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Determination of the resistance to hydrocarbon pool fires of fire protection materials and systems for pressure vessels

Détermination de la résistance aux feux de nappe d'hydrocarbure des matériaux et systèmes de protection incendie des récipients sous pression

Reference number
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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).

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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 92, *Fire safety*, Subcommittee SC 2, *Fire containment*.

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.

Introduction

This document describes a test procedure to assess the protection afforded by fire protection materials and systems to pressure vessels. It gives an indication of how fire protection materials perform when exposed to a set of specified fire conditions. Actual vessels can vary in construction from that tested and can utilise additional protection systems. The test conditions have been shown to be representative of the severity of unconfined pool fires fuelled by light and medium oil distillates such as LPG and petroleum products.

Test laboratories should be aware of the significant potential hazards involved in pressure vessels testing. Facilities intending to undertake tests in accordance with this document should be designed to be safe in the event of vessel failure.

Determination of the resistance to hydrocarbon pool fires of fire protection materials and systems for pressure vessels

1 Scope

This document specifies a test method for determining the fire resistance of pressure vessels with a fire protection system when subjected to standard fire exposure conditions. It does not address vessels cooled by water deluge or water monitor. The test data thus obtained permits subsequent classification on the basis of the duration for which the performance of the pressure vessel under these conditions satisfies specified criteria. The design of the pressure vessel is not covered in this document.

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.

There are no normative references in this document.

3 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 https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp3.1

3.1
blowdown valve
BDV
blowdown device
valve or device that opens to depressurize a pressure vessel

EXAMPLE Fusible plug.

3.2
burner arrangement
configuration of the equipment designed to engulf the test specimen in fire, with specific reference to the size, orientation, frequency and spacing of burner heads, and the design of fuel supply piping

3.3
burst pressure
calculated burst pressure
<vessel> pressure that gives a hoop stress equal to the ultimate strength of the vessel material at the specific wall temperature of interest

Note 1 to entry: For long duration tests, stress rupture analysis is also considered a realistic failure mode.

3.4
calibration test
test performed by the laboratory prior and separate to customer tests, to confirm that the chosen burner arrangement in combination with the desired test specimen conforms with the required conditions of this document

3.5
critical pressure
pressure calculated for a given critical wall temperature as the burst pressure divided by a factor of safety (FOS)

3.6
critical temperature
design limiting temperature, or a specified limiting wall temperature, that the vessel wall temperature shall not exceed during fire exposure

Note 1 to entry: This temperature is related to a factor of safety (FOS) for the vessel when exposed to fire.

3.7
directional flame thermometers
DFTs
passive thermocouple based sensors that can be used for the measurement of both temperature and heat flux

Note 1 to entry: Various designs are available. A simple design is described in this document.

3.8
factor of safety
FOS
ratio of the calculated ultimate strength of the vessel steel at the temperature of interest (e.g. critical temperature) divided by the actual hoop stress in the vessel

Note 1 to entry: A typical FOS is in the range 2 to 3.

3.9
fire protection system
thermal protection system
protection afforded to the vessel to reduce the rate of heat transfer from the fire to the vessel, throughout the period of exposure to fire, including any protection materials together with any encasement (such as a jacket), and supporting system (such as mesh reinforcement or framing system) and any specified primer and top coat if applicable

Note 1 to entry: Often referred to as a thermal protection system in North America.

3.10
pool fire
hydrocarbon diffusion fire that occurs over a static or flowing release of flammable liquids

Note 1 to entry: It simulates large turbulent diffusion flames that are strongly radiating.

3.11
pressure relief valve
pressure safety valve
PRV
pressure-activated valve intended to limit pressure rise to a specified value

Note 1 to entry: These valves have set opening and reclosing pressures.

3.12
pressure vessel
vessel capable of containing pressures significantly above ambient, even if normal operational procedure does not involve pressure rise above ambient

Note 1 to entry: Pressure vessels are often referred to as vessels or tanks.

3.13
radiation-convection balance
fraction or percentage of total heat transfer to a cool surface that is due to radiation

Note 1 to entry: The cool surface may be a water-cooled calorimeter at a temperature of up to 100 °C.

3.14
test related tube and pipe
additional tube or pipe added to the vessel for the purposes of performing tests

Note 1 to entry: They may not be present on the real application tank.

3.15
total containment pressure vessel
pressure vessel that has no automatic means of pressure relief or depressurization

3.16
ullage space
vapour-filled space at the top of the vessel, where there is no liquid contact with the wall

3.17
vessel shell
primary wall of the vessel

4 Symbols and abbreviated terms

A	area
f_{rad}	radiation fraction
T	temperature
t	time
m	mass
q_{net}	net absorbed heat flux (W.m^{-2})
q_{conv}	heat flux due to convection
q_{rad}	Heat flux due to radiation
ε	emissivity
σ	Stefan-Boltzmann constant (5,67 × 10^{-8} W.m^{-2}.K^{-4})

Subscript terms

cal	calorimeter
DFT	directional flame thermometer
f	fire
indic	indicated
s	substrate

5 Principle

The method provides an indication of how vessels protected with fire protection materials or systems perform when exposed to pool fires on solid surfaces. It simulates the thermal loads to a vessel engulfed in a large pool fire through the use of burners to create a flame capable of engulfing a vessel. To ensure that suitable test conditions are achieved and maintained, it describes calibration tests to be performed prior to fire testing, sets permitted tolerances from the calibrated set-up, and delimits environmental conditions.

6 Test equipment

6.1 General

The test procedure is intended to simulate a liquid hydrocarbon pool fire that achieves a heat flux to a cool surface of 90 kW/m^2 to 120 kW/m^2.

NOTE The literature suggests that heat flux to a cool surface in a large pool fire is 80 % to 90 % due to radiation and the remainder is by convection.

An example piping and instrumentation diagram for a vessel testing facility is shown in Annex A. Test equipment employed in the conduct of the test consists essentially of the following:

a) a specially designed burner arrangement to subject the test specimen to the conditions specified in the calibration section;

b) propane storage capable of fuelling the test for the required duration;

c) equipment to control and monitor the propane flow rate throughout the test;

d) equipment to vent and purge the vessel after testing.

6.2 Burner arrangement

This test procedure uses liquid propane fuelled burners to simulate a pool fire. Burners are used because they provide more control over the test conditions. The burner system shall be designed to produce a low momentum and luminous fire of sufficient thickness so that the resulting heat flux is predominantly by radiation (i.e. radiation fraction greater than 75 %).

To simulate pool fire conditions a burner system shall be used. Burners shall be designed to achieve total engulfment and uniformity of heating and shall be present on all four sides of the vessel. The maximum nozzle spacing shall be no greater than 0,5 m.

The burner design can be varied by the test laboratory to meet the calibration requirements; for informative purposes, an example of burner design is shown in Annex A.

The burner arrangement shall be designed to receive equal mass flow rates of propane to two diametrically opposite locations at the ends of the vessel to ensure broadly symmetrical heating. The supply line length and fittings shall also be designed to ensure equal propane flow to the burner arrangement and all supply lines. Cooling of the supply shall be provided as necessary to protect the burner supply for the duration of the test. The burner system shall be designed to ensure stabilization of the flow rate and stabilization of the flame temperatures (as defined by directional flame thermometers (DFTs) in Clause 9 and Annex B) shall be achieved within 2 min of the test commencing.

6.3 Fuel supply for burners

The burner system fuel shall be commercial propane or LPG. The fuel supply shall be capable of delivering up to 1,0 kg/s to the burner arrangement and controlling the flow rate to within ±0,05 kg/s of the target flow rate as determined by calibration testing.

6.4 Test fluids

The test fluid for the test vessel shall be commercial propane or LPG. Means of filling the test vessel (including air purge) prior to a test, and purging the vessel subsequent to the test to allow safe inspection, shall be provided. Equipment to pump or push liquid propane from the test vessel back to a storage vessel after the test may be utilised. A means of determining the total propane loss from the test vessel throughout the test shall be available.

6.5 Test building

Large-scale exterior fire tests are subject to environmentally induced variations due to wind. Stricter tolerances in deviation from the as-tested environmental conditions are imposed for testing if the test is not protected from the environment through the use of an enclosure in the form of a shed or building. These tolerances are described in 7.7

If used, environmental protection shall be suitably enclosed on all four sides and have full roof coverage. Openings for ventilation shall be equally distributed and sized, so far as is practicable.

7 Calibration tests

7.1 General requirements

Due to the variations involved in external large-scale testing, it is required to successfully perform three calibration tests before a particular fire burner system and test configuration is considered suitable as the basis for fire testing.

The net heat flux to a water-filled vessel shall be determined and DFTs shall be used to assess both the uniformity of heating and the radiation-convection balance. A thermal imager shall also be used to confirm uniformity of heating and radiation-convection balance in the calibration tests. See Annex D for methods to estimate the radiation-convection balance. All three tests shall be performed in accordance with 7.2 and 7.3 and shall use the same vessel, burner configurations and test parameters.

The calibration test results shall be assessed in accordance with 7.4. Once a test configuration has met the requirements in 7.5, it shall be considered suitable for testing of actual test specimens in environmental conditions as defined in 7.6. The tolerances in variation from the calibration test set up during actual fire testing are given in 7.7.

Calibration testing should be repeated in the event of any modifications to the test specimen beyond the permitted tolerances in 7.7, any modifications to the burner or nozzle arrangement or propane flow rate, any significant modifications to the test equipment or test building, or any departure from the environmental conditions as defined in 7.6.

Calibration tests shall be performed at least every three years even in the event of no changes as listed above, to ensure equipment functions as intended. Calibration test results shall be written up as calibration reports as described in 7.8 and retained by the test laboratory for reference when conducting future fire tests.

7.2 Calibration test vessel construction

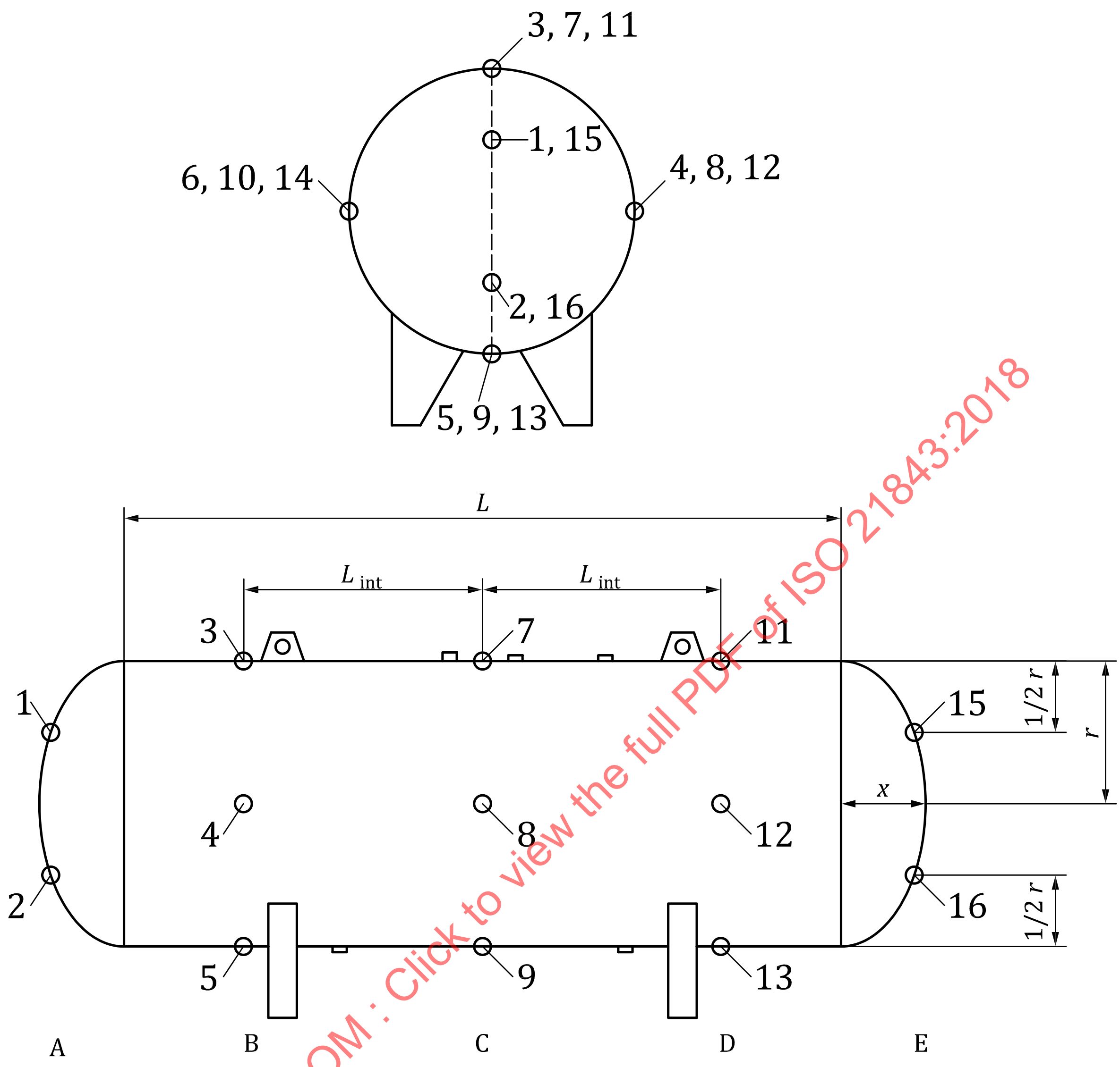
The calibration vessel shall be manufactured according to appropriate pressure vessel regulations. It shall have a minimum diameter of 1 200 mm, and a minimum length of 2 000 mm. The vessel shall be supported on two steel saddles, which shall be insulated or water-cooled. No fire protection materials or system shall be installed on the calibration vessel shell.

An appropriately sized vent shall be cut at the top of the vessel to permit extraction of thermocouples and to prevent pressurization during calibration. An agitator shall be installed within the vessel, located close to the middle. Only connecting piping required for operation of the agitator is permitted, and this piping may be water-cooled if necessary. Any covers or guards for gauges and connections shall be removed, and all remaining connections shall be sealed.

The vessel shell shall be instrumented with 16 DFTs. A simple design of DFTs is given as an example in Annex B. DFTs shall be attached to the vessel in locations shown in Figure 1. Individual TCs that conflict with the position of lifting lugs or fittings may be moved by up to 0,15 m. Thermocouples that conflict with saddles shall be moved horizontally towards the middle of the vessel until they are at least 0,25 m from the saddle.

The calibration vessel shall be internally instrumented with 10 insulated type k thermocouples (1,5 mm minimum diameter) for measurement of the water temperature. The internal thermocouples shall be located at two stations 1/3 and 2/3 along the primary axis of the vessel between the tangent lines (often referred to as tan lines) as shown in Figure 2. The thermocouples shall be spaced to measure the temperature of five horizontal zones of equal volume. The vessel shall be filled 100 % with water and a splash cover added to minimize splash cooling of the outer top surface of the vessel during fire, without allowing pressurization of the vessel.

A thermal imager with an appropriate temperature range and resolution (at least 480 × 240) shall be used to view the fire to assist in the confirmation of radiation-convection balance.



Key

1 to 16 directional flame thermometer (DFT) positions

L length of cylindrical part body of vessel (tan to tan length)

l_{int} $\dfrac{l + r\left(1 + \dfrac{1 - e^2}{e}\tanh^{-1} e\right)}{4}$

where $e^2 = \dfrac{x^2}{r^2}$.

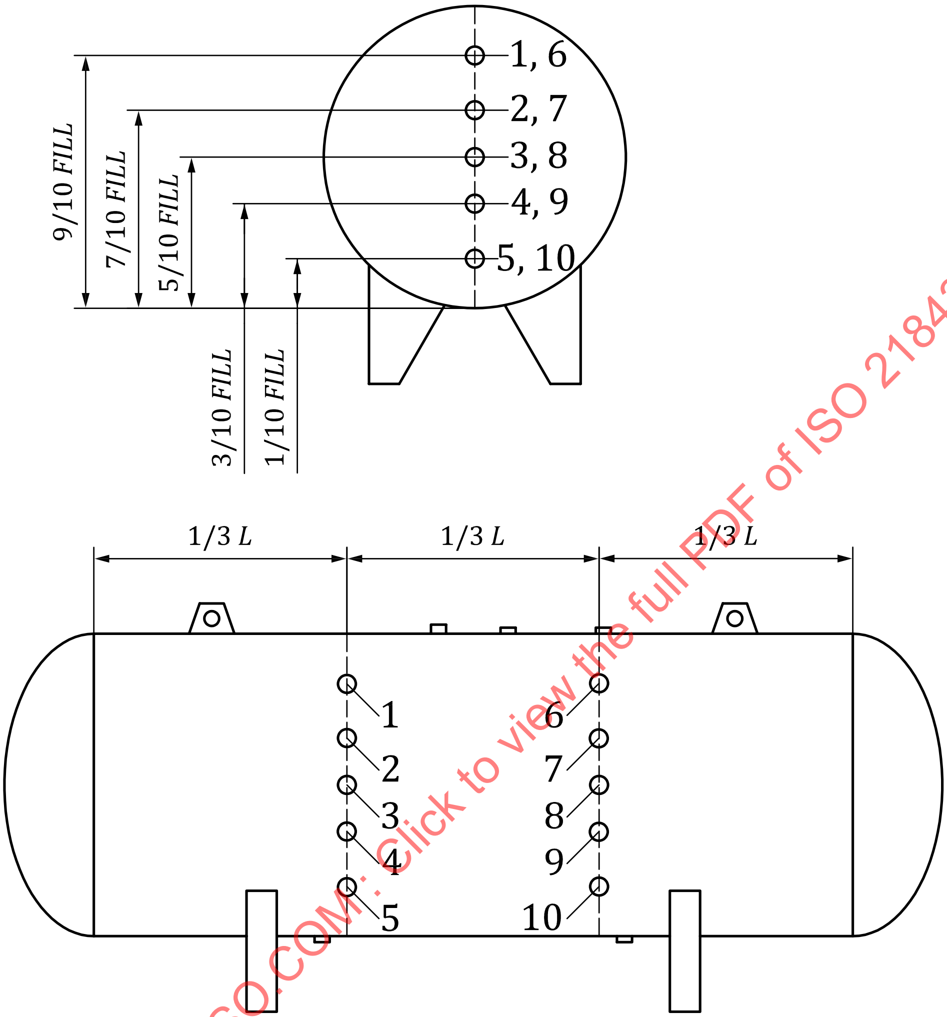
Figure 1 — Calibration test vessel

7.3 Calibration test procedure

Unless explicitly stated otherwise, the calibration tests shall be performed in accordance with Clause 11.

The calibration tests shall be initiated with water at a maximum temperature of 30 °C. The calibration tests terminated at the termination time (t_t), defined as the time when the average water temperature reaches 90 °C or the time when an individual water temperature reaches 95 °C, whichever is achieved first.

The environmental conditions, including wind speed and precipitation in the vicinity of the exterior of the test building, shall be monitored throughout the test. Results from the calibration test shall be reported along with detailed descriptions of the calibration vessel dimensions, environmental conditions, fuel mass flow rate and burner configuration. The report shall be retained by the test laboratory for future reference when setting up and conducting vessel fire tests.



Key

1 to 10 thermocouple positions

L length of cylindrical part body of vessel (tan to tan length)

Figure 2 — Internal thermocouple positions for the net heat flux test

7.4 Analysis of calibration tests

Prior to analysis of test results, calculation is required of the mass of water in the vessel, the surface area of the vessel shell, excluding the saddle contact area if insulated, and mass of the vessel shell excluding saddles, lifting lugs and connections. The average water temperature at any given time shall be calculated using Formula (1).

$$T_{w,t} = \frac{\overline{X}(T_{1,t}, T_{6,t}) + \overline{X}(T_{2,t}, T_{7,t}) + \overline{X}(T_{3,t}, T_{8,t}) + \overline{X}(T_{4,t}, T_{9,t}) + \overline{X}(T_{5,t}, T_{10,t})}{5} \quad (1)$$

where

$T_{w,t}$ is the average water temperature at time t;

$T_{n,t}$ is the temperature of Thermocouple n at time t.

$\overline{X}$ denotes the mean average

The average net heat flux to the vessel shall be calculated for t_t in accordance with Formula (2).

$$q_{net} = \frac{\Delta T_{s,t} m_s c_s + \Delta T_{w,t} m_w c_w}{t_t A_s} \quad (2)$$

where

$\Delta T_{s,t}$ is the vessel shell temperature, assumed equal to $\Delta T_{w,t}$ (°C);

$\Delta T_{w,t}$ is the result of $T_{w,t} - T_{w,0}$ (°C);

m_s is the mass of steel (kg);

m_w is the mass of water (kg);

c_s is the specific heat capacity of steel ($J.kg^{-1}K^{-1}$);

c_w is the specific heat capacity of water ($J.kg^{-1}K^{-1}$);

t_t is the duration of test (time of termination) (s);

A_S is the surface area of vessel shell (m^2).

For the purposes of calculating $T_{w,0}$ the start of the test (t equals zero) shall be taken as the time in the test when the propane burner mass flow rate first stabilises at the target flow rate.

The temperature of directional flame thermometer (T_{DFT}) shall be calculated for each individual DFT as an average temperature over the test period of stable propane mass flow rate.

7.5 Requirements for successful calibration tests

For the calibration test results to be valid the following criteria shall be met:

a) A minimum of 8 internal TCs shall be valid throughout the test;

b) A minimum of 13 DFTs shall be valid throughout the test;

c) A minimum of 2 DFTs shall be valid along the top of the shell throughout the test;

d) At least 1 DFT shall be valid on each side, the bottom and both ends throughout the test.

For the calibration test results to be acceptable the following criteria shall be met:

a) The calculated average net heat flux q_{net} shall be a minimum of 90 kW/m^2;

b) The average of all valid T_{DFT} values shall be within the range 816 °C to 927 °C;

c) 80 % of individual valid T_{DFT} values shall be within the range 816 °C to 927 °C;

d) All individual valid T_{DFT} values shall be within the range 670 °C to 1 070 °C;

e) The ratio of the average (reading in degrees Celsius) of the valid DFTs along the top of the vessel to the average (reading in degrees Celsius) of all valid direction flame thermometers shall be no lower than 0,85;

f) the average radiation-convection balance for a cool surface shall be greater than or equal to 75 %.

Failure to meet the above requirements shall require the calibration test to be repeated using a modified set-up or under different environmental conditions.

7.6 Environmental conditions

The wind speed and direction throughout all calibration tests shall be monitored and recorded at an interval of 5 s or less and the average over time calculated for each test respectively. The average wind speed recorded on the calibration report as the maximum permissible shall be the maximum recorded from the three calibration tests. Precipitation shall be recorded through a detailed description including type and severity (e.g. dry, snow, light rain, heavy rain).

7.7 Tolerances

On successful completion of all calibration tests, the test configuration is considered suitable to perform fire tests under the same conditions as reported during calibration tests, subject to the tolerances in deviations as described in Table 1.

Table 1 — Permitted deviations from calibration test conditions

Category	Parameter	Upper permitted deviation	Lower permitted deviation
Test specimen	Outer diameter	+50 mm	−200 mm
	Length	+50 mm	−500 mm
	Shell thickness	No limit	No limit
Environmental conditions: enclosed tests	Average wind speed	+5 m/s	No limit
	Wind direction	No limit	No limit
	Precipitation	No limit	No limit
Environmental conditions: external tests	Average wind speed	+0,5 m/s	No limit
	Average wind direction	+45°/−45° or +225°/135° relative to any average wind direction recorded among the calibration tests	
	Precipitation	Tests shall be performed when there is a reasonable expectation of no precipitation. Short periods of light precipitation shall not invalidate a test if less than 10 % of the test duration is affected.	
Test parameters	Propane flow rate	+0,05 kg/s	−0,05 kg/s
	Burner arrangement	No modifications permitted	
	Fuel composition	No modifications permitted	

Table 1 shall apply at the start of a test. In the event of changes in wind and environmental conditions during a test causing conditions to fall outside the permitted values the DFT data may be used to assess test validity, using the criteria stated in 18.6.

7.8 Calibration report

The calibration report shall contain the following:

a) The name of the testing laboratory, test date, unique test reference number and report identification;

b) complete description of the calibration specimen, including calibration vessel dimensions; parameters and details of additional gauges present; details of additional insulation systems used for tubing, piping and saddles;

c) complete description of instrumentation used, including pressure transducers and thermocouples, including positions and method used to affix them;

d) when appropriate, details of any deviations from the normal test configurations and the reasons for them;

e) record of test details and post fire characterization including:

   1) ambient conditions including precipitation, temperature, humidity, wind speed and wind direction (in the vicinity of the test specimen or test building) throughout the test at intervals of 5 s or less;

   2) fuel pressure and temperature at intervals of 2 s or less throughout the test, where these are used to calculate mass flow rate, and the method of control and calculation;

   3) fuel mass flow rate at intervals of 2 s or less throughout the test and total mass of fuel used;

   4) fuel composition;

f) the test result, in the format given below:

   1) the behaviour and appearance of the test specimen during and after the test and photographs;

   2) temperature/time graphs and spreadsheets of temperatures at no more than 30 s intervals for each thermocouple and DFT;

g) the results and intermediate calculation steps of calculations performed in accordance with 7.4;

h) a comparison of test results against the requirements in 7.5 and a statement of whether the test configuration meets the requirements and is suitable for fire testing;

i) an assessment of the environmental conditions in accordance with 7.6, including mean wind speed and precipitation throughout the test;

j) a description of permitted tolerances, in accordance with 7.7, for future fire testing.

8 Construction of fire test specimens

Fire test specimens shall be manufactured accordingly to appropriate pressure vessel standards (e.g. BS PD 5500, DIN 4680) and hydrostatically tested prior to fire testing. Test specimens shall be bullet-type vessels with rounded ends of dimensions identical to those used for calibration testing under Clause 7, subject to the tolerances in 7.7. The vessel shall be supported on two steel saddles, which may be insulated if required to ensure stability for the duration of the test. Unnecessary valves and gauges shall be removed, and all remaining connections shall be sealed. Covers or guards for gauges and connections shall be removed.

Any piping connecting to propane storage or venting that is to remain in place during the test shall be insulated for the duration of the test. Alternative insulation systems to the primary fire protection material or system tested may be used, subject to the termination detail at the joint of two insulation systems being designed to minimise the area of the vessel shell not protected by the primary test material and being documented in the test report.

Pressure relief valve (PRV) or blowdown valve (BDV) performance in a fire test is a variable outside the scope of fire protection material or system performance determination and is addressed in other standards (e.g. ISO 23251). PRVs or BDVs shall be simulated through the use of piping extending outside the fire engulfed zone to a fast acting (<0,5 s) full-port actuated valve connected to a discharge nozzle. The design of the discharge nozzle shall give the same flow capacity as the required PRV or BDV design standard, and control of the ball valve shall be set to mimic the appropriate activation pressure and re-close pressure as appropriate. A pilot flame shall be used to prevent formation of a cloud of unburnt gas. Further commentary on PRV and BDV and the applicability of test results is given in 16.1.

Pressure gauges, level gauges and any other vessel monitoring equipment utilised shall have a fire rating, or be insulated, equivalent to that of the design rating of the fire protection material or system.

The test vessel shall be filled to level of 20 % by volume with propane, representing a worst-case scenario in terms of fire protection material or system response. Further commentary on the applicability of results in consideration of fill level is given in 16.2.

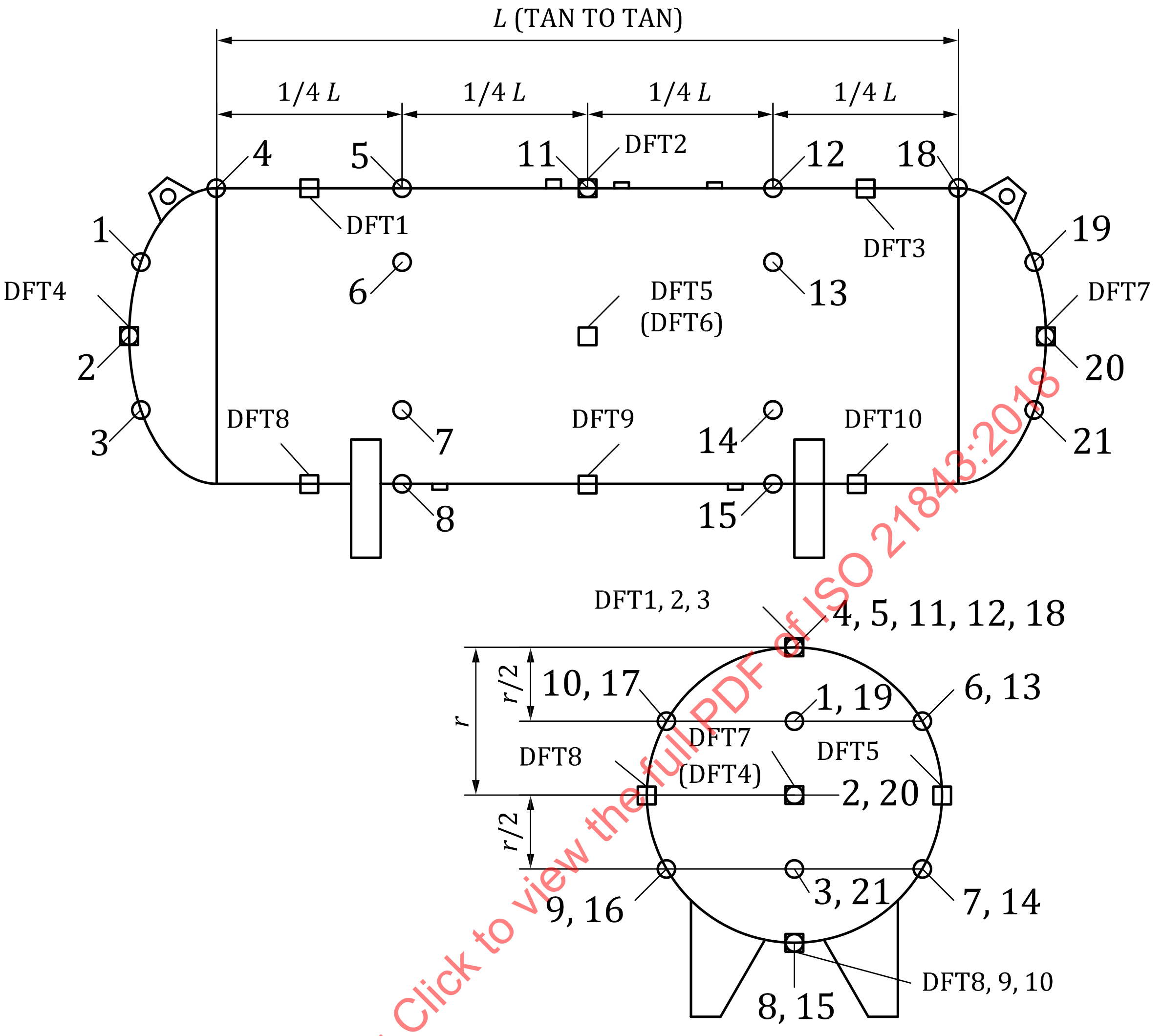
9 Instrumentation

The pressure vessel wall shall be fitted with 21 insulated type k thermocouples (1,5 mm minimum diameter) positioned in accordance with Figure 3. All thermocouples shall be attached to the vessel in accordance with the method in Annex C. Individual TCs that conflict with the position of lifting lugs or fittings may be moved radially by up to 0,1 m. Thermocouple positions that conflict with saddles shall be moved horizontally towards the middle of the vessel until they are at least 0,25 m from the saddle. Fire protection materials with joints shall have at least 4 thermocouples present at a joint, with at least one of these located at the top of the vessel and at least 2 further located above the fill line if possible.

The pressure vessel interior may be fitted with 5 type k thermocouples (1,5 mm) to give sample measurements of both the liquid and vapour space temperatures, if required by the test sponsor.

The vessel shell shall be fitted with 10 DFTs. Three shall be placed along the top of the vessel, three along the bottom, one at each end and one at the centre of each side. Nominal positions are indicated in Figure 3. DFT positions shall be moved from those indicated to give a minimum of 150 mm distance to each shell thermocouple position and any fittings or lifting lugs present. DFTs shall be oriented such that they face away from the vessel. In the event of the thermal protection system being of a nature that precludes direct DFT attachment, they shall be supported at a maximum distance of 150 mm from the vessel.

The vessel shall be fitted with 2 pressure transducers connected by tubing to the vessel. If the transducers are connected to the liquid space of the vessel, then all connecting tube exposed to fire shall be appropriately insulated to ensure boiling does not take place in the tubes.



Key

1 to 21	thermocouple positions
DFT1 to DF10	directional flame thermometer (DFT) positions
L	length of cylindrical part body of vessel (tan to tan length)

Figure 3 — Fire test specimen thermocouple positions

10 Fire protection materials and systems

10.1 General

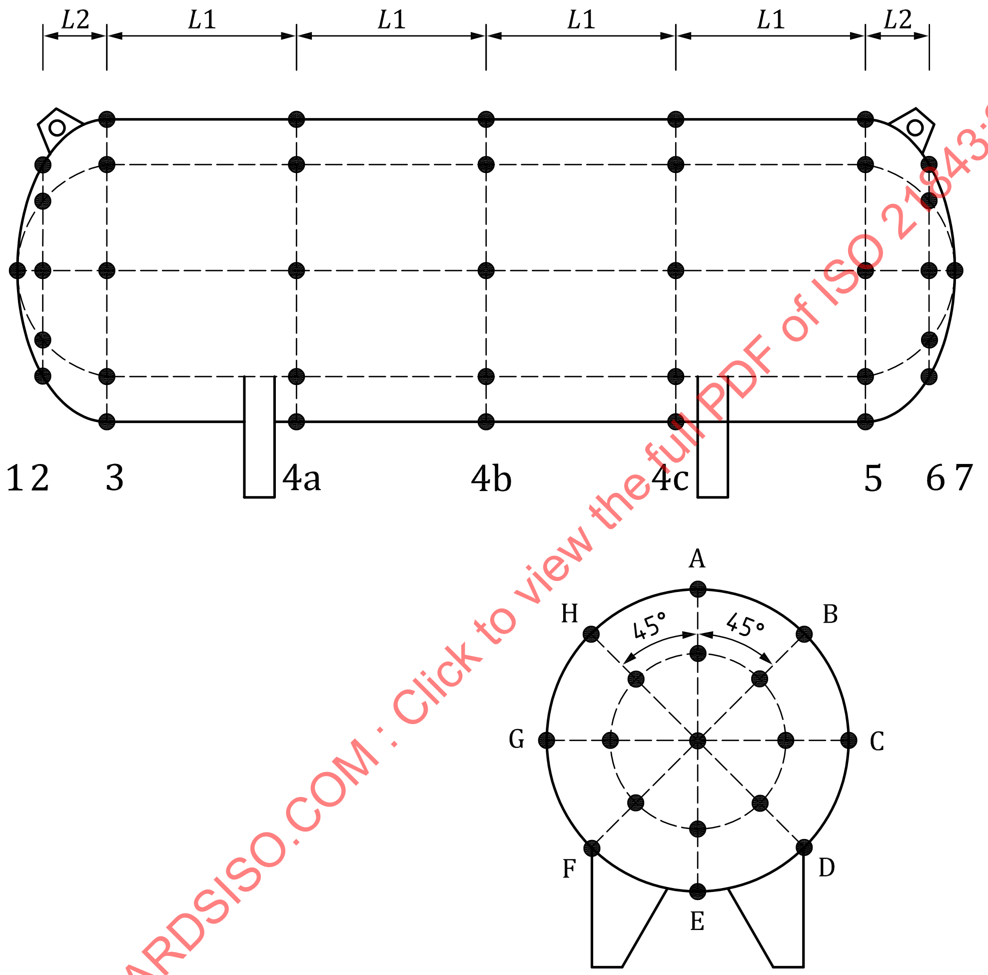
The fire protection materials are either coated directly onto the vessel or mounted directly onto the vessel or to a frame mounted on to the vessel. The surface of the vessel shell shall be prepared and the fire protection system applied in a manner representative of practice. The protection material shall be installed or applied to protect the entirety of the vessel shell, at thickness specified by the manufacturer of the protection.

10.2 Applied fire protection materials

If the fire protection is a coating material, the thickness shall be measured at the positions specified in Figure 4. Measurement shall be taken at the intersection position of eight lines that run parallel to the vessel axis, shown as A to H in Figure 4, and numerous circumferential bands, shown as numbers 1 to

7 in Figure 4. Bands 1 and 7 contain only a single measurement point and shall be omitted if the vessel has a flange in the same location. Bands 2 and 6 shall be at a distance from the tan line (L2) such that the distance to the adjacent bands is equal, as measured on the surface of the vessel. Bands 3 and 5 shall be at the tangent line. They may be moved by up to 100 mm towards the centre of the vessel to avoid the weld line if necessary. The number of bands on the cylindrical body of the vessel shall be the minimum number possible while ensuring that L1 does not exceed 500 mm.

At each measurement point the thickness shall be recorded as the average of a minimum of five spot measurements, 1 at the centre of the measurement point and 4 further points located 50 mm to 100 mm to each side.



Key

• measurement point

Figure 4 — Material thickness measurement positions

If thermocouple cover plates are used then a measurement point should be taken in the approximate centre of each cover plate.

If there are signs of thinning or thickening at positions away from the indicated measurement points additional measurements should be taken.

Measurements should be taken by non-destructive methods such as ultrasonic or eddy current depth gauges. Equipment should be described in the report with the method of calibration. Care should be taken to ensure mesh reinforcement does not lead to a false reading. If necessary, the thickness may be measured by drilling a 1,5 mm hole and then using a depth gauge. For cementitious sprays, a thickness gauge may be used with the measurement needle penetrating the soft sprayed material.

NOTE Figure 4 shows a total of 58 measurement positions, with three measurement positions on the cylindrical tank body along each line (4a to 4c). Longer tanks can require more measurement positions.

For reactive coatings and other applied fire protection materials the average primer thickness should be measured first and subtracted from the total average primer and reactive coating thickness. The resulting permitted thickness tolerances excluding primer and topcoat (assuming normal distribution of measured thickness) shall be as follows:

a) a minimum of 68 % of readings shall be within ±20 % of the mean;

b) a minimum of 95 % of readings shall be within ±30 % of the mean;

c) all readings shall be within ±45 % of the mean.

If the thickness is outside these limits the test specimens shall be adjusted to comply with above requirements.

10.3 Assemblies and mounted fire protection systems

For pre-fabricated protective (PFP) systems, the type of joints or fittings used to secure the protection system shall be the same as used in actual site-installation.

11 Test procedure

a) The sponsor shall specify the duration of the test. This may be varied during the test according to how the specimen performs. The maximum critical wall temperature and the maximum critical pressure reached within the vessel shall be specified in agreement with the test laboratory, taking into account sufficient safety margin for safe execution of the test.

b) The sponsor shall provide the specimen for the test in a condition representative of its practical application.

c) Photographs shall be taken of the test specimen before the test.

d) If the fire protection is a coating material, measure the thickness as described in 10.2.

e) For thermo-setting (e.g. intumescent) materials hardness measurements shall be made at a minimum of three positions, selected at the discretion of the test laboratory.

f) The vessel shall be filled to the level required and the exact fill level recorded.

g) Environmental conditions shall be measured immediately before the test and any significant changes during the test noted. Measurements taken shall include ambient temperature, vicinity wind speed, wind direction and a general description of any precipitation.

h) Ensure that a steady flow rate of fuel is provided. When the test flame first ignites a timer shall be started and the flow rate, temperatures and pressures monitored. Readings of the instruments shall be taken at the intervals no greater than the maximum specified.

i) Observations shall be recorded of significant detail of the behaviour and appearance of the test specimen during the test and after the fire is extinguished. Detail on deformation, spalling, cracking or burning of the fire protection material and continuance of flaming shall be noted.

j) Photographs of the test specimen shall be taken as soon as is practicable after the fire has been extinguished and also approximately one hour after the fire is extinguished. These shall be included in the test report.

k) Continuous visual records shall be made of the test.

12 Termination of the test

The test shall be continued until either the termination time or the critical temperature and/or critical pressure selected prior to the test is reached. The test laboratory may prematurely stop the test in the interest of safety if they observe, visually or through instrumentation, anything that would give them good reason to suspect the presence of a local hot spot that could compromise the integrity of the pressure vessel.

13 Repeatability and reproducibility

No direct data on repeatability (within laboratory variability) or reproducibility is currently available.

14 Uncertainty of measurement

There are many factors that can affect the result of a fire resistance test. Key factors requiring close control are the burner system fuel flow rate, the geometry of the test specimen and the burner arrangement. Environmental conditions outside the operators control can have a significant effect, hence the restrictions on environmental conditions imposed.

15 Test report

The test report shall include the following information:

a) the name of the testing laboratory, test date, unique test reference number and report identification;

b) names of the sponsor/customer, the manufacturer and the product or system;

c) documentation on how and when the test specimen was prepared, details of the application of the PFP material, the name of the applicator company and, if appropriate, the name of approval authority;

d) complete description of the test specimen, including:

1. pressure rating;
2. design code and standard;
3. vessel dimensions (diameter length, head type, wall and head thickness);
4. details of fittings, gauges and penetrations;
5. details of vessel supports;
6. details of vessel material;
7. details of any additional insulation systems used on the supports or fittings, etc.;
8. details of any connecting piping;
9. details of the test fluid;
10. test fill level;
11. PRV type, flow capacity, open and close pressures;

e) complete description of fire protection system present, including construction drawings wherever possible; measurements of the thickness of fire protection material including the mean, standard deviation and range of measurements; details of any intentional thickness steps or changes (if present); hardness if measured; details of any joint (if applicable) including positions, type, size of overlap and method of fixing;

f) when appropriate, details of any deviations from the normal test configurations and the reasons for them;

g) a record of test details and post fire characterization including;

 1) ambient conditions recorded at intervals of no more than 5 s;

 2) fuel pressure and temperature at intervals of no more than 2 s throughout the test, where these are used to calculate mass flow rate, and the method of control and calculation;

 3) fuel mass flow rate at intervals of no more than 2 s throughout the test and total mass of fuel used;

 4) for reacting materials, the thickness of unreacted or partially reacted material left at the end of the test and the char thickness at positions where the initial thickness was measured;

 5) for materials retained/supported by a reinforcing mesh, the condition of the mesh at the end of the test;

 6) for assemblies, a full inspection following the test to validate construction details and assess fire performance (the assembly should be dismantled so that all components of the system can be checked for flame penetration, integrity and general condition and a visual record made);

h) the test result, in the format given below:

 1) the behaviour and appearance of the test specimen during and after the test and photographs;

 2) temperature/time graphs and tabulated data of temperatures at no more than 30 s intervals for each thermocouple;

 3) pressure/time graphs and tabulated data of pressure at no more than 30 second intervals for each pressure transducer;

 4) the time and duration of activation of any PRVs, if present;

 5) an optional classification in terms of the type of specimen tested, maximum temperature rise and period of resistance in accordance with Clause 19.

The quantity of test fluid remaining in the vessel at the end of the test may be reported if agreed by the sponsor and test laboratory in advance of the test.

16 Practical application of test results

16.1 Pressure relief valve (PRV)

Activation of a PRV during the fire test mitigates the test severity by reducing the temperature of the vessel contents. In the event of PRV discharge, the direct classification as described in Clause 19 shall be either restricted to the time at which the PRV first opens, or shall be considered valid for the full duration of the test but restricted to the exact design of vessel and PRV as tested.

16.2 Propane (or alternative test fluid) fill level

A minimum fill level of 20 % is specified to provide an adequate rate of pressurization and represent an approximately worst-case balance between time to failure and severity of rupture. Increasing the fill level mitigates the severity of the test from the standpoint of the protection system, by increasing the heat sink and area of the shell wetted by the contents. Direct classification based on 20 % fill level tests shall be considered suitable for all vessel fill levels.

17 Performance criteria

17.1 General

It is not the purpose of this test method to provide guidance on the acceptability of a particular thickness of fire protection coating or method of assembly. Although the method specified has been designed to simulate some of the conditions that occur in a petroleum or LPG fuelled pool fire on solid surfaces, it cannot reproduce them all exactly. The results of this test do not guarantee safety but may be used as elements of a fire risk assessment for plant. This should also take into account all the other factors that are pertinent to an assessment of the fire hazard for a particular end use.

The criterion of performance, provided by the test, is the minimum time required to reach the critical temperature associated with the fire scenario to be protected against. However, the factors in subsequent subclauses shall also be considered when assessing performance.

17.2 Substrate temperature

The time-temperature profile at each measurement position shall be used to determine the maximum temperature at each position during the test. As pressurised vessels can rupture when a localised hot spot occurs, the mean substrate temperature shall not be used in the evaluation. The position and time of any sudden increase in the rate of temperature rise, if any, should be recorded as it is indicative of possible failure of the coating/system/assembly at that point. For the same reasons, the localized maximum temperature rise shall be reported in conjunction with the nearest fire protection material thickness for coating type systems.

17.3 Coatings and spray-applied materials

The amount of unreacted/partially reacted material remaining and the amount and condition of the reacted material (char for epoxy intumescent or subliming materials) provides an indication of performance. Particularly for the protection of any edge features, the condition of any reinforcement is important. The condition of the reacted material and the amount of unreacted/partially reacted material can be evaluated in terms of:

a) bare metal exposed and reinforcement destroyed;

b) no bare metal exposed but the reinforcement in poor condition and the reacted material easily detachable;

c) reacted material firmly attached and the majority of the reinforcement intact and attached;

d) unreacted/partially reacted material present, reacted material and reinforcement firmly attached.

If the temperature criterion is met, then a specimen meeting criterion d) clearly provides a wider safety margin than a specimen meeting criterion a). A statement of the criterion that is most appropriate should be included in the report.

Cementitious materials lose retained water during the test and then act as passive insulators. The external appearance and material thickness may not change significantly; however, whilst water is present, the temperature of the substrate remains at 100 °C and, when all the water has been driven off, the temperature increases to above 100 °C. Examination of the temperature-time curves provides an indication of whether there is retained water (unreacted or partially reacted material) at the end of the test.

17.4 Systems and assemblies

The penetration of flames or hot gases through any cracks, holes or breaches in joints should be considered when assessing the integrity of a system. Particularly for flexible systems (e.g. fibretype materials), the condition of the method of fixing (straps, etc.) is also important. The amount of penetration and condition of the method of fixing can be evaluated in terms of:

a) evidence of passage of flames through the system with the fixing system ineffective;

b) evidence of passage of hot gases/smoke through the system with the fixing system effective;

c) no passage of hot gases through the system and with the fixing system effective.

If the temperature criterion is met, then a specimen meeting criterion c) clearly provides a wider safety margin than a specimen meeting criterion a). A statement of the criterion that is most appropriate should be included in the report.

18 Factors affecting the validity of the test

18.1 Interruption of the test

It is inevitable that, in some tests, a control or instrumentation failure results in an interruption. Due to the total energy content within the vessel being critical to the severity of the test, interruptions shall terminate the test. Restarting the test shall not be permitted. In the event of unintentional interruption occurring within the first 2 min of the test (e.g. failure to light all burners) the test may be restarted, commencing at a time of 0.

18.2 Failure of thermocouples and DFTs

Up to one shell thermocouple may fail prior to a test after application or fitting of the protection material and the test shall be allowed. During fire testing, a maximum of three shell thermocouples may fail and the test shall still be considered valid. This shall be reduced to a maximum of two shell thermocouples if one failed prior to commencement of the test. No more than two failures may occur from the five shell thermocouples across the top of the vessel.

Up to two DFTs may fail and the test shall still be considered valid.

18.3 Failure of pressure transducers

An unexpected pressure transient can be an indication of a defect in a fire protection system. During fire testing a maximum of one pressure transducer may fail and the test shall be considered valid.

18.4 Test related tube and pipe

Any tube and pipe connected to the test tank that is not present in the real application vessel is regarded as a test related tube and pipe. This test related tube and pipe is used to connect instruments or other necessary lines (e.g. emergency dump, etc.). This tube or pipe can affect the thermohydraulics within the test tank.

All test related tube and pipes connected to the tank bottom shall be filled with liquid by gravity. These liquid filled lines shall be well insulated from the fire to ensure that boiling does not take place in the tube/pipe. Boiling in the tube/pipe can cause jetting of liquid and vapour into the tank causing mixing that would not be present in a real application vessel installation. This mixing affects how the tank pressurizes. If boiling takes place in pressure transducer lines it affects the indicated tank pressures. These liquid filled lines shall include thermocouples to clearly show that the liquid does not reach the boiling temperature for the measured tank pressure during the test.

A tube and pipe connected to the top of the tank shall be filled with vapour. Condensation is possible in these lines. The volume of a test related vapour filled tube and pipe shall be kept to a minimum and shall not exceed 2 % of the tank vapour space volume.

18.5 Variation in environmental conditions

It is recognised that environmental conditions are outside the control of the test operator or sponsor. Despite this, the significant effect they can have on exposed tests requires limitations on acceptable conditions. The tolerances described in 7.7 shall apply to all tests. Tests conducted in conditions which exceed these limits shall be considered invalid unless further calibration testing can be done to extend the range of acceptable environmental conditions.

18.6 Directional flame thermometer (DFT) results

For the test result to be valid the following criteria shall be met:

a) The average of all valid T_{DFT} values shall be within the range 816 °C to 927 °C;

b) All individual valid T_{DFT} values shall be within the range 670 °C to 1 070 °C;

c) The ratio of the average of the valid DFTs along the top of the vessel to the average of all valid direction flame thermometers shall be no lower than 0,85.

The DFT data shall exclude the first two minutes of the test.

19 Recommended classification procedures

19.1 General

For pressure vessels in fires the classifications/requirements are specified in one of two ways:

i) specified fire exposure duration and specified maximum allowable measured wall temperature.

ii) specified fire exposure duration for no vessel failure.

The regulator/authority will specify which one of these to use in a given test.

19.2 Type of fire

ISO 13702 distinguishes between cellulosic fires (CF), hydrocarbon pool fires (HC) and jet fires. Testing performed to this test procedure shall be designated HC.

19.3 Type of application

The test specimen is a pressure vessel. The following details shall be included in the description of this vessel:

a) pressure rating;

b) design code and standard;

c) vessel dimensions (diameter, length, head type, wall and head thickness);

d) details of fittings and penetrations;

e) details of vessel support;

f) details of vessel material;

g) details of test fluid;

h) test fill level;

i) PRV type, flow capacity, open and close pressures.

19.4 Classification based on temperature rise and period of resistance

The period of resistance is the total time that the specimen is exposed to the fire. This is the overall test period or the time of interruption of the fire as described in 18.1. The period of resistance shall be rounded down to the nearest 5 min. The temperature rise shall be taken at the highest temperature rise observed at any location during the test.

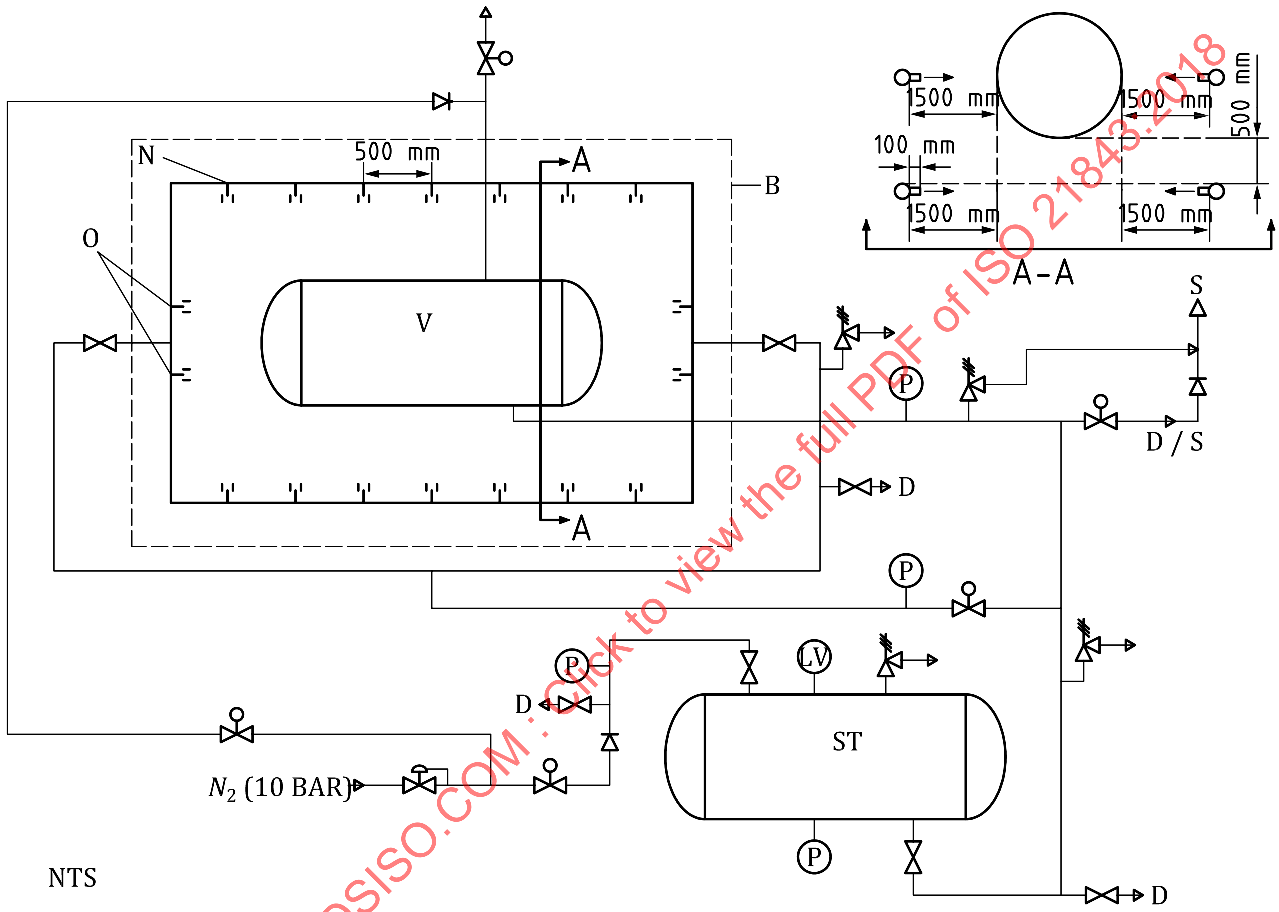
19.5 Classification based on duration before failure

The duration before failure is the time before tank failure while the vessel is fully engulfed in a steady fire as indicated by the DFT measurements. Tank failure is when there is a release of test fluid from an opening in the vessel other than a PRV. Further information is given in Annex E.

Annex A
(informative)

Example P&I diagram for test facility

See Figure A.1.



Key

N	nozzle
O	optional nozzle
V	test vessel
B	building for enclosure of test
S	stack
D	drain
P	pressure transducer
LV	level gauge
ST	storage vessel
N_2	nitrogen supply
NTS	not to scale

Figure A.1 — Diagram

Annex B
(informative)

Directional flame thermometers (DFTs)

B.1 General

The DFTs (see example illustrated in Figure B.1) should be capable of withstanding temperatures of 1 100 °C for a period of 15 min and consist of a type k thermocouple attached centrally to the rear-surface of a small steel plate. Rear-surface insulation ensures the instrument reaches the black-body equivalent fire temperature in the hemispherical direction viewed by the instrument.

The small steel plate shall not exceed 0,3 mm thickness or measure more than 80 mm × 80 mm.

The rear side of the steel plate shall be insulated with a low-density insulation capable of withstanding 1 100 °C. The minimum insulation thickness shall be 25 mm.

For constructability purposes the steel plate may wrap around the edges of the insulation and be attached to a rear surface. It is recognized that this increases the field-of-view of the instrument beyond truly hemispherical, however the results are considered valid for the purposes of calibration testing.

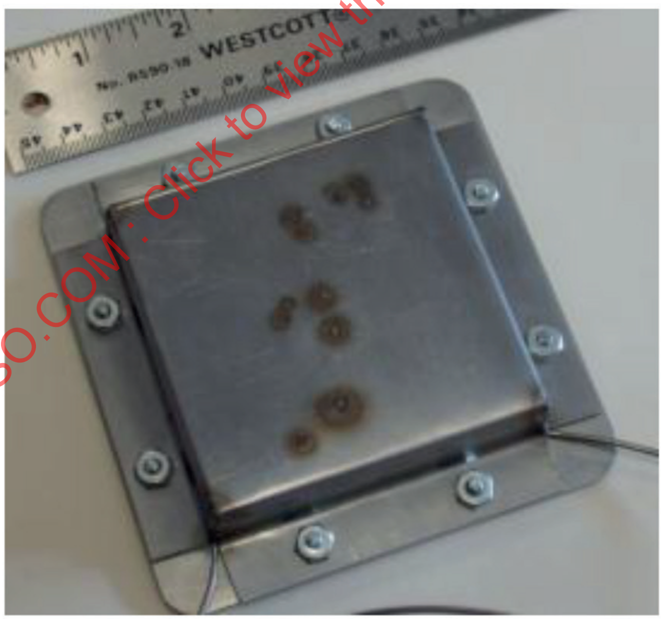


Figure B.1 — Example DFT[10]

Annex C
(normative)

Method of affixing thermometers

C.1 General

Thermocouples shall be affixed by the use of spot welded wire or thin strips of metal. The retaining metal shall terminate with 5 mm and 30 mm from the end of the thermocouple to ensure it is flush with the vessel surface (as shown in Figure C.1).

Figure C.1 — Method of affixing thermocouples

Optional cover plates may be used to assist uniform application of fire protection systems. These shall not exceed 150 mm × 150 mm in size, and shall be affixed to the vessel using spot welding or the same method as the thermocouples. No insulation shall be permitted under the cover plates. See Figure C.2.

Figure C.2 — Optional thermocouple cover plates

Vessels being re-used shall undergo appropriate surface preparation and hydrostatic testing prior to installation of fire protection systems. Thermocouples may be retained subject to testing. Any faulty thermocouple shall be replaced prior to installation of fire protection systems.

Annex D
(informative)

Radiation convection balance

D.1 General

The radiation-convection (R-C) balance is an important parameter to determine whether a burner based fire is a good simulation of a large pool fire. The R-C balance can be estimated in two ways[11]. One method is by calculation from DFT temperatures and water-cooled calorimeter data, and the other method is by using a thermal imager. There is uncertainty in both methods.

D.2 Method 1: Calculation from temperature data

This method is based on the energy balance equations of the directional flame thermometer (DFT) and the water-cooled calorimeter. It is adapted from reference [9]. It requires estimation of the flame temperature and the surface emissivity of the DFT and calorimeter.

D.2.1 Flame temperature

For the purpose of this analysis, the flame temperature shall be assumed to be 1 100 °C.

NOTE It is recognised that there is an inherent error caused by assuming the flame temperature, however the degree of error can be considered acceptable in the interest of standardising the calculation.

D.2.2 Surface emissivity (ε_S)

The DFT and water-cooled calorimeter shall be subjected to fire prior to the calibration test or actual test to allow soot deposits and increase the emissivity. A surface emissivity of 0,85 ± 0,05 shall be used in the calculation.

D.2.3 Calorimeter temperature (T_{cal})

It shall be taken as the average water temperature at the point of termination of the calibration test, calculated in accordance with Formula (1).

D.2.4 DFT temperature (T_{DFT})

It shall be the average of all valid DFT average temperature values, calculated in accordance with 7.4

NOTE For the purposes of the calculation the DFT receiving surface shall be assumed to behave adiabatically. Heat losses are not considered in the calculation.

D.2.5 Ambient temperature (T_{amb})

It shall be the average ambient temperature recorded during the period of the calibration test.

D.2.6 Calculation methodology

The convection heat transfer coefficient shall be calculated using Formula (D.1).

$$h = \frac{q_{\text{net}} + \sigma \varepsilon_{\text{s}} \left(T_{\text{cal}}^4 - T_{\text{DFT}}^4 \right)}{\left(T_{\text{DFT}} - T_{\text{cal}} \right)} \quad \text{(D.1)}$$

The calculated convection coefficient, assumed flame temperature, ambient temperature and the surface emissivity shall be substituted into Formula (D.2). The equation can then be solved iteratively, varying the flame emissivity (ε_{f}) between 0 and 1 until the calculated heat flux equals the net heat flux (q_{net}) determined during the calibration test in accordance with Formula (2).

$$q_{\text{net}} = \sigma \varepsilon_{\text{s}} \varepsilon_{\text{f}} T_{\text{f}}^4 + \sigma \varepsilon_{\text{s}} \left(1 - \varepsilon_{\text{f}} \right) T_{\text{amb}}^4 + h \left(T_{\text{f}} - T_{\text{cal}} \right) - \sigma \varepsilon_{\text{s}} T_{\text{cal}}^4 \quad \text{(D.2)}$$

The individual convection and radiation components shall be calculated in accordance with Formulae (D.3) and (D.4) using the assumed fire temperature and the flame emissivity value determined iteratively in accordance with Formula (D.2), as appropriate.

$$q_{\text{conv}} = \left(T_{\text{f}} - T_{\text{cal}} \right) \quad \text{(D.3)}$$

$$q_{\text{rad}} = \sigma \varepsilon_{\text{s}} \varepsilon_{\text{f}} T_{\text{f}}^4 + \sigma \varepsilon_{\text{s}} \left(1 - \varepsilon_{\text{f}} \right) T_{\text{amb}}^4 - \sigma \varepsilon_{\text{s}} T_{\text{cal}}^4 \quad \text{(D.4)}$$

The radiation fraction shall be calculated in accordance with Formula (D.5).

$$f_{\text{rad}} = \frac{q_{\text{rad}}}{q_{\text{rad}} + q_{\text{conv}}} \quad \text{(D.5)}$$

D.3 Method 2: Thermal imager use

This method uses a thermal imager to estimate the effective black body radiating temperature of the fire. This temperature is compared to the DFT temperatures. An appropriate thermal imager is needed to view the fire and calibration tank during the calibration tests. This thermal imager views the fire engulfed tank and measures the wall (water-cooled) temperature and the DFT temperature on the tank side. These temperature measurements are referred to as the indicated temperatures. The indicated temperatures are different to (generally higher than) the true DFT and true wall temperatures because the thermal imager is looking through the fire.

The energy balance equations for the indicated temperatures and for the real DFT and wall temperatures can be solved simultaneously to calculate the fire emissivity and the convective heat transfer coefficient.

D.3.1 Emissivity

The emissivity in the thermal imager shall be set to equal 1. The range from the imager to the fire and the air humidity shall be set according to the conditions at the time of measurement.

NOTE Setting the thermal imager emissivity as 1 ensures the imager shows the effective black body fire temperature in the direction facing the thermal imager. This is not exactly the same as what the tank sees because the imager sees the tank behind the fire, and the tank sees the cool surroundings behind the fire. If the fire has high emissivity this error is small. This calculation is not exact but it gives a reasonable estimate of these variables.

D.3.2 Assumptions

This method is based on the following assumptions:

i) the thermal imager spectral operating window is appropriate for fire analysis;

ii) the fire has high soot concentration (volume fraction > 1 ppm) and therefore radiates and absorbs as a gray body;

iii) the fire is steady;

iv) the fire thickness is constant and uniform;

v) the fire temperature and emissivity are constant and uniform;

vi) atmospheric attenuation can be ignored;

vii) viewed surfaces have high surface emissivity (e > 0,9);

viii) view factor for surface to fire is F = 1;

ix) convection heat transfer coefficient on the calorimeter tank and on DFT are the same.

D.3.3 Measurement position

The position of the DFTs and the cool wall measuring points on the wall shall be selected to ensure the fire depth is equal for all the surfaces viewed.

NOTE 1 This is necessary because the fire emissivity is related to the fire depth. For example, the fire depth is usually thinner at the tank mid height than at the tank top. If the DFT is mounted at the tank mid height and the cool wall is viewed at the tank top then the depth of fire is different and this leads to different flame emissivities for these two samples. This adds uncertainty to the calculation of the radiation convection balance.

NOTE 2 The flame temperature, thickness, soot content, etc. will inevitably vary over the tank surface and with time. This analysis is a spot check at one location. This method can optionally be repeated at numerous locations to derive an average value.

D.3.4 Fire emissivity

Considering a fire as a gas volume radiating to a surface, the flame emissivity is given by Formula (D.6)[8].

$$\varepsilon_{\mathrm{f}} = 1 - e^{-\alpha L_{\mathrm{m}}} \qquad \text{(D.6)}$$

where

ε_{f} is the flame emissivity;

α is the flame extinction coefficient (m^{-1});

L_{m} is the mean path length for the flame volume, equal to 1,8 L, where L is the depth of fire at the measuring point (m).

Thermal imagers view through narrow angles equivalent to a straight line path. The signal the element gets is due to radiation along this path line. Emission and absorption along a straight-line path is given by Formula (D.7).

$$\varepsilon_{\text{fire-line}} = 1 - e^{-\alpha L_{\text{line}}} \qquad \text{(D.7)}$$

where L_{line} is the path length, equal to the depth of fire at the measuring point (m).

D.3.5 Flame temperature

For the purpose of this analysis the flame temperature shall be assumed to be 1 100 °C.

NOTE It is recognised that there is an inherent error caused by assuming the flame temperature, however the degree of error can be considered acceptable in the interest of standardising the calculation.

D.3.6 Surface emissivity (ε_s)

The DFT and water-cooled calorimeter shall be subjected to fire prior to calibration test or actual test to allow soot deposits and increase the emissivity. A surface emissivity of 0,85 ± 0,05 shall be used in the calculation.

D.3.7 Calorimeter temperature (T_{cal})

Shall be taken as the average water temperature at the point of termination of the calibration test, calculated in accordance with Formula (1).

D.3.8 DFT temperature (T_{DFT})

Shall be the average of all valid DFT average temperature values, calculated in accordance with 7.4

NOTE For the purposes of the calculation the DFT receiving surface shall be assumed to behave adiabatically. Heat losses are not considered in the calculation.

D.3.9 Ambient temperature (T_{amb})

Shall be the average ambient temperature recorded during the period of the calibration test.

D.3.10 Indicated calorimeter temperature ($T_{cal\text{-}indic}$)

Shall be the average temperature recorded by the thermal imager at the calorimeter measurement spot averaged over a representative period of stable flame. Periods shall be considered stable when there are no large decreases caused by obvious wind effects.

D.3.11 Indicated DFT temperature ($T_{DFT\text{-}indic}$)

Shall be the average temperature recorded by the thermal imager at the DFT measurement spot averaged over a representative period of stable flame. Periods shall be considered stable when there are no large decreases caused by obvious wind effects.

D.3.12 Energy balance equations

The energy balance equation for the indicated calorimeter temperature is given by Formula (D.8).

$$\sigma T_{\text{cal-indic}}^4 = \varepsilon_s (1-\varepsilon_{\text{fire-line}})\sigma T_{\text{cal}}^4 + (1-\varepsilon_s)(1-\varepsilon_{\text{fire-line}})\varepsilon_f \sigma T_{\text{cal}}^4 + \varepsilon_{\text{fire-line}}\sigma T_f^4 + (1-\varepsilon_s)(1-\varepsilon_{\text{fire-line}})(1-\varepsilon_f)\sigma T_{\text{amb}}^4 \quad \text{(D.8)}$$

where

ε_s is the surface emissivity;

T_{amb} is the average ambient temperature during the calibration test period (°C);

$T_{cal\text{-}indic}$ is the indicated calorimeter tank temperature (°C);

T_{cal} is the calorimeter temperature (°C);

T_f is the assumed flame temperature (°C).

The energy balance equation for the indicated DFT temperature is given by Formula (D.9).

$$\sigma T_{\text{DFT-indic}}^4 = \varepsilon_s (1-\varepsilon_{\text{fire-line}}) \sigma T_{\text{DFT}}^4 + (1-\varepsilon_s)(1-\varepsilon_{\text{fire-line}}) \varepsilon_f \sigma T_{\text{DFT}}^4 + \varepsilon_{\text{fire-line}} \sigma T_f^4 + (1-\varepsilon_s)(1-\varepsilon_{\text{fire-line}})(1-\varepsilon_f) \sigma T_{\text{amb}}^4 \quad \text{(D.9)}$$

where

$T_{\text{DFT-indic}}$ is the indicated DFT tank temperature (°C);

T_{DFT} is the average DFT temperature (°C).

The energy balance equation for the calorimeter is given by Formula (D.2).

The energy balance equation for the DFT is given by Formula (D.10).

$$q_{\text{net}} = \sigma \varepsilon_s \varepsilon_f T_f^4 + \sigma \varepsilon_s (1-\varepsilon_f) T_{\text{amb}}^4 + h(T_f - T_{\text{DFT}}) - \sigma \varepsilon_s T_{\text{DFT}}^4 \quad \text{(D.10)}$$

D.3.13 Calculation methodology

Formulae (D.2) and (D.6) to (D.10) shall be solved simultaneously (or iteratively) using appropriate software to give the fire emissivity and the convection coefficient. The radiation fraction shall then be calculated using Formulae (D.3) to (D.5).

When solved iteratively, the following steps shall be undertaken:

1. For a range of flame temperatures iteratively determine the flame emissivity value that gives the correct indicated DFT temperature [Formula (D.9)];
2. For the combinations of flame temperature and flame emissivity calculated in step 1, calculate the indicated calorimeter temperature [Formula (D.8)]. The flame temperature and corresponding emissivity combination that gives the correct indicated calorimeter temperature shall be considered the 'correct' result;
3. Using the 'correct' values of flame temperature and emissivity iteratively determine the convective heat transfer coefficient that gives the measured heat flux to the calorimeter [Formula (D.2)];
4. Calculate the radiative fraction using Formula (D.3) to (D.5).

When calculated iteratively, the calculated heat flux to the DFT does not equal 0. This is attributed to conduction losses from the DFT receiving surfaces. The net heat flux should be calculated [Formula (D.10)] using the results from steps 1 to 3. If the result is relatively small (less than 5 % of the calorimeter measured heat flux) then the result is considered acceptable.