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EFECTIS FIRE TEST PROCEDURE

Fire test procedure for concrete structures in Oil & Gas, Petrochemical and Chemical installations

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PREFACE

In the oil & gas industry, a long tradition exists with regard to fire protection of structures. Steel structures are protected with proven systems that are evaluated according to fit for purpose test methods. Concrete load bearing structures are often designed to carry processing equipment or provide the foundation for other structures such as structural steel. In any case the load bearing capacity of these concrete structures shall be maintained in order to avoid further escalation of the fire event, avoid damage to the facility and minimize subsequent downtime of the facility.
However, for concrete elements the fire resistance is often deemed to satisfy, without further assessment. Developments in concrete design and knowledge about the behaviour of concrete in the last two decades show that, especially in an industry like oil & gas where reliability of the installations is the most important objective, concrete merits a more thorough evaluation of its fire resistance. The result of such an analysis can be that fire protection of the concrete structure is recommended in order to avoid damage during fire.

In order to provide a method for the evaluation of the fire protection of concrete, Efectis Nederland has produced this test procedure taking into account the experience and knowledge obtained through research and fire tests on concrete structures since the 1980's.

The purpose of this document is to provide a test procedure which reflects the current state of the art and which is suitable for a practical range of construction types and fire protection systems.

1. INTRODUCTION

Unprotected or insufficiently protected concrete structures can be seriously damaged during a fire, especially a hydrocarbon fire. Also such damage will jeopardise in many cases the (steel) structures resting on the concrete (sub)structure. To prevent or at least mitigate such damage during and after a fire, measures can be taken to protect the concrete structure. Measures may aim to:

- avoid or limit spalling of concrete,
- limit temperatures or the heating rate of the concrete surface,
- limit temperatures of the reinforcement,
- limit temperatures of the concrete around the reinforcement.

Depending on the situation, different fire protection measures may be chosen. These measures can be basically divided into two categories:

1. measures inside the concrete (concrete mix, additives, polypropylene fibres, etc.),
2. measures outside the concrete (external fire protection systems).

If easy repair and limitation of downtime of the facility after a fire is considered a relevant requirement, external fire protection systems are the indicated solution. Also if an existing structure needs to be refurbished, obviously the concrete mix cannot be changed so external fire protection is the only option.

The general performance characteristic of the external fire protection system is its insulating capacity. The better the insulating capacity, the slower the concrete will heat up during fire.

In order to determine the required fire protection thickness, the following information shall be observed:

- the insulating capacity of a fire protection system as a function of the protection thickness and
- the requirement for the maximum allowable concrete temperature.

The maximum allowable concrete temperature depends on different factors. If the concrete does not spall, limitations can be set for the concrete surface temperature and/or the reinforcement temperature, in order to avoid excessive deformation and difficult repair. If the concrete is sensitive to spalling, it is often necessary to require a lower maximum concrete surface temperature.

Some important indicators for higher sensitivity to spalling are:

- exposure to hydrocarbon fires,
- prefabricated concrete elements,
- concrete elements with high durability, low permeability,
- concrete elements in an environment with high relative humidity,
- pre-stressing, post-tensioning, high compression or restrained thermal expansion.

Indicators for lower sensitivity to spalling are:

- low compressive strength (indicatively up to C20/25),
- dry environment.

In case of spalling-sensitive concrete, it is recommended to perform project specific spalling tests.
For this reason two different tests are described in this testing procedure, aiming to provide information on:

- temperatures of the concrete surface, protected by an external fire protection system (“thermal insulation test”),
- spalling behaviour of the concrete structure (“spalling test”).

Table 1 Main characteristics of spalling tests and thermal insulation tests

Thermal insulation test	**Spalling test**
(Chapter 2)	(Chapter 3)
Fire protection system included in test	If applicable, fire protection system included in test
Simple and small concrete geometry	Realistic and full scale concrete geometry
No mechanical load	Mechanical load (compression)
Low quality concrete mix to avoid spalling during the test	Real concrete mix, moisture content, ageing
One single test required, although multiple tests with different protection thicknesses open possibility for interpolation	Two identical tests required (incl. identical fire protection system and thickness)

Besides carrying out fire tests, it may be required to demonstrate the resistance of a fire protection system against other influences such as air pressure waves, frost-thaw cycles, chemically aggressive environments, UV radiation etc. Such tests are not described in this document. Relevant ETAG (018) can be used for these purposes.

1.1 THERMAL INSULATION TEST

The insulation capacity of an external fire protection system can be determined by doing small-scale fire tests on unloaded elements, made out of a low quality concrete mix that is unlikely to spall. The set of test elements covers a range of practical element sizes. A high moisture content of the concrete elements should be avoided in order to avoid spalling, because spalling of concrete is not the objective of this test.[i]

Subject of the test is the fire protection system including application procedure, curing conditions, fixings, joints, and a low (or representative) moisture content.

The test aims to:
- assess the suitability of the insulation material to withstand the temperature during a fire according to a prescribed time-temperature curve (the fire curve as described in UL 1709),
- assess if the fire protection system is properly fixed to the concrete in order to prevent it from falling down during the fire,
- assess the required thickness of the insulation material in relation to the stated temperature requirements.

The procedure for performing a thermal insulation test is described in chapter 2.

Note: it is recognised that a passive fire protection system comprises the application, the material, the fixings etc. Therefore, although small, all test specimens must have a representative scale to investigate the behaviour of the complete system. Usually an element length of 2 m suffices, but this needs to be evaluated for the fire protection system under consideration. The chosen measure is therefore not driven by furnace dimensions.

1.2 SPALLING TEST

Spalling tests are needed to assess the suitability of a concrete structure for application in practice, given the possibility that during a fire unacceptable damage to the structure may occur due to spalling of the concrete. The test therefore comprises the concrete structure including intended measures to prevent spalling such as the application of an external fire protective layer, addition of polypropylene fibres to the concrete mix or other adjustments of the concrete formula.

The test specimens should resemble the practical situation as closely as possible, including the exact concrete mix and possible fire protection measures. A spalling test shall incorporate at least the following characteristics based on the real situation:

- concrete mix (proportions, sizes and types of all ingredients, if applicable: including the polypropylene fibres);
- representative compressive load;
- conditioning of the specimen (storage of the specimens wrapped in plastic foil; concrete age of at least 90 days at the time of testing)[ii];
- if applicable: fire protection system (including application procedure, curing conditions, fixings, joints, and a low moisture content).

The phenomenon of spalling is very complex and involves a combination of physical, chemical and mechanical processes, influencing each other. This is one of the reasons why scale tests or computer modelling are considered inadequate to conclude on the spalling risk for a given situation.

It is required to do fire tests on at least two identical test specimens which represent the actual geometry as closely as possible. The procedure for performing a spalling test is described in chapter 3.

2. THERMAL INSULATION TEST

A thermal insulation test serves to prove the thermal insulating capacity of a fire protection system. This type of test is not linked to a specific project. The test results can be used for any given concrete structure, observing the fact that fire protection systems for calcareous aggregate concrete and siliceous aggregate concrete must be tested separately because of the different thermal behaviour of the two concrete types.

The test result does not provide any answers with regard to spalling of concrete, because the concrete specimen is simplified to a simply supported element, without taking into account all other conditions (geometry, loading, conditioning, etc.) that can influence spalling. If the concrete structure of a specific installation is expected to be sensitive to spalling, a project related spalling test must be done, see chapter 3.

2.1 TEST SPECIMENS

The test specimens are chosen in such a way that they are considered representative for both beams and columns. Beams and columns have the following relevant characteristics:

- Three- or four sided fire exposure. Columns are usually fire exposed on all four sides. Beams may be exposed on three sides (vertical sides and bottom) if there is a floor slab on top, or on all four sides if there is no floor slab directly on top of the beam. Four sided exposure is more onerous with regard to the temperature increase inside the concrete element.
- Horizontal or vertical orientation of the element. For the performance of the fire protection system, horizontal orientation is more onerous because gravity will negatively influence the stickability of the external fire protection system on the bottom side.

Based on these considerations, the test specimen is a horizontal element with fire exposure on all four sides. The element is 2.0 m in length. The cross-section is mentioned in Table 2, with four chamfered corners of 15x15 mm.

In order to cover a relevant range of concrete cross section and fire protection thicknesses, the following specimens shall be tested:

Table 2 test specimens for a thermal insulation test

	Concrete cross section 150x150 mm	Concrete cross section 300x300 mm	Concrete cross section 450x450 mm
Minimum fire protection thickness	X	O1	X
Intermediate fire protection thickness	O2	O1&O2	O2
Maximum fire protection thickness	X	O1	X

X = obligatory
O1 = optional (for more accurate interpolation between concrete sections)
O2 = optional (for more accurate interpolation between protection thicknesses)

The test specimen shall be made with a concrete mix using calcareous or siliceous aggregates, depending on the intended application, and shall be optimized to avoid spalling of concrete. The strength class of the concrete is not relevant for the thermal behaviour, but in order to avoid spalling of the specimen during the fire test it is usually necessary to make a relatively low strength concrete.

A practical reinforcement is to be included in the concrete specimen. At both end surfaces of the specimen, connectors for lifting equipment can be included to facilitate the handling of the specimen without damaging the fire protection on the four long side surfaces.

2.2 CONCRETE TEMPERATURE MEASUREMENTS

The main objective of the fire test is to evaluate if the fire protection system remains intact during the exposure to the applicable fire curve and if the tested thickness provides sufficient insulation capacity. Temperature measurements at the concrete surface, behind the fire protection, are key to the evaluation of the performance. The location of these thermocouples is referred to as the "interface".

Along the length of the element, three cross sections are equipped with thermocouples. These cross-sections are located at mid-span and 200 mm to either side of mid-span. Each cross section is equipped with twelve thermocouples, located in the concrete surface:

- At 50 mm from the corners,
- In the middle of each side.

If a board protection is applied as lost formwork (i.e. applied before casting the concrete) then the chamfered corners may be omitted. In that case, at each corner two thermocouples are placed in the concrete surface at 50 mm from the corner.

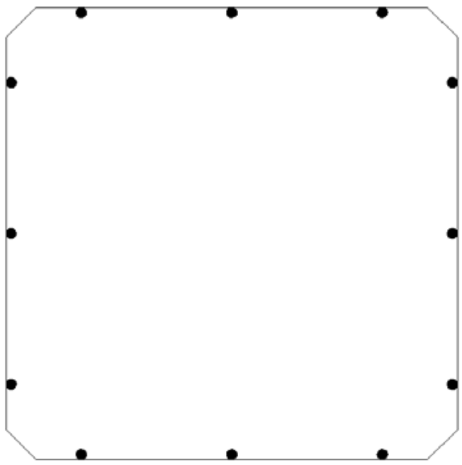

Figure 1 Schematic cross section and schematic thermocouple locations

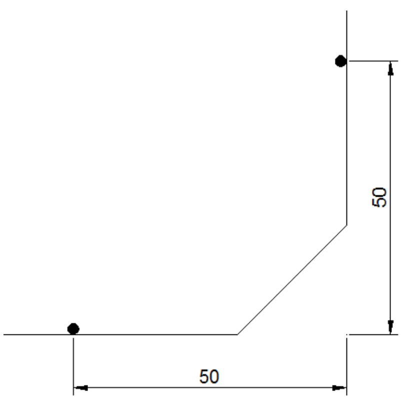

Figure 2 Thermocouple positions at chamfered corner

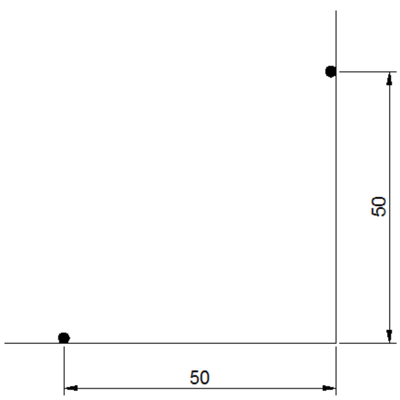

Figure 3 Thermocouple positions at corner in case of lost formwork board protection

2.3 FIRE PROTECTION SYSTEM

This paragraph describes how the fire protection system should be applied on the concrete test specimen in order to be representative for the practical situation.

A number of external fire protection systems are currently available:
- spray mortar;
- post-fixed boards;
- pre-fixed boards (insulation material applied in the formwork before casting of the concrete).

2.3.1 Positioning of the concrete element during application of the fire protection

Depending on the chosen fire protection system, the quality of the application of the system depends on the orientation of the concrete element. This is for example the case when applying a spray mortar, where a quality difference may occur depending on spraying up, down or sideways. If the testing lab judges that there is such a dependency, the element shall be positioned horizontally, with the top and bottom surfaces clearly marked (preferably on the ends of the element, so that after application of the material this is still readable).

At the ends of the bottom side, a length of 200 mm may be used for supporting the element during spraying. This area will remain unprotected. During the fire test, the same area can be used to support the element.

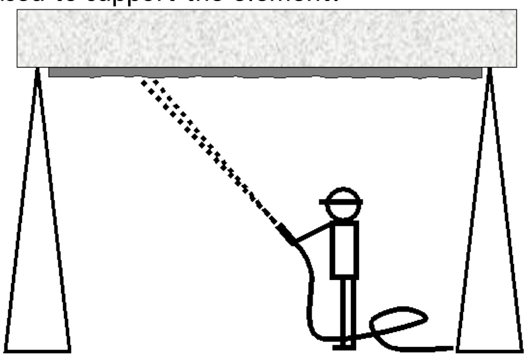

Figure 4 Overhead spraying of spray mortar

In order to be able to spray the bottom side of the element in an overhead position and be able to spray the sides and top surfaces, easy accessibility from all sides shall be provided during application of the spray mortar (e.g. by means of a scaffold).

The same top-bottom orientation during spray application shall afterwards be maintained during drying, storage and fire testing of the element.

2.3.2 Joints between boards

The board protection system shall exist of board panels with joints of the type intended to be used in practice (butt joint or rebated joint). If the board system includes cover strips behind the joints, these shall also be included in the test, including their dimensions, material type and fixings.
The joint shall be located at the middle ring of thermocouples. In case of overlapping board patterns and/or multilayer board systems, the individual joint sections shall be on different thermocouple rings. The overlap is then 200 mm, in order to coincide with the thermocouple rings. In practice, overlaps greater than or equal to 200 mm are allowed. In order to allow smaller overlaps in practice, an additional thermocouple ring is required in order to match the thermocouple locations to the board joints.

2.3.3 Requirements for the fixing of protective materials

All fire protection materials shall be applied to the concrete in such a way that the protective material, when used in practice, will not fall down during normal operation and during a fire. The anchoring system (direct bonding, anchors, wire mesh etc.) is the supplier's choice. The system that is tested must be equal to the system to be applied in practice.

The bonding of spray mortars to the surface is strongly influenced by the surface treatment of the concrete before spraying. If the concrete surface is roughened e.g. by high pressure water jet washing, the test result is only valid for situations in which the concrete is treated to the same surface roughness. Also the cleaning of the concrete before applying the spray mortar shall be the same in the test specimen as in the real situation.

If anchors are used to fix the material (board, spray mortar) to the concrete, the fixing pattern should resemble the real situation as closely as possible:

- the same centre distance between two anchors;
- the same distance between anchors and board joints (boards only).

If a wire mesh is used to fix a spray mortar to the concrete, the same type of wire mesh (mesh size, diameter, shape, etc.) shall be applied in the test specimen as in practice.

If boards are fixed using anchors with a diameter of maximum 6 mm, it is not required to measure the concrete surface temperatures near the anchors. If larger diameter anchors are foreseen, it should be considered that these may cause a significant heat leakage into the concrete and therefore it may be required to measure the temperatures near the anchors. These measured temperatures will be used as an input for thermal finite element analyses in order to evaluate if the reinforcement temperature remains below 250 °C (482 °F). For more details see chapter 2.8.

2.3.4 Thickness of protective materials

The thickness of the protective material shall be measured as follows:

- ❑ sprayed material (in wet condition):
  - measurement in 7 rings spaced every 200 mm (the three rings of thermocouple locations shall coincide with the three middle rings of thickness measurements);
  - each ring containing at least 1 measurement at each corners (under a 45º angle, measurement of thickness over the chamfered corner) and on each side 1 measurement (150 mm element), 2 measurements (300 mm element) or 3 measurements (450 mm element). If the applied thickness is irregular, the lab shall perform additional measurements in order to accurately define the applied thickness distribution.
- ❑ board materials:
  - before the application of the protection on the test element at least nine random measurements of board shall be taken for board thickness measurement.

The thickness mentioned in the report will be the mean thickness, as well as the minimum and maximum values and a standard deviation based on a normal distribution. A 95% characteristic upper limit thickness is equal to the average measured thickness + *t**standard deviation, where *t* can be found in table 3.

Table 3 t-values for a 95% characteristic value based on the Student's t-distribution

Number of measurements	*t*
≥9	1.833
≥25	1.708
≥40	1.684
≥60	1.671
≥100	1.660

2.3.5 Other requirements for fire protection systems

Besides fire resistance, other properties of a fire protection system such as frost/thaw resistance may also be relevant. These aspects are not considered in this document.

2.4 CONDITIONING OF THE TEST SPECIMENS

The performance of fire protection systems is strongly dependent on their moisture content. Therefore, the conditioning of the specimens and the actual moisture content at the time of testing shall meet the requirements as described in this paragraph.

<u>Moisture content of the fire protection material before the start of the test</u>
It is important to execute the tests with a moisture content which represents the actual situation during operation.

- The moisture content of the fire protection shall be sufficiently low as to represent the equilibrium moisture content in a relatively dry environment (in principle ≤ 5 % (m/m) for boards and ≤ 8 % (m/m) for spray mortars unless proven otherwise);
- If the measured moisture content is more than 3 %, the influence of the present moisture shall be numerically treated (see 2.4.2);
- Additionally, if the intended application is in a potentially wet environment, optional extra tests shall be done with water saturated fire protection.

A summary of the requirements is given in Table 4.

2.4.1 Samples for determination of the moisture content

Each fire test specimen shall be accompanied by at least the following test samples:

a) One sample of the protective material as specified in Figure 7 (spray mortar only)
b) Two samples of concrete and protective material as specified in figure Figure 8.

ad a)
This sample is needed to monitor the moisture content of the insulation.
A steel tray must be sprayed to the same spray mortar thickness as the test element. The tray shall be weighed before and directly after the application of the sprayed protective material. After spraying, the tray shall be stored together with the test specimen. The tray will be weighed at regular intervals, to monitor the decreasing moisture content of the insulation material.

Figure 5 Steel tray with spray mortar

ad b)
This sample is needed for the final determination of the moisture content and density of the insulation material and the concrete.

- For post-fixed boards, the sample can be a piece of board from the same batch as used for protecting the specimen. The piece of board shall be at least 300x300 mm^2.
- For post-applied spray mortars, the sample consists of a small concrete slab (measuring 300 x 300 x ≥50 mm^3) protected with the intended mean thickness of insulation material. The slab shall be protected by spray mortar in the same way as the fire test specimen but without wire mesh reinforcement. The application of the spray mortar may commence at a concrete age of at least 28 days.
- For pre-fixed materials (e.g. lost formwork board systems), the sample consists of a small concrete slab (measuring 300 x 300 x ≥50 mm^3) protected with the intended mean thickness of insulation material. The small slab shall be produced by casting the concrete on top of the pre-applied material. The vertical sides of the specimen shall be prevented from drying, e.g. by leaving a formwork around the small slab.

Figure 6 Concrete sample in its formwork, with spray mortar applied to the top surface

The fire test should not take place before the protective material have reached the following conditions:

- For “dry” specimens: average moisture content of insulation materials: in principle ≤ 5 % (m/m) for boards and ≤ 8 % (m/m) for spray mortars; a higher moisture content is only allowed if the supplier can prove that this will be the case in practice. Please note that for commonly used spray mortars the drying time needed to reach this level may be more than two months (depending on storage conditions and insulation thickness).[iii]
- For optional “saturated” specimens: the fire protection shall be fully saturated by water with a temperature of (20 ± 5) °C ((68 ± 9) °F) sprayed on its surface until the moisture content does not further increase. Alternatively, immersion in water is also allowed. In case of a spray mortar, the application of the water shall occur at least 28 days after spraying. The time between saturation and the fire test shall be as short as possible (≤ 4 h).

2.4.2 Evaluation of the influence of the protective material moisture content

Since the water included in the protective material has a major influence on its insulating capacity, the impact of the moisture shall be numerically treated. If the final measured moisture content is more than 3 %, the residual moisture above 3 % shall be numerically excluded by reducing the duration of the moisture plateau by continual proportion.[1] The start of the moisture plateau for each thermocouple is defined as the time when the thermocouple exceeds 85 °C (185 °F). The end is defined as the time when that same thermocouple exceeds 120 °C (248 °F). The duration of the moisture plateau is defined as the average of the moisture plateau durations of all individual thermocouples not behind a joint.
This will result in the reduction of time of reaching all measured temperatures above this moisture plateau (approx. 100 °C (212 °F)). The resulting shifted time-temperature curves shall be used as an input for the assessment as described in chapter 2.7.

[1] Example: if the measured moisture content is e.g. 4.8 %, the duration of the moisture plateau should be reduced by factor 1.6

Table 4 Summary of the moisture content requirements

Moisture content	**Requirement**
0 – 3 (%)	No numerical treatment of the moisture content
boards: 3 – 5 (%)	Numerical treatment of the moisture content according to 2.4.2
spray mortar: 3 – 8 (%)	
boards: >5 %	Numerical treatment of the moisture content according to 2.4.2 and a proof is required that the moisture content is representative for the practice
spray mortar: >8 %	

2.4.3 Accelerated drying

For a test on a concrete specimen protected by post-fixed or pre-fixed boards or sprayed materials it is allowed to speed up the process of drying of the insulation material by artificial means (slightly increased temperature, low relative humidity). The heating should remain below a level which is not detrimental to the insulation material (e.g. max. 40 ºC (104 °F)). Moreover, for spray mortars it is required to wait at least 28 days after spraying before accelerated drying is started, because the strength of the mortar and the bond strength of the mortar to the concrete need to be fully developed first. Also, the accelerated drying should not be prolonged for more than 28 days.

Table 5 Time schedule of the preparation of a fire test

	Time [days]	Activity
t_0	-	Casting of the concrete specimen
t_1	$t_0 < t_1 < t_2$	Demoulding, wrapping the specimen in plastic foil
t_2	$t_2 \geq t_0 + 28$	Removal of plastic foil and application of fire protection
t_3	$t_3 \geq t_1 + 28$	Initiation of accelerated drying of spray mortar (max. 40 ºC (104 °F) unless proven otherwise)
t_4	$t_4 \leq t_3 + 28$	End of accelerated drying
t_5	probably $t_5 \geq t_2 + 60$	Fire protection has reached equilibrium moisture content (max. 5% by mass for boards and max. 8 % by mass for spray mortars unless proven otherwise)
t_6	$t_6 \geq t_0 + 90$ and $t_6 \geq t_5$	Fire test

2.4.4 Final determination of the average moisture content

The final determination of the moisture content is done by taking samples of fire protection material from the concrete dummy slabs some days (but not more than one week) before the date of the fire test. The samples of the protective material shall be weighed, then dried in an oven (105 ± 5)°C ((221 ± 9) °F) [2)] and weighed regularly in order to monitor the mass loss. Drying in the oven shall continue until no more mass is lost (i.e. equilibrium mass is reached [3]). This is usually the case within 24 hours.
For board materials, a board sample will be weighed and dried in the same manner.

The average moisture content shall be calculated as follows:

Moisture content in % m/m = $(W_w - W_d)/W_d$

where:
W_w is the weight of the core sample before drying;
W_d is the weight of the core sample after drying.

2.4.5 Determination of the density of the protective material at the date of the fire test

The density ρ shall be determined on the basis of the weight and dimensions of a sample of the fire protection material. A sample of at least 200x200 mm^2 (and thickness as applied) shall be taken from the dummy slab for this purpose. The sample shall be weighed and dried in the same manner as for the determination of the average moisture content. Both the original (moist) density and the dry density shall be reported.

2.4.6 Curing of the concrete element

The concrete specimen does not need to be at least 90 days of age. However it is required that the moisture content of the concrete by mass with respect to the dry weight shall be between 3 and 4 %[iv]. If the concrete element is at least 90 days of age at the time of testing, no proof is needed. Otherwise the moisture content of the concrete shall be measured in the same way as for the fire protection, taking samples from the concrete dummy slab.

2.5 FIRE TEST

The test elements shall be placed in a horizontal position inside the testing furnace, with sufficient distance to the furnace walls and other test elements to ensure full fire exposure on all sides. The elements shall be placed on blocks at both ends, in order to ensure sufficient distance between the furnace floor and the element. The blocks may occupy max. 200 mm of each element's length at both ends. In case of spray mortar, this is the same area where the element was supported during spraying.

The ends and the supports of the concrete elements shall be insulated by mineral blanket or other fire protection, in order to limit local heating of the elements.

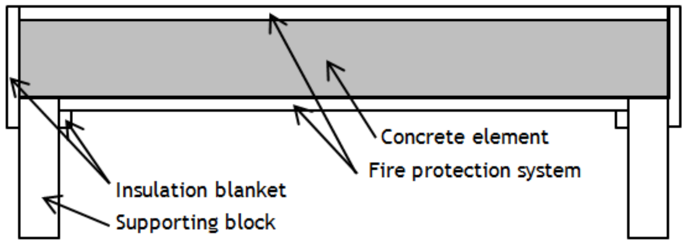

Figure 7 Schematic lay-out of test elements on supporting blocks

[2] Not applicable for gypsum based materials.
[3] Equilibrium mass = the difference between two weighings is less than 0.1 % in 24 h

2.6 HEATING CURVE

The heating of the furnace shall be according to the fire curve described in chapter 3 of UL 1709:2011. The fire environment within the furnace is to develop an average temperature of (1093 ± 56) ºC ((2000 ± 100) °F) within 5 minutes from the start of the test. This temperature is to be maintained throughout the remainder of the fire test.

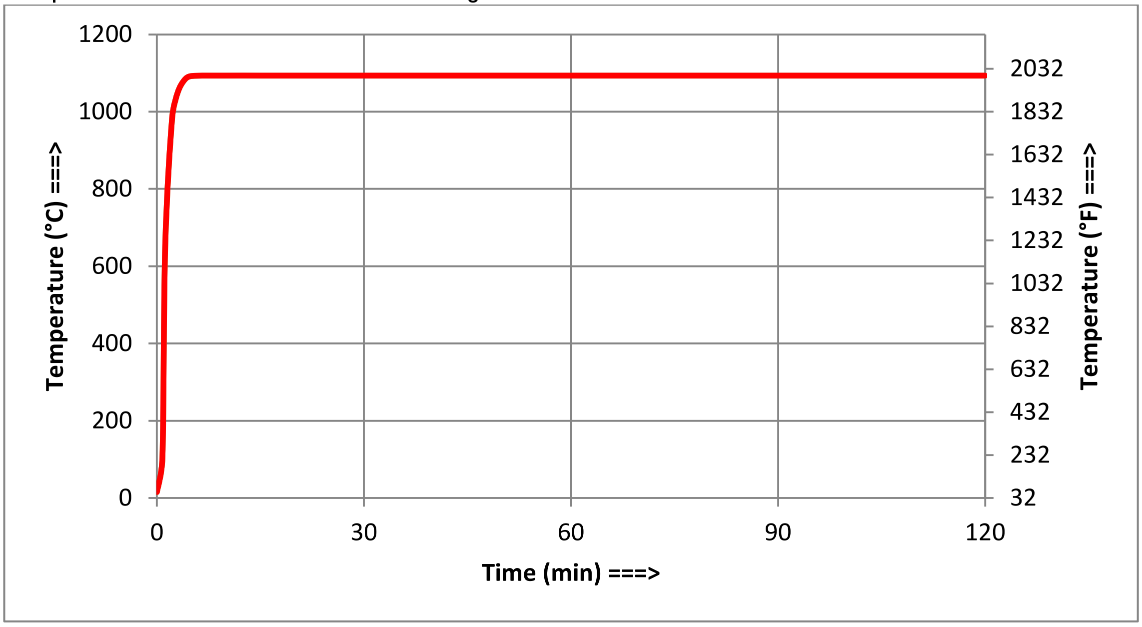

Figure 8 UL 1709:2011 fire curve

In order to correctly take into account the heat transfer by radiation, the furnace temperatures shall be measured by sheathed thermocouples in combination with the calibration procedure described in chapter 4 of UL 1709:2011 or alternatively by using plate thermometers according to EN 1363-1:2012.

At least four thermocouples shall be placed around each test element, in the middle of its length, with a distance of 100 mm to the test specimen. The thermocouples shall be positioned above, below and on both sides of each test elements. In case of plate thermometers, face 'A' according to EN 1363-1:2012 shall be facing away from the test element.

The furnace is to be controlled to maintain the area under the time-temperature curve to be within 10 % of the corresponding area under the prescribed time-temperature curve for fire tests of 60 min or less duration; to within 7.5 % for tests longer than 60 min but not longer than 120 min; and to within 5 % for tests exceeding 120 min in duration. The area under the time-temperature curve is to be obtained by averaging the results from the thermocouple readings.

Depending on the situation, authorities can prescribe another fire curve (such as the hydrocarbon fire curve according to EN 1363-2:1999) and they may also add a prescribed cooling down phase if they expect significant temperature penetration or other physical effects during the cooling down phase.

2.7 ASSESSMENT OF TEMPERATURE DATA

This paragraph describes how the test data shall be numerically assessed in order to define the relation between element cross section dimension, fire resistance time, concrete surface temperature and fire protection thickness. A distinction is made between temperatures at the corners of the test elements and at the top, side and bottom planes.

If the measured moisture content of the protective material is more than 3 %, all temperature data used for this assessment shall be reduced according to guideline in 2.4.2.

For each test specimen, collect the temperature data at the corners (usually 12 measurement locations, 24 locations for lost formwork board protection) and at the planes (12 measurement locations).
During fire tests, thermocouples may sometimes fail. Out of a set of 12 (or 24) thermocouples, at least 9 (or 18) shall function correctly.

As function of time, determine the characteristic (95% upper limit) temperature for both corners and planes. The 95% upper limit characteristic temperature is calculated as the average temperature + *t**standard deviation, where *t* can be found in table 6.

Table 6 t-values for a 95% characteristic value based on the Student's t-distribution

Number of functioning measurement points	*t*
9	1.84
10	1.82
11	1.80
12	1.79
18	1.74
19-21	1.73
22-24	1.72

Collect the characteristic temperatures per element for corners and planes after 30, 60, 90, 120 etc. minutes. For each time interval, temperatures for intermediate fire protection thicknesses or concrete cross section geometries can be calculated by interpolation. If the interpolate point is both an intermediate protection thickness and an intermediate concrete dimension, first linearly interpolate between the concrete dimensions and then between the fire protection thicknesses.

By interpolation in this way, tables or graphs can be produced that show the relation between element cross section dimension, fire resistance time, concrete surface temperature and fire protection thickness.

2.8 RANGE OF APPLICATION

The results of the interpolation are valid for
- Either corner temperatures or plane temperatures,
- Concrete containing either calcareous or siliceous aggregates,
- Fire protection either dry or saturated.

Concrete containing calcareous aggregates has a lower conductivity than concrete with siliceous aggregates, leading to higher interface temperatures for calcareous aggregates. Therefore, if elements with calcareous aggregates are tested the results of the interpolation are also conservative for siliceous aggregate concrete.

Moreover the concrete cross section dimensions shall be between 150 and 450 mm, with the following remarks:

- For dimensions greater than 450 mm, the results of the 450 mm test element may be used,
- For other than square cross section shapes, the shortest rib shall be taken. For more complex shapes such as I-beams this can be the thickness of the flange or the width of the web,
- For loadbearing walls and floors, the results of the 450 mm test element may be used, provided that anchor distances, panel sizes etc. do not exceed the tested size. Alternatively, separate wall or floor specimens can be tested to allow for larger system dimensions.

The following temperature criteria are recommended:

- A temperature level that demonstrably prevents spalling of concrete for a specific concrete structure,
- 380 ºC (716 °F) maximum temperature (at corners and planes) in order to limit deformations during fire and irreparable damage, in case the concrete does not spall,
- It is recommended to limit the reinforcement temperatures to a maximum of 250 ºC (482 °F) in order to limit deformations during fire and irreparable damage. As the concrete cover on the reinforcement varies from structure to structure, it is recommended to perform two-dimensional thermal finite element analyses using the test results as surface temperatures in order to determine the cross section temperatures as a function of time. For such an analysis, material properties can be taken from EN 1992-1-2.

2.9 REPORT

The test report shall contain the following information:

a) the name and address of the supplier;
b) the date of the test(s);
c) the name of the manufacturer of the protective material and the trade name of the product (or components) together with identification marks as well as a global description of the composition;
d) construction details of the test specimens, i.e. a description, drawings and the exact position of the thermocouples as well as a statement concerning the laboratory's involvement in the manufacturing of the test specimens;
e) the method of applying and fixing the protective material on the test specimens;
f) details and dates with respect to the manufacturing and conditioning of the test specimens and small scale samples;
g) the measured thickness, densities and moisture content of the protective material;
h) the measured temperatures in the furnace and in the test specimens;
i) the conclusion with respect to the performance criteria;
j) for sprayed materials the report must also include or refer to the supplier's/manufacturer's directions for application and the conditions for application in practice (such as a qualified sprayer, surface treatment, spraying equipment, spraying distance etc.) to guarantee the quality of the material.

3. SPALLING TEST

Spalling is an unpredictable phenomenon that cannot reliably be evaluated by doing only one fire test. Therefore, in order to have a valid test result, tests should be performed at least twice on identical specimens, with identical composition, insulation material, thickness etc.[v] The requirements for the test specimens, fire protective materials, conditioning, fire test and reporting are described in this chapter. Because the test specimens need to resemble the real structure as closely as possible, the test result in principle is only valid for the installation for which the test was performed.

3.1 TEST SPECIMENS

When designing a test specimen for a spalling test, a number of aspects shall be considered. These aspects are described in the following paragraphs.

3.1.1 Geometry

The geometry of the specimen shall resemble the real situation. For prefabricated elements this means that full elements shall be tested, with a view to avoid unwanted (because uncontrollable, unpredictable and unrealistic) effects of artificially introduced boundaries. For linear elements such as columns and beams, the length of the prefabricated element may be reduced, provided that the length of the test element is at least 6x the cross-sectional dimension (maximum of width and depth).

For large (cast in situ) structures, a sufficiently large specimen shall be made to avoid size effects, because spalling is dependent on the geometry. Therefore, the cross section of the linear element (column or beam) must be identical to the actual cross section in practice. The length of the element must be at least 6x the cross-sectional dimension (maximum of width and depth).

If a range of element dimensions is to be covered by the tests, in principle every foreseen cross section must be tested, where each can be protected with an individually optimized fire protection thickness.
Alternatively, only the smallest and the largest cross sections may be tested with identical fire protection systems (including identical thickness). In that case, if both tests demonstrate that spalling does not occur, intermediate cross sections with the same fire protection are also considered spalling-free.

3.1.2 Reinforcement

The steel reinforcement in the concrete shall be similar to the real structure. This applies to

- maximum bar diameter,
- minimum concrete cover, in particular on corners,
- type of spacers,
- mesh distances.

3.1.3 Casting of the specimens

The manufacturing process of the specimens shall include the correct orientation of the specimen during casting, and be as close to actual manufacturing as reasonably possible. This with a view to exclude unwanted effects of differences in the actual concrete properties. Test results indicate that the direction of casting can have a significant influence on spalling. Also the surface (material, roughness) of the formwork may be of influence.

For cast in situ structures this means that columns shall be cast vertically. Beams shall be cast horizontally with the bottom (formwork) side facing down also inside the furnace. In terms of spalling, a beam test is more onerous in terms of gravity (bottom side spalls in the direction of gravity) and in terms of casting direction (bottom side is the most well-compacted so most likely to spall). Therefore, provided that the geometries are the same, a longitudinal compression is applied in the member, and the element is exposed to fire on all four sides, beam tests are also conservative for column applications.

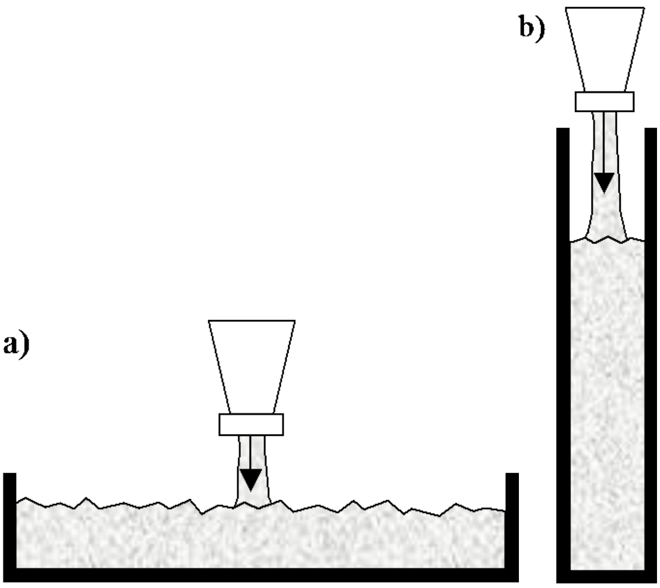

Figure 9 Specimens cast in the correct position; a) beam or column; b) column only

3.1.4 Loading

The compressive loading which exists in practice (including the effect of pre-stressing or post-tensioning in practice, if relevant) shall also be applied to the specimen. In the specimen a compressive loading shall be applied in such a manner that at least the fire-exposed sides of the element are under compression. The value of the compressive stress shall be equal to the maximum compression level of the fire exposed surface of the actual structure. In case a non-uniform compression load (i.e. eccentric normal force) is chosen, no parts of the cross-section may be in tension.
The load can be applied by hydraulic actuators. During the fire test, the load level shall remain constant, also in case the element deforms. Close to the moment of failure it may be no longer possible to maintain the constant load level.
Alternatively, the load can be applied by internal post-tensioning.

3.1.5 Concrete mix

The concrete mix as used in practice shall also be used for the test specimens. This includes aggregate types and sizes, cement type and quantity, water cement ratio, possible micro-fillers, type and dosage of polypropylene fibres etc.

3.2 CONCRETE TEMPERATURE MEASUREMENTS

A spalling test aims to establish whether or not spalling occurs. Therefore in principle it is not necessary to measure concrete temperatures. Nevertheless it is highly recommended to measure the temperatures in a number of locations (reinforcement, concrete surface, etc.). This may also be required by the client, especially if thermal criteria are imposed on top of the criteria concerning spalling. If it is chosen to apply thermocouples in a spalling test than the same principles which apply for thermal insulation tests (see paragraph 2.2) also apply for the spalling test[vi].

If required, additional information can be obtained by applying extra thermocouples at other depths.[vii] In case of pre-stressed or post-tensioned concrete, it is recommended to apply some thermocouples to the cables, rods or their ducts in order to be able to monitor the temperature of the cables/rods during the test.

The positioning and fixing of the thermocouples shall be done in such a way that it does not disturb the measurement values and that the thermocouple does not move during casting of the concrete. Therefore it is recommended to fix thermocouples to reinforcement bars parallel to the exposed surface(s). If no reinforcement bar is present it is recommended to add a small diameter steel frame where the thermocouple can be fixed. Also in this case, the direction of the thermocouple shall be parallel to the exposed surface(s)

The thermocouples - of the type K (chromel/alumel) - must have characteristics appropriate to the range of temperatures to be measured.

3.3 FIRE PROTECTION SYSTEM

The provisions for application of the fire protection system to the test specimen are the same as for the thermal insulation test, see paragraph 2.3.

Often in practice, other structures or installations are fixed to the concrete structure. If a steel anchor penetrates the fire protective layer, the heat is easily conducted into the concrete which may cause local spalling. Such local spalling can damage the fire protection system and therefore grow in area during the fire. Therefore, some local connection of a steel part to a concrete structure may initiate spalling which finally consumes a large area of the concrete structure.

Little conclusive information is available as to the appropriate configuration of such fixings, but any fixings with bolts with a diameter of 8 mm or more is suspect to negatively influence the spalling behaviour.

Such configurations should be tested to evaluate whether or not spalling occurs. In order to simulate the stresses in the concrete around the steel anchor it is recommended to apply a load to the fixing which represents its intended use.

Alternatively, two- or three dimensional finite element simulations can be made in order to optimize local additional fire protection around the steel penetration. The material properties for such simulations must be calibrated on fire tests (for the fire protection system) or taken from standards (such as EN 1992-1-2 and EN 1993-1-2 for concrete and steel). Temperature criteria for acceptance of the simulation result shall be based on successful spalling tests for the given structure.

3.4 CONDITIONING OF THE TEST SPECIMENS

The provisions of the thermal insulation test apply, see paragraph 2.4, with the exception of the moisture content numerical treatment as described in 2.4.2 (due to its significant influence on the rate of heating of the concrete and corresponding spalling behaviour).

Additionally a number of items must be observed when doing a spalling test.

- The concrete specimen shall be at least 90 days of age in order to achieve a sufficiently mature micro-structure.[ii]
- The concrete specimen shall be sealed by plastic foil after removing the formwork, in order to achieve a moisture content which will be on the conservative (high) side compared to the real situation.[viii] The plastic foil shall be removed just before fire

testing. In case of a sprayed insulation material the plastic foil on the bottom side shall stay until the moment the application of the insulation material starts. The application of the spray mortar may commence at a concrete age of at least 28 days.
- For a test on a concrete specimen protected by post-fixed or pre-fixed boards or sprayed materials it is allowed to speed up the process of drying of the insulation material by artificial means (slightly increased temperature, low relative humidity).
- A small concrete slab (measuring 300 x 300 x ≥150 mm^3) shall be produced in order to measure the moisture content of the concrete. The vertical sides and bottom of the concrete specimen shall be prevented from drying, e.g. by leaving a formwork around the small slab. Core samples of the concrete, with a diameter of approx. 50-100 mm, shall be taken from this small slab some days (but not more than one week) before the planned date of the fire test. The core sample of the concrete shall be weighed, then dried in an oven during 168 hours at (105 ± 5)°C ((221 ± 9) °F) and be weighed again, and the moisture content shall be calculated according to the same formula as for fire protection materials.
- The moist density of the concrete shall be calculated by means of the weight and dimensions of the same core as used for determination of the moisture content of concrete. Both the original (moist) density and the dry density shall be calculated.

3.5 FIRE TEST

The specimen shall be placed in the furnace in the same orientation as the position of the structural element it represents. I.e. a column specimen should be tested vertically, a beam specimen should be tested horizontally. [ix]

However,
- a test result on a horizontal element, exposed on all four sides, is valid for both columns and beams,
- a test result on a vertical element is only valid for columns.

Therefore it is recommended to test the specimen in a horizontal orientation, as the results will be valid for both vertical and horizontal orientations.

3.6 HEATING CURVE

The provisions of the thermal insulation test apply, see paragraph 2.6. The furnace thermocouples shall be evenly distributed around the test specimen.

If spalling of concrete occurs, the temperatures in the furnace will be reduced due to the on-going exposure of new, cold, concrete surfaces. In that case it cannot be guaranteed that the furnace temperature remains within the tolerances.

The fire laboratory reserves the right to stop the test whenever it is considered unsafe to continue, e.g. because of severe spalling of concrete, heating of the post-tensioning steel or (near) collapse.

3.7 PERFORMANCE CRITERIA

The main objective of the spalling test is to investigate the spalling behaviour during fire. It is recommended to define the requirement as "no spalling", with the exception of some local damages of a few millimetres depth.

Spalling depths shall be measured on all fire exposed sides of the element, after cooling down. Measurements shall be taken on corners and on surfaces in a grid of max. 25x25 cm. Although it is recommended to avoid spalling at all, the measured spalling depths can be statistically interpreted, e.g. by using a 95% characteristic value of all measured spalling depths. It is recommended to exclude the measurement of spalling depths close to the (supported) ends of the element because the spalling depth is locally influenced by edge effects.

In case of a concrete mix with calcareous aggregate, spalling of concrete may occur also during cooling down phase, i.e. after the fire test. Therefore, it is expected that it will not be possible to quantify the spalling depth during the fire and during the cooling down phase, but only the final depth after cooling down.

Apart from this, temperature criteria can apply such as recommended in paragraph 2.8.

3.8 REPORT

Apart from the provisions in paragraph 2.9, the following items must be included in the report:

k) the name of the project for which the test specimens are representative;
l) the measured spalling depths;
m) a description of observations with regard to the nature of the spalling process (time of occurrence, noises, visible effects).

APPENDIX A: NOTES CONTAINING BACKGROUND INFORMATION

[i] Moreover, if a wet concrete slab is used for the test, it will absorb more thermal energy and therefore heat up slower than a dry slab.

[ii] Spalling is strongly dependent on the microstructure of the concrete. The generally accepted age of 28 days for determination of e.g. the compressive strength is insufficient for a spalling test. After 28 days, hydration of the cement will still continue and the microstructure of the concrete will change. The effect of ageing on the microstructure of the concrete is strongly dependent on the mix (cement type, micro-fillers, etc.). By lack of detailed information on the influence of concrete ageing on spalling, a value of 90 days is recommended as a minimum age for concrete specimens to be used in a spalling test.

[iii] The moisture content of the insulation material has a major influence on its insulating capacity. Therefore the moisture content of the insulation material should be less than or equal to the moisture content in practice. 5 % (for boards) and 8 % (for spray mortar) by mass is considered a safe value, but for specific materials it may be shown on basis of measurements in real situation that this percentage can be higher.

[iv] The moisture content of the concrete influences the temperature development inside the slab during the test. A high moisture content will slow the heating rate of the concrete surface. In order to do a conservative test, the concrete slab has to be sufficiently dry.

[v] Spalling is very difficult to predict, because many parameters play a role and the combined effects of these parameters can be surprising. Also, small changes in assumptions may lead to a very different result. Therefore it is necessary to confirm that the obtained test-result is reproducible.

[vi] By monitoring the concrete temperatures during the spalling test, useful information is obtained. This is especially the case if a test should fail (spall). In that case, the concrete temperature at the time of spalling (which may be as low as approx. 200 ºC (392 °F) provides an indication for how much additional fire protection thickness will be needed in a next test.

[vii] The temperature measurements inside the concrete only give additional information, but there is usually no requirement related to it. Such additional information may serve to know when spalling occurs during the test (sudden increase of concrete temperatures) or to improve the design of the fire protection system in case the test should fail.

[viii] The moisture content depends on climate, season and weather effects. Therefore it is hard to predict which moisture conditions are representative for practice. Since moisture inside the concrete is one of the main factors influencing spalling, a high moisture content is considered conservative. Also, the test result should be reproducible. Therefore it is chosen to wrap the concrete in plastic foil. In this way, the concrete will retain its original moisture content.

[ix] This is important because gravity may influence the spalling process. It is conservative to test horizontally with the exposed side down, because in that case gravity will pull loose pieces of concrete away from the specimen.