if the total pressures had been used, then:

$(p_u - p_d)_x = 1{,}013 \times 10^5$ Pa

i.e. as before, but

$(p_u - p_d)_y = 2{,}026 \times 10^5 - 1{,}013 \times 10^5$

$= 1{,}013 \times 10^5$ Pa

and

$Q_{N(SLR)} = 5{,}8 \times 10^{-9}$ Pa·m^3·s^{-1} SLR

D.11.10 Step 10

The tracer gas is a mixture of 50 % helium and 50 % air. For the test:

$p_u = 1{,}013 \times 10^5$ Pa for helium

$p_u = 1{,}013 \times 10^5$ Pa for air

$p_d = 0$ Pa

First, compare the leakage of helium to $Q_{N(SLR)}$.

Let x represent air and y represent helium. Use Formula (B.3) and assume that $T_x = T_y$. Since Formula (B.3) reduces to:

$$Q_x = Q_y \times \sqrt{\frac{M_y}{M_x}}$$

$Q_x = 2{,}91 \times 10^{-9}$ Pa·m^3·s^{-1} SLR

$M_y = 0{,}004$ kg·mol^{-1}

$M_x = 0{,}029\ \text{kg·mol}^{-1}$

Then:

$Q_y = 7{,}84 \times 10^{-9}\ \text{Pa·m}^3\text{·s}^{-1}$ SHeLR

To determine the permissible test leakage rate, Q_{TDN}, for the mixture, two factors shall be applied to Q_y. Firstly, Q_y shall be reduced by the factor:

$$f = 1 + \frac{\sqrt{M_x}}{\sqrt{M_y}} = 1{,}37$$

to account for the fact that, during the test, only the helium component of the mixture will be detected. Secondly, this document requires that the sensitivity of the leakage test procedure shall be one-half of the maximum allowable leakage rate.

Therefore:

$$Q_{\text{TDN}} = Q_y \times \frac{1}{2} \times \frac{1}{1{,}37} = 2{,}86 \times 10^{-9}\ \text{Pa·m}^3\text{·s}^{-1}$$

D.12 Sensitivity of gas bubble immersion test

The purpose of this example is to show how bubble generation can be affected by different liquids and by pressure differences across a leak.

The closure of a containment system is subjected to a gas bubble test. The containment system is pressurized to $2{,}0 \times 10^5$ Pa with air. The immersion depth is 0,1 m and the liquid may be either water or ethylene glycol.

Assume that there is a single leak with a diameter of 3×10^{-5} m and that the air-leakage rate from the leak is $1{,}0 \times 10^{-4}\ \text{Pa·m}^3\text{·s}^{-1}$ under operating conditions and at 25 °C.

Compare the bubble diameter and bubble generation rates for the two immersion liquids:

$g = 9{,}81\ \text{m·s}^{-2}$

$g_0 = 1\ \text{kg.m.N}^{-1}\text{·s}^{-2}$

$\rho_1 = 10^3\ \text{kg.m}^{-3}$ (for water)

$\rho_1 = 1{,}125 \times 10^3\ \text{kg.m}^{-3}$ (for ethylene glycol)

$\rho_g = 1{,}184\ \text{kg.m}^{-3}$ (for air at 25 °C)

$\sigma = 7{,}2 \times 10^{-2}\ \text{N·m}^{-1}$ (for water in contact with air)

$\sigma = 4{,}8 \times 10^{-2}$ N·m^{-1} (for ethylene glycol in contact with air)

First, see B.12 to show that the internal pressure of the bubble will overcome the surface tension of the liquid.

$p_u = 2{,}0 \times 10^5$ Pa

For water, an immersion depth of 0,1 m generates a pressure head of $0{,}009\ 8 \times 10^5$ Pa.

Then

$p_d = 1{,}013 \times 10^5 + 0{,}009\ 8 \times 10^5$

$= 1{,}023 \times 10^5$ Pa

For water in contact with air:

$\sigma = 7{,}2 \times 10^{-2}$ N·m^{-1}

$D = 3 \times 10^{-5}$ m

Then,

$$p_d + \frac{2\sigma}{D} = 1{,}023 \times 10^5 + 2 \times \frac{7{,}2 \times 10^{-2}}{3 \times 10^{-5}}$$

$$= 1{,}07 \times 10^5 \text{ Pa}$$

This result is less than p_u, and therefore bubbles will be generated. A similar conclusion results for the ethylene glycol.

Next, use Formula (B.10) to estimate the bubble diameter.

Therefore, for water:

$D_B = 1{,}10 \times 10^{-3}$ m

$V_B = 6{,}97 \times 10^{-10}$ m^3

and, for ethylene glycol:

$D_B = 1{,}10 \times 10^{-3}$ m

$V_B = 4{,}08 \times 10^{-10}$ m^3

Finally, use Formula (B.11) to estimate the generation rates of the bubbles.

To determine L, in cubic metres per second ($m^3 \cdot s^{-1}$), use the relationship:

$$Q = p \times L$$

where p is the pressure of the air at the exit point of the leak.

$$P = p_d = 1{,}023 \times 10^5 \text{ Pa}$$

Then,

$$L = \frac{1{,}0 \times 10^{-4}}{1{,}023 \times 10^5}$$

$$= 9{,}775 \times 10^{-10} \text{ m}^3 \cdot \text{s}^{-1}$$

and

$v = 1{,}4 \text{ s}^{-1}$ (for water)

$v = 2{,}4 \text{ s}^{-1}$ (for ethylene glycol)

These results indicate that, for the ethylene glycol, the bubbles will be about 15 % smaller in diameter than for water, but the generation rate will be 70 % greater. Thus, a gas bubble test using ethylene glycol would be superior to a test using water.

One procedure that is commonly used with ethylene glycol is to evacuate the space above the ethylene glycol bath. In this case, the calculations give:

$v = 220 \text{ s}^{-1}$

This result shows that the sensitivity of the test procedure has been increased by a factor of about 100.

D.13 Containment for tritiated water

D.13.1 General

This example illustrates the use of the gas leakage test methodology for normal conditions of transport but a different methodology for accident conditions of transport. This example also illustrates that the packaging design and the radioactive contents can influence the selection of a suitable leakage test procedure for preshipment verification.

A package consists of an outer protective packaging and a drum that contains 200 l of tritiated heavy water with an activity per unit volume of 1,25 $TBq \cdot l^{-1}$ The drum has two standard openings of 50 mm diameter. Specify suitable leakage tests for design verification and preshipment verification.

The steps and their sequence are defined in Figure 1.

NOTE 6 Pressure rise due to radiolysis of the tritium and permeation of the tritium is neglected (see example D.14).

D.13.2 Step 1

The radioactive contents are tritiated heavy water and the total activity is 200 × 1,25 = 250 TBq. The containment system is the drum and the medium is the tritiated heavy water.

D.13.3 Step 2

Assume that the release fractions, FC_i and FE_i, have values of 1,0.

D.13.4 Step 3

A_2 = 40 TBq (for tritium)

$R_N = 1{,}11 \times 10^{-8}$ TBq·s^{-1}

$R_A = 6{,}61 \times 10^{-5}$ TBq·s^{-1}

D.13.5 Step 6

The activity per unit volume of the medium is:

$C_N = C_A = 1{,}25$ TBq·l^{-1}

$= 1{,}25 \times 10^{3}$ TBq·m^{-3}

D.13.6 Step 7

$$L_N = \frac{R_N}{C_N}$$

$$= 8{,}89 \times 10^{-12}\ \mathrm{m^3 \cdot s^{-1}}$$

$$L_A = \frac{R_A}{C_A}$$

$$= 5{,}29 \times 10^{-8}\ \mathrm{m^3 \cdot s^{-1}}$$

D.13.7 Step 8

Under normal conditions of transport only, L_N for the tritiated heavy water can be converted to an equivalent air-flow rate by the method given in B.8. First, determine D_N.

Assume:

$p_u = 1{,}083 \times 10^5$ Pa (due to the head of heavy water)

$p_d = 1{,}013 \times 10^5$ Pa

$\mu = 1{,}2 \times 10^{-3}$ Pa·s

The thickness of the drum wall, a, which is assumed to be the same as the capillary length, is

$a = 1{,}6 \times 10^{-3}$ m

Therefore,

$D_N = 1{,}78 \times 10^{-5}$ m

D.13.8 Step 9

Under normal conditions of transport only, determine the standardized leakage rate from Formula (B.1).

Assume:

$p_u = 1{,}013 \times 10^5$ Pa

$p_d = 0{,}0$ Pa

$D_N = 1{,}78 \times 10^{-5}$ m

$\mu = 1{,}85 \times 10^{-5}$ Pa·s (for air)

$a = 1{,}6 \times 10^{-3}$ m

$T = 298$ K

$M = 0{,}029$ kg·mol^{-1}

Therefore:

$$Q_{N(SLR)} = 4{,}3 \times 10^{-4} + 4{,}4 \times 10^{-5}$$

(viscous) (molecular)

$$= 4{,}7 \times 10^{-4} \text{ Pa·m}^3\text{·s}^{-1} \text{ SLR}$$

NOTE This result indicates that the viscous flow mode predominates.

D.13.9 Step 10

See the last statement given in Step 9.

D.13.10 Step 11

To select an appropriate test method for design verification, refer to Table A.1.

Methods that use halogen or helium gas could be selected but they are too sophisticated.

The choice is therefore to the gas pressure drop, or gas pressure rise, since a quantitative method is required.

Under normal conditions of transport only, the containment requirement is $A_2 \times 10^{-6}$ TBq·h^{-1} or 40×10^{-6} TBq·h^{-1}. During the tests, the drum will be filled with ordinary water to simulate the radioactive contents. Because it is impractical to conduct a gas leakage test when the drum is full of water, the following procedure will be specified:

a) fill the drum with ordinary water;

b) prepare the package for shipment;

c) conduct the tests for normal conditions of transport;

d) drill an extraneous hole in the drum lid;

e) drain the water from the drum;

f) vacuum-dry the drum;

g) complete a gas pressure-drop test.

See B.14 to determine a suitable test duration H, and values of p_1 and p_2 in order to fulfill Step 8.

D.13.11 Step 12

Under accident conditions of transport only, the containment requirement is A_2, or 40 TBq, in one week.

This represents 16 % of the package contents, or 35 kg. In this case, $Q_{A(SLR)}$ need not be determined because a simple mass-loss measurement would suffice to demonstrate compliance with the regulations. This is an example of the use of another methodology.

To select an appropriate test method for preshipment verification, the packaging design and the radioactive contents will affect the choice of method. Once the drum is filled with tritiated heavy water and the 50 mm closures are installed, there will be no access to the interior of the drum. None of the test methods in Table A.1 are suitable.

The following alternative methodology will be used:

Before the drum is filled, complete a gas bubble test by pressurizing the drum internally with air and rotating the drum in a water bath.

The gas bubble test, rather than the gas pressure-drop test is preferred because the latter test procedure is time consuming.

Load the drum with its radioactive contents.

Install the drum closures in accordance with the check-list procedures.

Place the drum in an enclosure and sample an air flow with a tritium monitor. The tritium monitor has a sensitivity which can easily detect the regulatory limit of 40×10^{-6} TBq·h^{-1}.

D.14 Containment of liquids using double containment and taking radiolysis into account

D.14.1 General

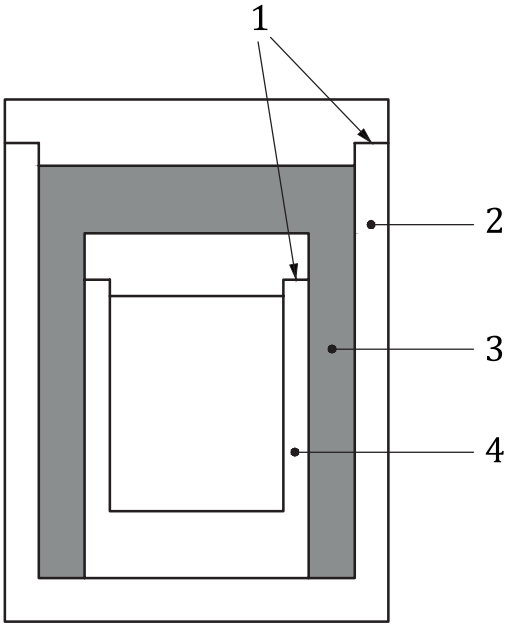
This example illustrates one method of complying with the containment requirements for a Type B(U), Type B(M) or Type C package carrying radioactive contents in liquid form. It takes into account the radiolysis of liquids, which results in gas generation and pressurization which increases the leakage rate.

A package provided with a double containment system composed of inner and outer containment vessels, can be shown to meet the IAEA transport regulations by providing a high degree of containment for liquids.

The seals of the inner containment vessel ensure that the leakage into the space between the inner and outer containment vessels that may occur in one year is small. The absorbent material between the inner and outer containment vessels prevents the small leakage of liquid from the inner containment vessel from reaching the seals of the outer containment vessel: there can therefore be no leakage from the outer containment vessel, provided that a sufficient quantity of absorbent material is present.

D.14.2 Containment system

Figure D.3 provides a typical example of a double containment system. The dimensisons which are considered in this example are provided in the table below.



Key

1 seals
2 outer container
3 absorbent material
4 inner container

Figure D.3 — Containment system

Dimensions	Outer container	Inner containers
External diameter (m)	0,15	0,11
External length (m)	0,20	0,17
Cavity diameter (m)	0,13	0,10
Cavity length (m)	0,18	0,15
Cavity volume (m^3)	$2,4 \times 10^{-3}$	$1,2 \times 10^{-3}$

D.14.3 Retention of liquid containers

In order to demonstrate that, in the event of leakage from the inner containment vessel, liquid contents will be retained within the outer containment vessel, it is necessary to determine:

a) the rate of gas generation due to radiolysis;

b) the pressure drive which causes any leakage;

c) the quantity of liquid which could escape from the inner containment vessel in 1 year;

d) the quantity of absorbent required to retain any liquid within the outer containement vessel.

For the purpose of this example, it is assumed that the internal pressurization of the inner container is due solely to radiolysis.

Assumptions for this example:

Leakage rate = 1×10^{-6} Pa·m^3·s^{-1} SLR

Decay power = 0,1 W

Atmospheric pressure = $1{,}013 \times 10^5$ Pa (absolute)

Gas generation constant for the solution G = 1×10^3 molecules.MeV^{-1}

The temperature of the contents does not vary significantly from the ambient temperature.

Liquid contents consist of an aqueous solution.

That the above conditions exist for a period of one year.

D.14.4 Determination of the rate of gas generation due to radiolysis

The gas generation rate due to radiolysis, v_g, in moles per second (mol·s^{-1}), can be determined using the following formula:

$$v_g = DP \times G \times k \times N_0^{-1}$$

where

DP is the decay power (= 0,1 W);

G is the gas generation constant (= 1×10^3 molecules.MeV^{-1});

k is a conversion factor (= $6{,}24 \times 10^{12}$ MeV.J^{-1});

N_0 is Avogadro's number (= $6{,}02 \times 10^{23}$ molecules·mol^{-1}).

The gas generation rate is therefore:

$$v_g = 1{,}04 \times 10^{-9} \text{ mol·s}^{-1}$$

D.14.5 Determination of the pressure within the inner containment vessel

Assuming that the gas generated by radiolysis is released from the primary container (which contains the liquid contents) into the free volume within the inner containment vessel, the pressure within the inner container will increase with time as follows:

$$p(t) = p_c + p_r$$

where

$p(t)$ is the internal pressure within the containment vessel at time t, in pascals;

p_c is the initial pressure within the containment;
It is assumed to be the atmospheric pressure p_a (= $1{,}013 \times 10^5$ Pa).

p_r is the pressure rise due to radiolysis, in pascals;
$p_r = v_g \times t \times R \times T_c \times V_c^{-1}$

t is the duration of radiolysis, in seconds;

T_c is the initial temperature within the containment vessel (= 298 K);

V_c is the free volume of the containment vessel (= $0{,}7 \times 10^{-3}$ m^3).