
**Gas cylinders — Cylinders and tubes
of composite construction — Modal
acoustic emission (MAE) testing for
periodic inspection and testing**

*Bouteilles à gaz — Bouteilles et tubes composites — Essai par
émission acoustique modale (EAM) pour les besoins du contrôle et des
essais périodiques*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

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For an explanation of 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 www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 4, *Operational requirements for gas cylinders*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

In recent years, new non-destructive examination (NDE) techniques have been successfully introduced as an alternative to the conventional retesting procedures of gas cylinders, tubes and other cylinders.

One of the alternative NDE methods for certain applications is acoustic emission testing (AT), which in several countries has proved to be an acceptable testing method applied during periodic inspection. This AT method is described in ISO 16148, which authorizes pressurization pneumatically to a value equal to 110 % of the cylinder's working pressure and hydraulic pressurization to a value equal to the cylinder's test pressure. Since ISO 16148 was developed for periodic inspection and testing of monolithic materials (seamless steel and aluminium-alloy cylinders), the test method was not appropriate for composite cylinders. The modal acoustic emission (MAE) test method described in this document was developed to address this shortcoming.

The MAE test method described in this document applies during periodic inspection and testing, and it uses either hydraulic (liquid) pressurization or pneumatic (gas) pressurization to a level equal to the design test pressure of the cylinder. It detects structural damage that can result in a compromised burst pressure strength in a composite cylinder. The MAE waveforms can be used to identify damage such as fibre breakage and delamination. An MAE waveform is distinguished by the wave (mode) shapes, velocities, waveform energy and frequency spectrums. This MAE test method is not intended for newly manufactured composite cylinders.

The application of MAE testing on composite overwrapped gas cylinders with metallic and polymer liners was applied to a sample of composite cylinders [180 self-contained breathing apparatus (SCBA) cylinders selected from 50 000] that were near the end of their 15-year service life. The MAE testing was performed during physical testing, which was similar to design qualification testing for this type of composite cylinder. The physical testing included pressure cycling, burst testing, flaw tolerance testing and ISO 11119-2 drop testing. The MAE testing consistently detected and differentiated each cylinder that had a compromised burst pressure strength, which had been defined for this project to be a pressure less than the original design burst pressure of the cylinder, by the presence of background energy oscillation (BEO) at or near the test pressure.

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Gas cylinders — Cylinders and tubes of composite construction — Modal acoustic emission (MAE) testing for periodic inspection and testing

CAUTION — Some of the tests specified in this document involve the use of processes (e.g. pneumatic pressurization) which could lead to a hazardous situation.

1 Scope

This document describes the use of modal acoustic emission (MAE) testing during periodic inspection and testing of hoop wrapped and fully wrapped composite transportable gas cylinders and tubes, with aluminium-alloy, steel or non-metallic liners or of linerless construction, intended for compressed and liquefied gases under pressure.

This document addresses the periodic inspection and testing of composite cylinders constructed to ISO 11119-1, ISO 11119-2, ISO 11119-3, ISO 11515 and ISO/TS 17519 and can be applied to other composite cylinders designed to comparable standards when authorized by the competent authority.

Unless noted by exception, the use of “cylinder” in this document refers to both cylinders and tubes.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

ISO 11623, *Gas cylinders — Composite construction — Periodic inspection and testing*

ASTM E1106-12, *Standard Test Method for Primary Calibration of Acoustic Emission Sensor*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1.1

modal acoustic emission

MAE

branch of acoustic emission (AT) focused on the detection, capture and analysis of the sound waves generated by acoustic events due to *fibre tow* (3.1.19) breakage, cracking, crazing, rubbing, delamination or fracture of structural components

Note 1 to entry: The sound waves can be produced either by defects [e.g. *fibre tow* (3.1.19) breakage, crack growth, delamination] or by surface rubbing. The wave frequencies typically extend from the sonic to the lower ultrasonic range. MAE is distinguished from AT by its focus on capturing waveforms with broader bandwidth sensors and analysing the waveforms according to wave propagation physics in an attempt to determine the type of source, as is done in seismology, whereas AT has been generally concerned with counts, amplitudes and other signal features based on different theories of analysis than MAE.

3.1.2

broadband piezoelectric sensor

sensor having a response that is flat-with-frequency (± 6 dB) when calibrated in an absolute sense over the frequency range of interest

Note 1 to entry: Due to a lack of signal distortion or “coloration”, broadband piezoelectric sensors enable the observation of the extensional and flexural plate waves which facilitates the direct comparison to physical models for proper damage mechanism identification.

3.1.3

preamplifier

amplifier that converts a lower level voltage signal to a higher level voltage signal

Note 1 to entry: A preamplifier can also have a 0 dB gain where it would function purely as a buffer or unity gain amplifier.

3.1.4

high-pass filter

electronic filter applied to the wave signals to reduce mechanical noise

3.1.5

low-pass filter

electronic filter applied to the wave signals to prevent *aliasing* (3.1.13)

3.1.6

analogue-to-digital converter

A/D converter

electronic device that changes an analogue electrical signal into a digital representation

3.1.7

input impedance

value of the impedance, denoted as Z , at the input to the voltage *preamplifier* (3.1.3) to which the transducer is directly connected

3.1.8

Nyquist frequency

bandwidth of the sampled signal, equal to half the sampling rate

3.1.9

primary AE

acoustic emissions caused by damage mechanisms (e.g. fracture, crack propagation, defect growth) originating from the material under test

3.1.10**secondary AE**

acoustic emissions caused by sources other than damage mechanisms originating from the material under test (frictional rubbing against containment, EMI, flow noise, etc.)

Note 1 to entry: See [Clause 10](#) for information regarding filtering out extraneous noise.

3.1.11**background energy****BE**

minimum energy in a windowed portion of a given waveform

3.1.12**background energy oscillation****BEO**

excursion of greater than *BEO multiplication factor* (M_2) ([3.1.26](#)) between neighbouring maxima and minima of an N point moving average calculated from all *background energy* ([3.1.11](#)) values

3.1.13**aliasing**

effect resulting from under sampling that causes different signals to become indistinguishable (or aliases of one another) when sampled

3.1.14**clean front end**

pre-trigger energy of less than $0,01 \times 10^{-15}$ J when accounting for gain

3.1.15**working pressure**

settled pressure of a compressed gas at a uniform reference temperature of 15 °C in a full gas cylinder

Note 1 to entry: In North America, service pressure is often used to indicate a similar condition, usually at 21,1 °C (70 °F).

Note 2 to entry: In East Asia, service pressure is often used to indicate a similar condition, usually at 35 °C.

[SOURCE: ISO 10286:2015, 736]

3.1.16**developed pressure**

pressure developed by the gas contents in a cylinder at a uniform reference temperature of $Temp_{max}$

Note 1 to entry: $Temp_{max}$ is the expected maximum uniform temperature in normal service as specified in international or national cylinder filling regulations.

[SOURCE: ISO 10286:2015, 733, modified — “ T_{max} ” replaced with “ $Temp_{max}$ ”]

3.1.17**composite overwrap**

combination of *fibres* ([3.1.18](#)) and *matrix* ([3.1.20](#))

3.1.18**fibre**

load-carrying part of the *composite overwrap* ([3.1.17](#))

EXAMPLE Glass, aramid or carbon.

3.1.19**fibre tow**

group or bundle of *fibres* ([3.1.18](#))

3.1.20

matrix

material used to bind and hold *fibres* (3.1.18) in place

3.1.21

extensional waves

collection of wave modes characterized by dominant in-plane deformation characteristics

Note 1 to entry: Extensional wave modes are analogous to symmetric (S) wave modes in isotropic plate-type structures.

3.1.22

flexural waves

collection of wave modes characterized by dominant out-of-plane deformation characteristics

Note 1 to entry: Flexural wave modes are analogous to antisymmetric (A) wave modes in isotropic plate-type structures.

3.1.23

fibre bundle rupture energy multiplication factor

F_1

allowance factor for *fibre* (3.1.18) bundle rupture energy

Note 1 to entry: The value of F_1 is determined by analysis of the composite material and pressure vessel design.

3.1.24

total single event energy multiplication factor

F_2

allowance factor for single event energy

3.1.25

BE multiplication factor

M_1

multiplicative factor that corresponds to a rise in the *background energy* (3.1.11) level above the quiescent level

Note 1 to entry: The value of M_1 is a function of vessel type, *fibre* (3.1.18) construction, size and pressure rating of the composite cylinder and is determined through theory and/or testing.

Note 2 to entry: M_1 indicates that the damage accumulation has commenced in the composite pressure vessel under test.

Note 3 to entry: See 3.1.27.

3.1.26

BEO multiplication factor

M_2

difference factor between neighbouring maxima and minima of an N point moving average calculated from all *background energy* (3.1.11) values

Note 1 to entry: The value of M_2 is a function of vessel type, *fibre* (3.1.18) construction, size and pressure rating of the composite cylinder and is determined through theory and/or testing.

Note 2 to entry: M_2 indicates that the composite pressure vessel under test is progressing towards failure.

3.1.27

quiescent background energy

U_{QE}

energy determined in a windowed portion of a waveform during a period of inactivity

3.1.28**wave energy** U_{WAVE}

$$U_{\text{WAVE}} = \frac{1}{Z} \int_0^t V^2 dt$$

Note 1 to entry: For comparison to physical energy values (e.g. the theoretical energy released by a fibre fracture event), the total system gain is accounted for by dividing V by the gain factor before squaring, e.g. 40 dB gain is a gain factor of 100, 48 dB is a gain factor of 251,2, 60 dB is a gain factor of 1 000, etc.

3.2 Symbols

C_E	speed of the first arriving frequency in the E wave
C_F	speed of the last arriving frequency in the F wave
d	diameter of the fibre
E	Young's modulus of the fibre
ε	strain to failure of the fibre
g	acceleration due to gravity
h	vertical height of the centre of the rolling ball at the top of the inclined plane
I	ineffective fibre length for the fibre and matrix combination
L	distance between sensors, in m
m	mass
N	constant value relating to the type of fibre in the composite cylinder
T	period of the cycle
t_1	time, in μs , when the first part of the direct E wave will arrive (i.e. the arrival of the lowest observable frequency of interest in the E mode)
t_2	time, in μs , when the last part of the direct F wave will arrive (i.e. the arrival of the lowest observable frequency of interest in the F mode)
t	time
$Temp_{\text{max}}$	expected maximum uniform temperature in normal service
$U_{\text{FB}}^{\text{AE}}$	energy produced by the occurrence of fibre breakage
$U_{\text{FBB}}^{\text{AE}}$	energy produced by the occurrence of fibre bundle breakage
$U_{\text{RBI}}^{\text{AE}}$	rolling ball impact acoustical wave energy
U_{FB}	theoretical fibre break energy
U_{mgh}	known mechanical energy
U_{RBI}	rolling ball impact energy