ANNEX 6

Recommendations for additional fire protection of structural elements

1 Scope

This Annex contains a series of recommendations applicable to structural concrete structures which, for general fire safety reasons, must meet the following conditions when exposed to fire:

- Prevent the premature collapse of the structure (loadbearing function).
- Limit the spread of the fire (flames, hot gases, excessive heat) outside specific areas (separating function).

This Annex sets out simplified methods and tables allowing the resistance of structural concrete elements to the action represented by the standard time-temperature curve, according to UNE EN 1363-1, to be safely determined. These methods must be regarded as sufficient for establishing the fire resistance of structural concrete elements but not as essential for establishing this as other more precise or advanced methods may always be used, including experimental methods, to determine the fire resistance of these elements, as laid down in section 4 of this Annex.

Other fire models may be used to represent the development of temperature during the fire, such as those known as parametric curves or, for local purposes, those fire models for one or two zones or for localised fires, or methods based on fluid dynamics such as those considered in standard UNE-EN 1991-1-2.

Both shell structures and those with external prestressing, as covered by this Code, must be checked using specific methods. In particular, the simplified methods and the checking methods involving tables included in this Annex will not be applicable. Likewise, for concrete with a characteristic strength in excess of 80 N/mm², reference must be made to the specialised bibliography.

In shell structures which fundamentally work by form, the main problem is the effect of deformations caused by heat. This aspect is not covered by the simplified methods proposed which only take account of the sectional problems deriving from the action of the fire.

2 Definitions

The fire resistance of a structure or part thereof is defined as its capacity to maintain, over a given period of time, the required loadbearing function and also the integrity and/or thermal insulation under the terms specified in the corresponding standard test (RD No 312/2005).

The standard fire resistance of a structure or part thereof (usually only isolated elements) is therefore defined as its resistance to a standard fire given by the time-temperature curve in UNE EN 1363-1. The maximum exposure time until the loss of capacity to fulfil the required functions becomes imminent is known as the standard fire resistance period and is expressed in minutes as specified in a scale laid down in UNE-EN 13501-2.

The nominal standard fire resistance time periods used in this Annex are those included in UNE-EN 13501-2: 30, 60, 90, 120, 180 y 240 minutes

There are three criteria for classifying fire behaviour:

- Loadbearing capacity of the structure (R criterion)
- Barrier to the passage of flames and hot gases (E criterion)

- Thermal insulation in the event of fire (I criterion)

3 Design bases

3.1 Combinations of actions

To determine the stresses due to the action of the fire and other concomitant actions, the combination corresponding to an accidental situation, as expressed in Article 13 of this Code, will be used.

When the simplified 500°C isotherm method is used, as set out in section 7, the stresses determined for the worst combination of actions at ambient temperature, reduced by an overall factor η_{fi}, may be used, in a simplified manner, as the stresses for checking the accidental fire situation.

$$E_{fi,d,t} = \eta_{fi} E_d$$

where:

$E_{fi,d,t}$ Value of the design stresses to be taken into account when checking the accidental fire situation.

E_d Value of the design stresses to be taken into account when checking permanent or temporary situations at ambient temperature.

η_{fi} Reduction factor which can be determined using the following expression:

$$\eta_{fi} = \frac{G_K + \psi_{1,1} Q_{K,1}}{\gamma_G G_K + \gamma_{Q,1} Q_{K,1}}$$

The following may be used to simplify matters:

$\eta_{fi} = 0.6$ for normal cases.
$\eta_{fi} = 0.7$ for storage zones.

3.2 Partial safety factors for materials

The partial safety factors for materials are regarded as equal to one: γ_c=1.0 and γ_s=1.0.

4 Checking methods

As a general rule, several different fire checking methods may be used with different levels of accuracy and, as a result, complexity.

The general method involves checking the various Ultimate Limit States bearing in mind, both when determining the design stresses and when analysing the structural response, the influence of the fire action in view of the fundamental physical behaviour.

The structural analysis model must adequately represent the temperature-related properties of the material, including stiffness, temperature distribution in the various elements of the structure and the effect of thermal expansions and deformations (indirect actions due to the fire).

Furthermore, the structural response must take account of the characteristics of the materials at the different temperatures which may be produced in one cross-section or structural element.

Any failure mode not explicitly taken into account in the stress analysis or structural response (for example, insufficient rotational capacity, expalling of the cover, local buckling of the compressed reinforcement, bond and shear stress failures, damage to the anchoring devices) must be avoided by using appropriate construction details.

Simplified checking methods may be used provided that these lead to equivalent or safe results with regard to those which might be obtained using the general methods.

As a general rule, the simplified methods involve checking the various Ultimate Limit States by considering isolated structural elements (ignoring the indirect actions due to the fire – expansions, deformations, etc.), pre-established temperature distributions, generally for box sections, and, as variations in the material properties due to the temperature effect, simplified and simple models. Section 7 of this Annex includes the simplified isotherm 500°C method.

Using the checking method involving tables, which is set out in section 5 of this Annex, involves checking the dimensions of the cross-sections and mechanical covers using simplified and safe assumptions. For some situations, other additional checks may be required and, in these cases, more specific data can be obtained from the corresponding product standard.

In all cases, it is also valid to assess the behaviour of a structure, part thereof or a structural element by carrying out the tests set out in Royal Decree N 312/2005 of 18 March.

5 Checking method involving tables

5.1 General

Using the following tables and sections, the resistance of structural elements to the action represented by the standard time-temperature curve for structural elements can be determined according to their dimensions and the equivalent minimum distance to the axis of the reinforcements.

In order to apply the tables, the equivalent distance to the axis, a_m, for the purposes of fire resistance, is defined as follows:

$$a_m = \frac{\sum\left[A_{si} f_{yki}\left(a_{si} + \Delta a_{si}\right)\right]}{\sum A_{si} f_{yki}}$$

where:

A_{si} area of each passive or active reinforcement i;

a_{si} distance from the axis of each reinforcement i to the closest exposed face, taking into account the covers under the conditions laid down below;

f_{yki} characteristic strength of the steel in the reinforcements i;

Δa_{si} correction due to the different critical temperatures of the steel and due to the particular fire exposure conditions, in accordance with the values in Table A.6.5.1.

TABLE A.6.5.1

Values of Δa_{si} (mm)

μ_{fi}	Reinforcing steel		Prestressing steel			
	Beams(1) and slabs (floor slabs)	Other cases	Beams(1) and slabs (floor slabs)		Other cases	
			Bars	Wire rods	Bars	Wire rods
≤ 0,4	+5		-5	-10		
0,5	0	0	-10	-15	-10	-15
0,6	-5		-15	-20		

(1) In the case of reinforcements placed at the corners of beams with a single layer of reinforcement, the values of Δa_{si} will be decreased by 10 mm when the width of these is less than the values of b_{min} specified in column 3 of Table A.6.5.5.2.

where μ_{fi} is the overdimensioning factor of the section under study, defined as:

$$\mu_{fi} = \frac{E_{fi,d,t}}{R_{fi,d,0}}$$

where:

$R_{fi,d,0}$ resistance of the structural element in a fire situation in the initial instant t=0, at normal temperature.

Corrections for values of μ_{fi} less than 0,5 in beams, slabs and floor slabs may only be taken into account where these elements are subject to loads distributed relatively uniformly.

Intermediate values may be determined by linear interpolation.

To simplify matters, for situations with a normal control level, the value of μ_{fi} may be taken as 0,5 in general and 0,6 in storage zones.

The values given in the tables apply to normal density concretes with a characteristic strength of $f_{ck} \leq 50$ N/mm^2, produced using siliceous aggregates.

When concretes containing limestone aggregates are used, the following reductions may be permitted:

- For beams and slabs, 10% in both the minimum dimensions of the straight section and in the equivalent minimum distance to the axis of the reinforcements (a_{min}).
- For non-loadbearing walls (partitions), 10% of the minimum thickness.
- For loadbearing walls and pillars, no reduction shall be permitted.

When concretes with a characteristic strength of 50 N/mm^2 $< f_{ck} \leq$ 80 N/mm^2 and an active silica content less than 6% by weight of the cement content are used, the minimum section dimensions established in the tables must be increased by:

- For components exposed to the fire on one face only: $0,1 \cdot a_{min}$, for concretes with a characteristic strength of 50 N/mm^2 $< f_{ck} \leq$ 60 N/mm^2 and $0,3 \cdot a_{min}$ for concretes with a characteristic strength of 60 N/mm^2 $< f_{ck} \leq$ 80 N/mm^2;

- For other components: double the values defined for the above case.

Where a_{min} is the equivalent minimum distance to the axis specified in the corresponding tables.

In tension zones with concrete covers in excess of 50 mm, a skin reinforcement must be used to prevent the concrete spalling during the fire resistance period. This skin reinforcement consists of a mesh with distances of less than 150 mm between reinforcements (in both directions), regularly anchored in the concrete mass.

5.2 Supports

Using Table A.6.5.2, the fire resistance of circular and rectangular supports exposed on three or four faces can be determined with reference to the equivalent minimum distance to the axis of the reinforcements in the exposed faces.

TABLE A.6.5.2
Supports

Fire resistance	Minimum dimension b_{min} / Equivalent minimum distance to the axis a_{min} (mm)(*)
R 30	150(**)/15
R 60	200(**)/20
R 90	250/30
R 120	250/40
R 180	350/45
R 240	400/50

(*) Higher values may be required for the covers due to durability requirements.
(**) The minimum dimension shall comply with the provisions of Article 54.

For fire resistances higher than R 90 and where the reinforcement of the support is more than 2% of the concrete section, this reinforcement shall be distributed across all its faces. This condition does not apply to reinforcement overlap areas.

5.3 Walls

5.3.1 Non-loadbearing walls

It is recommended that non-loadbearing solid walls, enclosing walls or partitions have a geometric slenderness ratio between the wall height and its thickness of less than 40 and that they comply with the minimum dimensions indicated in Table A.6.5.3.1.

TABLE A.6.5.3.1

Fire resistance	Minimum thickness of wall (mm)
EI 30	60
EI 60	80
EI 90	100
EI 120	120
EI 180	150
EI 240	175

5.3.2 Loadbearing walls

Using Table A.6.5.3.2, the fire resistance of loadbearing solid walls exposed on one or both faces can be determined with reference to the equivalent minimum distance to the axis of the reinforcements in the exposed faces.

TABLE A.6.5.3.2

Fire resistance	Minimum dimension b_{min} / Equivalent minimum distance to the axis a_{min} (mm)(*)	
	Wall exposed on one face	Wall exposed on both faces
REI 30	100/15	120/15
REI 60	120/15	140/15
REI 90	140/20	160/25
REI 120	160/25	180/35
REI 180	200/40	250/45
REI 240	250/50	300/50

(*) Higher values may be required for the covers due to durability requirements.

5.4 Tie rods. Elements subject to tension

The minimum dimension of a tie rod and the equivalent minimum distance to the axis of the reinforcements shall not be less than those recommended for any of the combinations indicated in Table A.6.5.4.

In all cases, the concrete cross-sectional area must be greater than or equal to $2b^2_{min}$ where b_{min} is the minimum dimension indicated in Table A.6.5.4.

TABLE A.6.5.4

Fire resistance	Minimum dimension b_{min} / Equivalent minimum distance to the axis a_{min} (mm)(*)
R 30	80/25
R 60	120/40
R 90	150/55
R 120	200/65
R 180	240/80
R 240	280/90

(*) Higher values may be required for the covers due to durability requirements.

Where the structure supported by the tie rod is vulnerable to elongation due to the effect of heat caused by the fire, the covers defined in Table A.6.5.4 shall be increased by 10 mm.

5.5 Beams

5.5.1 General

For variable-width beams, the minimum width b shall be regarded as that at the height of the mechanical centre of gravity of the reinforcement tensioned in the exposed zone, as indicated in Figure A.6.5.5.1.

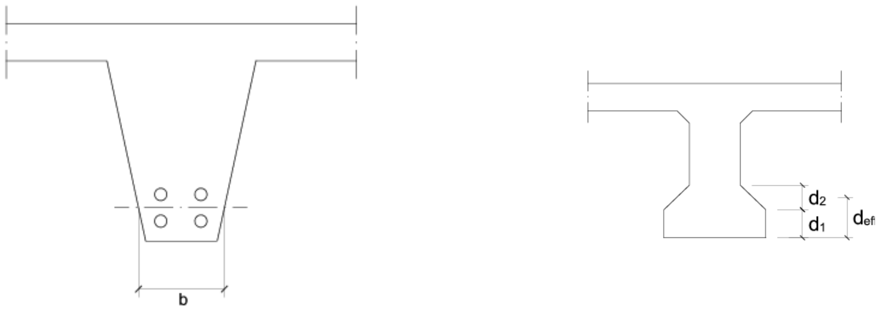


Figure A.6.5.5.1
Equivalent dimensions in the event of a variable width in the depth

For double-T beams, the depth of the lower flange shall be greater than the dimension established as the minimum width. Where the depth of the lower flange is variable, this shall be taken, for the purposes of this check, as that indicated in the figure where $d_{ef} = d_1 + 0.5d_2$.

5.5.2 Beams with three faces exposed to the fire

Using Table A.6.5.5.2, the fire resistance of sections of beams supported at the ends with three faces exposed to the fire can be determined with reference to the minimum width of the section and the equivalent minimum distance to the axis of the tensioned lower reinforcement.

TABLE A.6.5.5.2

Fire resistance	Minimum dimension b_{min} / Equivalent minimum distance to the axis a_{min} (mm)(*)				Minimum width of the web $b_{0,min}$ mm(**)
	Option 1	Option 2	Option 3	Option 4	
R 30	80/20	120/15	200/10	-	80
R 60	100/30	150/25	200/20	-	100
R 90	150/40	200/35	250/30	400/25	100
R 120	200/50	250/45	300/40	500/35	120
R 180	300/75	350/65	400/60	600/50	140
R 240	400/75	500/70	700/60	-	160

(*) The covers will normally be higher due to durability requirements (see Table 37.2.4).
(**) Must be given in a length equal to twice the depth of the beam, on each side of the elements supporting the beam.

For standard fire resistance of R 90 or higher, it is recommended that the negative reinforcement of continuous beams extends up to 33% of the span length with a quantity not less than 25% of that required on supports.

5.5.3 Beams exposed on all faces

In this case, in addition to checking the conditions in Table A.6.5.5.2, it must be confirmed that the cross-sectional area of the beam is not less than $2(b_{min})^2$.

5.6 Solid slabs

Using Table A.6.5.6, the fire resistance of sections of solid slabs can be determined with reference to the equivalent minimum distance to the axis of the tensioned lower reinforcement. If the slab must fulfil a fire compartmentalisation function (R, E and I criteria), its thickness must be at least that established in the table. However, when only a loadbearing function (R criterion) is required, the thickness need only be that required to meet the design requirements at ambient temperature. For these purposes, the flooring or any other element maintaining its insulating function throughout the fire resistance period may be regarded as the thickness.

TABLE A.6.5.6

Fire resistance	Minimum thickness h_{min}	Equivalent minimum distance to the axis a_{min} (mm) (*)		
		Bending in one direction	Bending in two directions	
			l_y/l_x (**) $\leq 1{,}5$	$1{,}5 < l_y/l_x$ (**) ≤ 22
REI 30	60	10*	10*	10*
REI 60	80	20	10*	20
REI 90	100	25	15	25
REI 120	120	35	20	30
REI 180	150	50	30	40
REI 240	175	60	50	50

(*) Higher values may be required for the covers due to durability requirements.

(**) l_x and l_y are the slab spans, where $l_y > l_x$.

For solid slabs on linear supports and in cases of fire resistance of R 90 or higher, the negative reinforcement must extend along 33% of the section length with a quantity not less than 25% of that required on supported ends.

For solid slabs on point supports and in cases of fire resistance of R 90 or higher, 20% of the upper reinforcement on supports must extend along the whole section. This reinforcement must be placed on the support strip.

Flat slabs with side packing of more than 10 cm may be likened to one-way slabs.

5.7 Two-way floor slabs

Using Table A.6.5.7, the fire resistance of sections of two-way ribbed slabs can be determined with reference to the minimum rib width and the equivalent minimum distance to the axis of the tensioned lower reinforcement. If the floor slab must fulfil a fire compartmentalisation function (R, E and I criteria), its thickness must be at least that established in the table. However, when only a loadbearing function (R criterion) is required, the thickness need only be that required to meet the design requirements at ambient temperature. For these purposes, the flooring or any other element maintaining its insulating function throughout the fire resistance period may be regarded as the thickness.

TABLE A.6.5.7

Fire resistance	Minimum rib width b_{min} / Equivalent minimum distance to the axis a_m (mm)(*)			Minimum thickness h_s of the top slab
	Option 1	Option 2	Option 3	
R 30	80/20	120/15	200/10	60
R 60	100/30	150/25	200/20	70
R 90	120/40	200/30	250/25	80
R 120	160/50	250/40	300/25	100
R 180	200/70	300/60	400/55	120
R 240	250/90	350/75	500/70	150

(*) Higher values may be required for the covers due to durability requirements.

If floor slabs have brick or concrete infill blocks and a lower cover, for fire resistance of R 120 or lower, it will only be necessary to comply with the value of the equivalent minimum distance to the axis of the reinforcements established for solid slabs in Table A.6.5.6.For the purposes of this distance, the equivalent concrete thicknesses may be taken into account in accordance with the criteria and conditions indicated in section 6.

For ribbed slabs on point supports and in cases of fire resistance of R 90 or higher, 20% of the upper reinforcement on supports shall be distributed along the whole length of the span, in the support strip. If the ribbed slab is placed on linear supports, the negative reinforcement shall extend along 33% of the span length with a quantity not less than 25% of that required on supports.

5.8 One-way floor slabs

If floor slabs have brick or concrete infill blocks and a lower cover, for fire resistance of R 120 or lower, it will only be necessary to comply with the value of the equivalent minimum distance to the axis of the reinforcements established for solid slabs in Table A.6.5.6. For the purposes of this distance, the equivalent concrete thicknesses may be taken into account in accordance with the criteria and conditions indicated in section 6. If the floor slab has a fire compartmentalisation function, it must also comply with the thickness h_{min} established in Table A.6.5.6.

For a fire resistance of R 90 or higher, the negative reinforcement of continuous slabs must extend up to 33% of the section length with a quantity not less than 25% of that required at the ends.

For fire resistances higher than R 120 or where the infill blocks are not brick or concrete or a lower cover has not been provided, the specifications established for beams with three faces exposed to the fire in section 5.5.2 must be met. For the purposes of the thickness of the concrete top slab and the rib width, the thicknesses of the flooring and the infill blocks which maintain its insulating function during the fire resistance period may be taken into account. This period may be assumed to be 120 minutes in the absence of experimental data. Brick flooring blocks may be regarded as additional concrete thicknesses equivalent to twice the actual thickness of the flooring block.

6. Protective layers

The required fire resistance may be achieved by applying protective layers whose contribution to the fire resistance of the protected structural element shall be determined in accordance with standard UNE ENV 13381-3.

Plaster covers may be regarded as additional concrete thicknesses equivalent to 1.8 times their actual thickness. When these are applied to ceilings, for values less R 120, it is recommended that these are sprayed. However, for fire resistance values higher than R 120, their contribution can only be checked by testing.

7 Simplified isotherm 500°C method

7.1 Scope

This method applies to reinforced and prestressed concrete elements with a characteristic strength of $f_{ck} \leq 50$ N/mm^2, stressed by compressive, flexural or flexural-compressive stresses. For concrete with a characteristic strength in excess of 50 N/mm², additional provisions must be taken into account in accordance with the specialised bibliography.

In order to apply this method, the dimension of the smaller side of the beams or supports exposed on this side and those adjacent must be greater than that indicated in Table A.6.7.1.

TABLE A.6.7.1 Minimum dimension of beams and supports

Standard fire resistance	R 60	R 90	R 120	R 180	R 240
Minimum dimension of the straight section (mm)	90	120	160	180	200

7.2 Determination of the design loadbearing capacity of the cross-section

The loadbearing capacity of a reinforced concrete section is checked using the methods established in this Code, taking into account:

a) a reduced concrete section determined by eliminating, for calculation purposes in order to determine the loadbearing capacity of the cross-section, the zones which have reached a temperature higher than 500°C during the period of time in question;
b) that the mechanical characteristics of the concrete in the reduced section are not affected by the temperature but retain their initial values in terms of strength and modulus of elasticity;
c) that the mechanical characteristics of the reinforcements are reduced in accordance with the temperature reached at their centre during the fire resistance period in question. All reinforcements will be taken into account, including those placed outside the reduced concrete cross-section.

The section-by-section checking of beams or slabs produces safe results. A more refined procedure is to check that, in a fire situation, the residual capacity, at moments of each sign, of the set of sections is equal to the load.

7.3 Reduction in the mechanical characteristics

The strength of materials must be reduced, according to the temperature reached at each point, by the fraction of the characteristic value indicated in Table A.6.7.3:

TABLE A.6.7.3

Relative reduction of the strength of the steel according to the temperatura

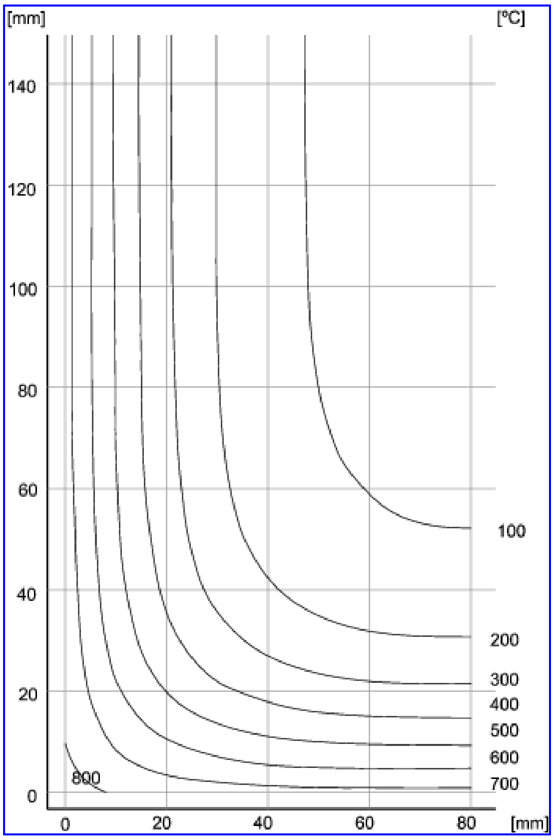
Temperature (ºC)		100	200	300	400	500	600	700	800	900	1000	1200
Reinforcing steel	Hot-rolled	1,00	1,00	1,00	1,00	0,78	0,47	0,23	0,11	0,06	0,04	0,00
	Cold-drawn	1,00	1,00	1,00	0,94	0,67	0,40	0,12	0,11	0,08	0,05	0,00
Prestressing steel	Cold-drawn	0,99	0,87	0,72	0,46	0,22	0,10	0,08	0,05	0,03	0,00	0,00

7.4 Isotherms

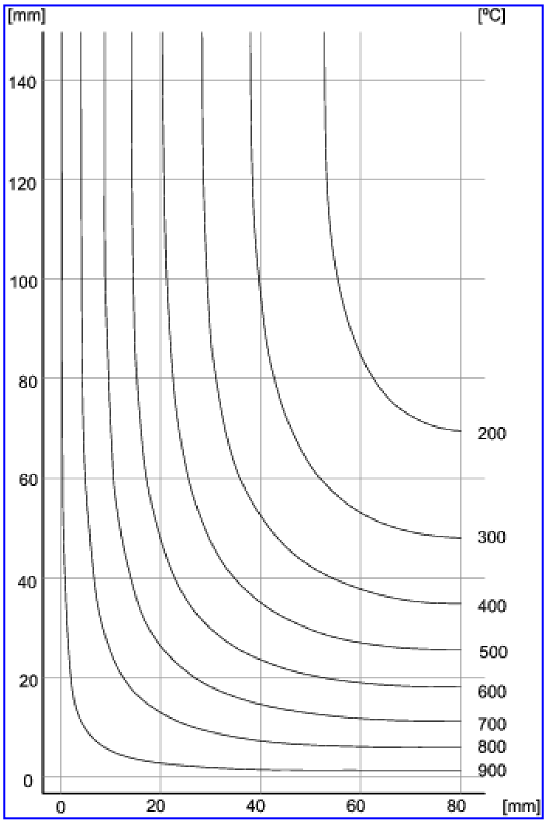
The temperatures in a concrete structure exposed to fire can be obtained by experiment or analysis.

The isotherms shown in the figures in this section can be used to determine the temperatures in the straight section of concretes containing siliceous aggregates and exposed to fire according to the standard curve up to the instant of maximum temperature. These isotherms produce safe results for most types of aggregate but cannot generally be used for exposure to fire other than standard fire.

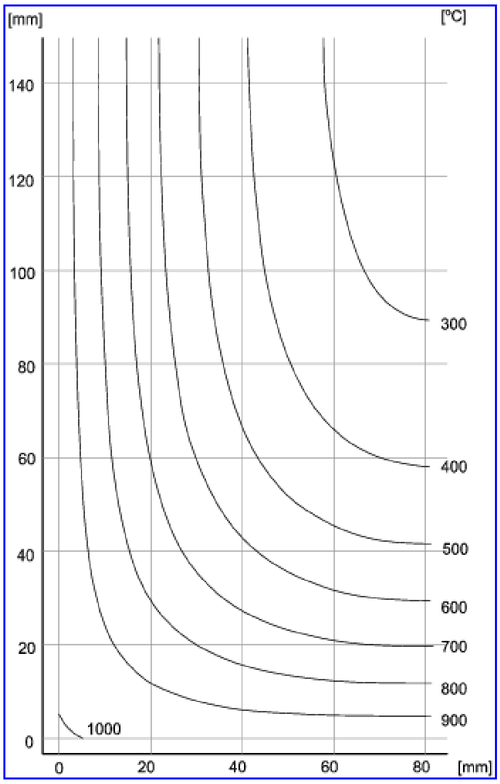
Figure A.6.7.4.a
Isotherms for rooms with a section of 300 x 160 mm exposed on both faces



R-30

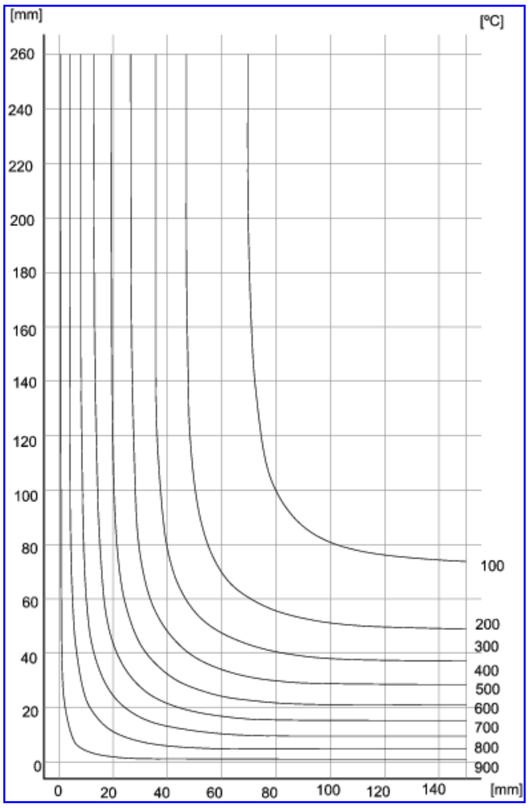


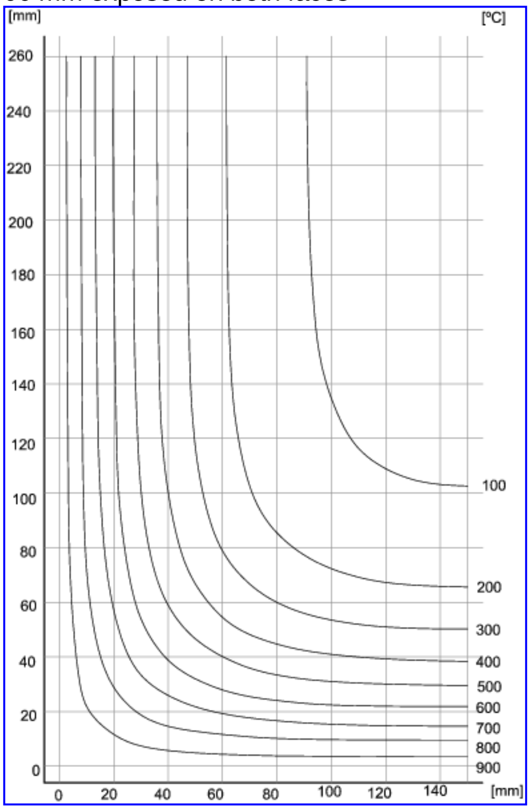
R-60



R-90

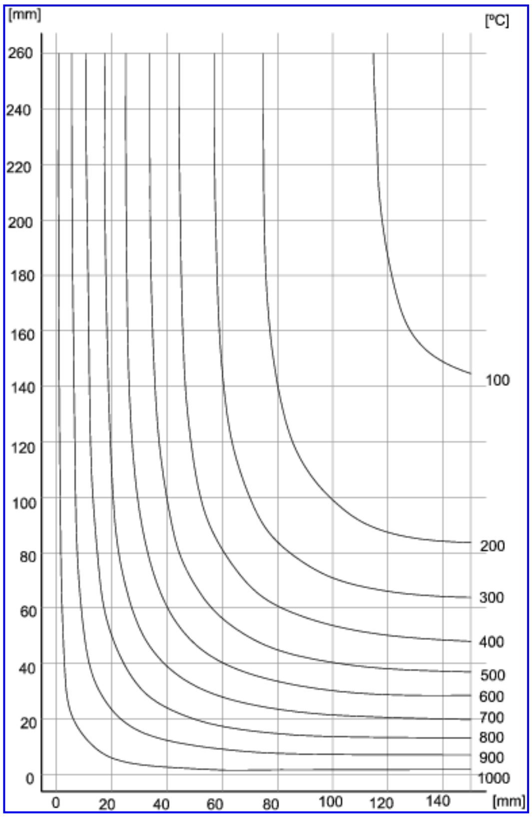
Figure A.6.7.4.b
Isotherms for rooms with a section of 600 x 300 mm exposed on both faces





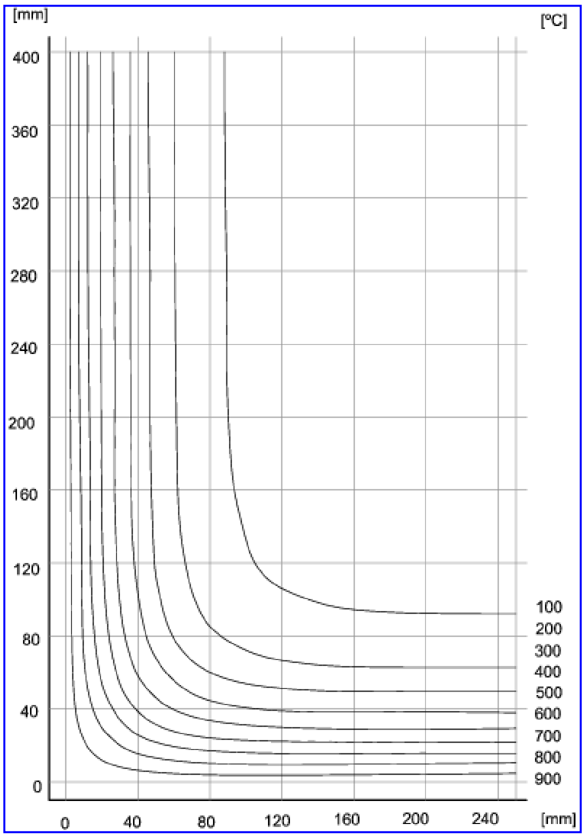
R-60

R-90

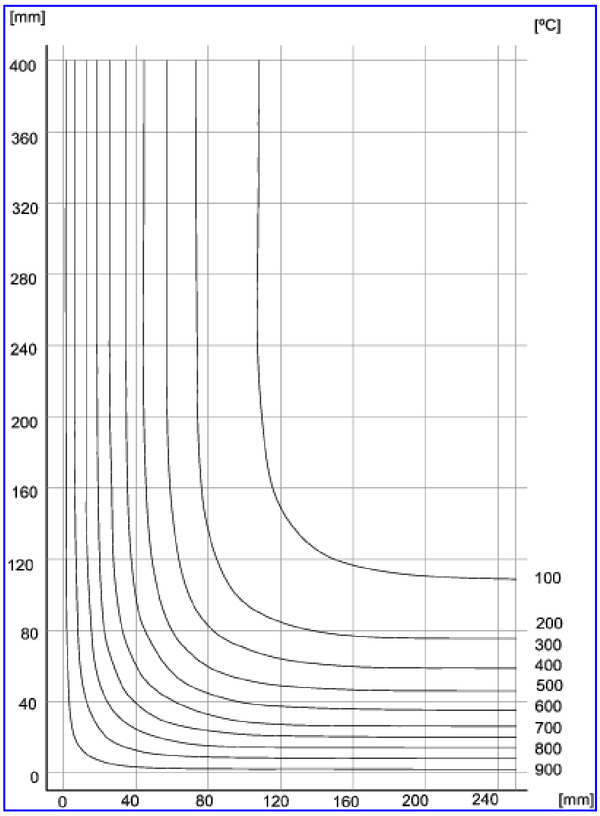


R-120

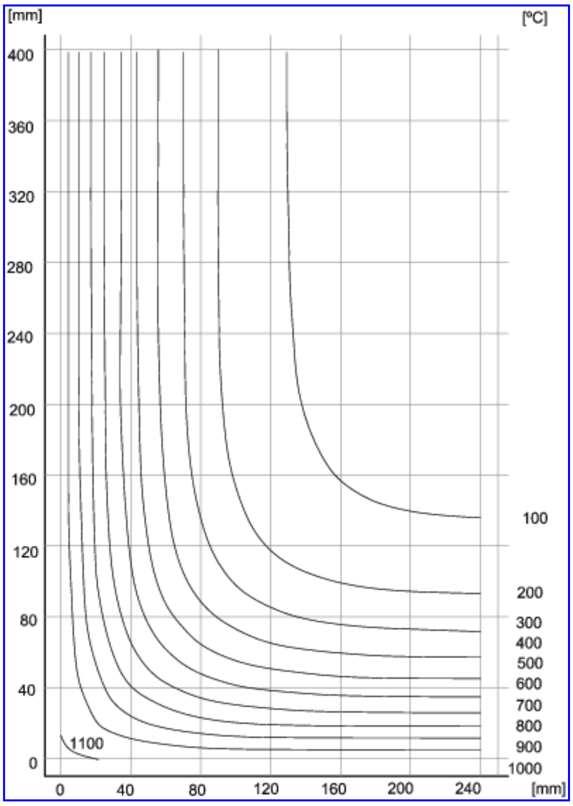
Figure A.6.7.4.c
Isotherms for rooms with a section of 800 x 500 mm exposed on both faces



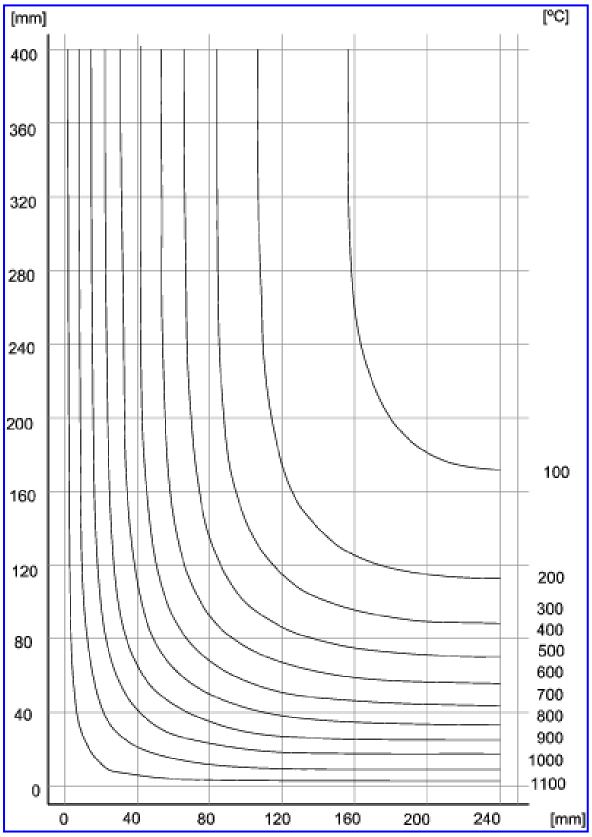
R-90



R-120



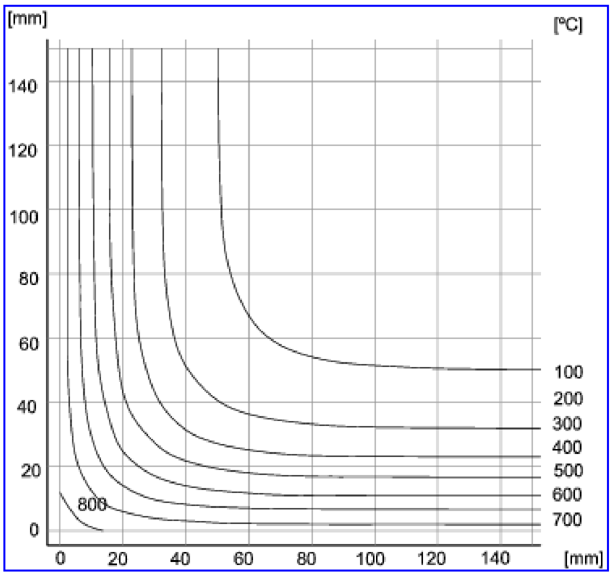
R-180



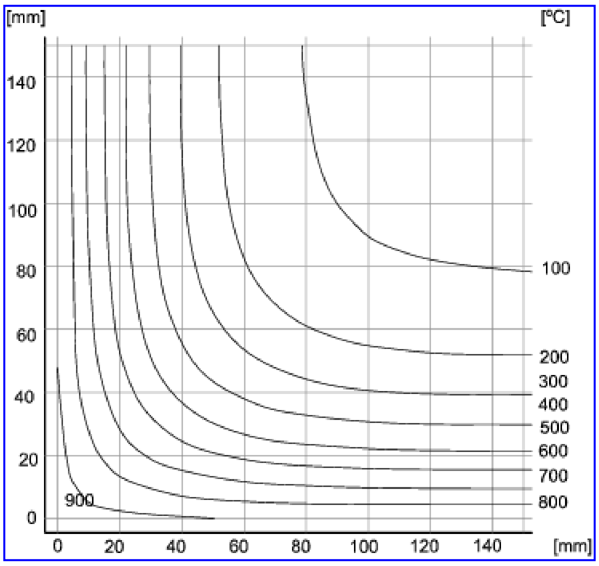
R-240

Figure A.6.7.4.d

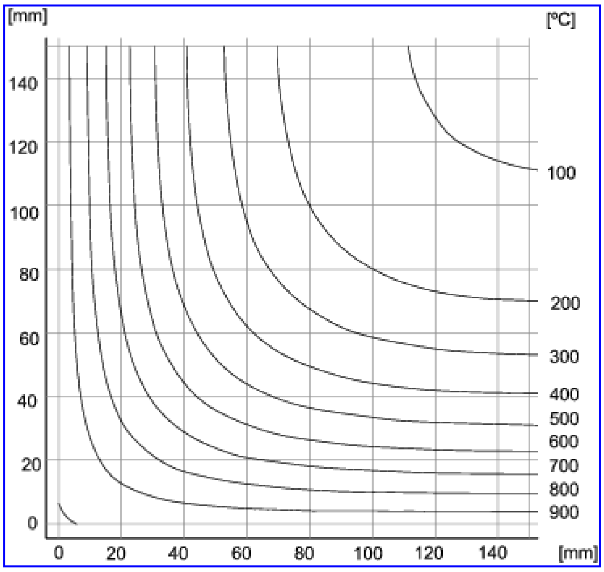
Isotherms for rooms with a section of 300 x 300 mm exposed on both faces



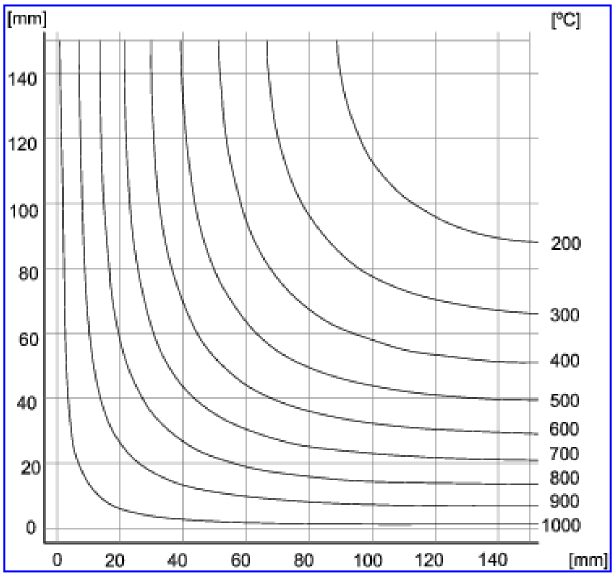
R-30



R-60



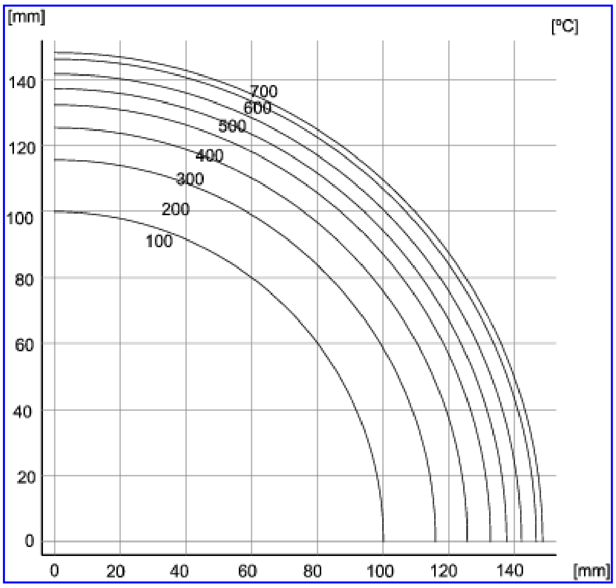
R-90



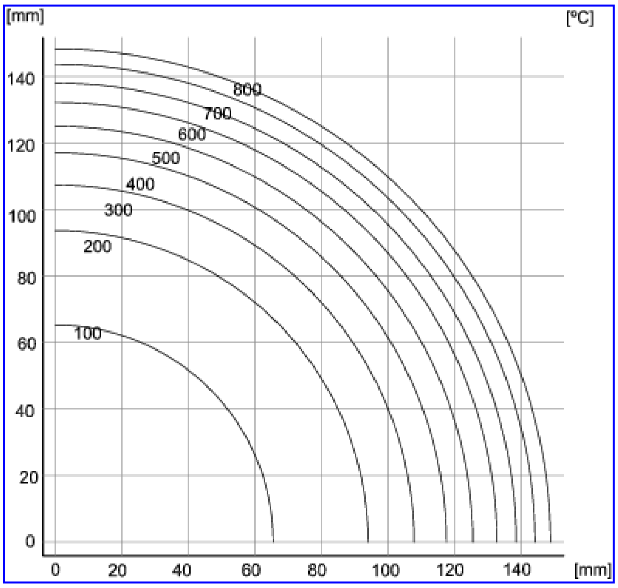
R-120

Figure A.6.7.4.e

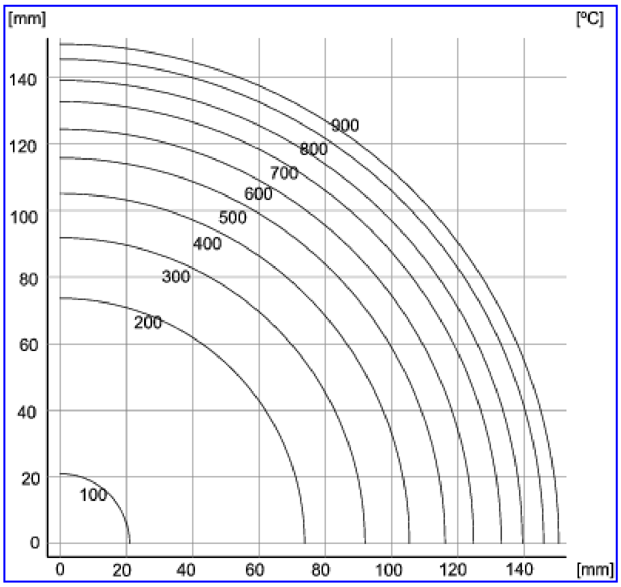
Isotherms for a room with a circular section 300 mm in diameter exposed around the perimeter



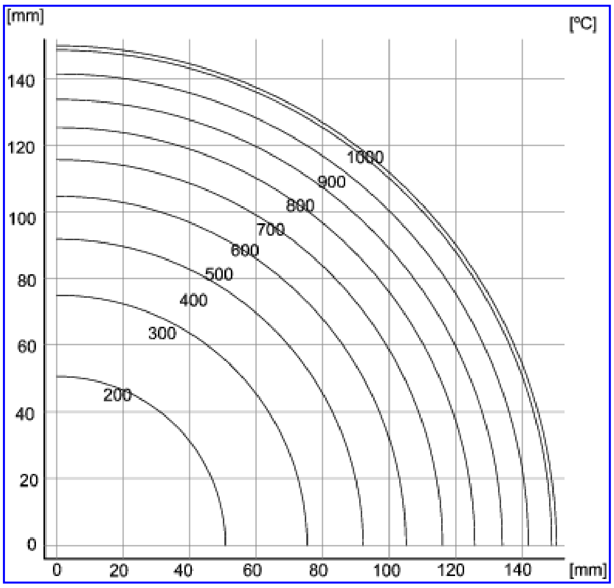
R-30



R-60



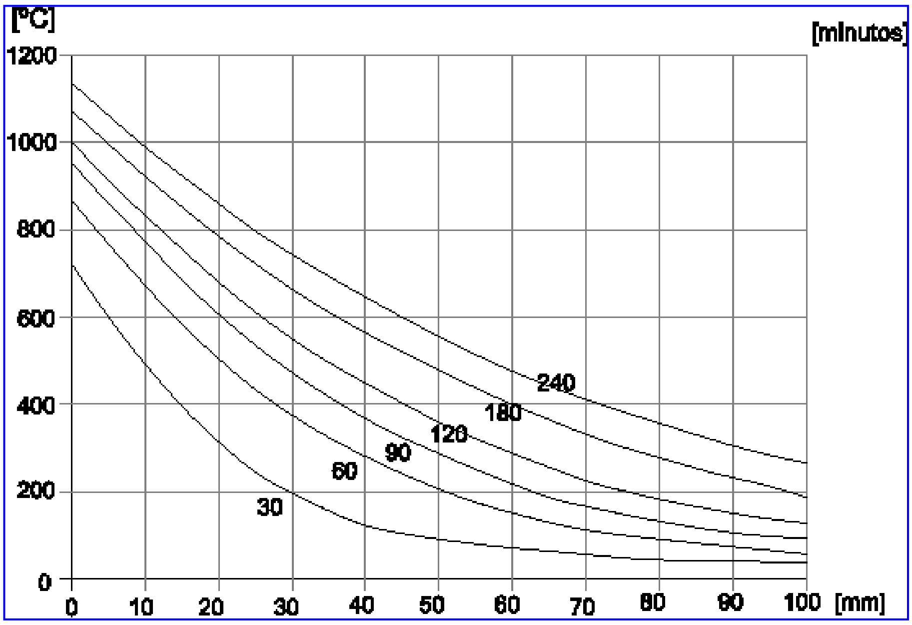
R-90



R-120

Figure A.6.7.4.f

Temperature distribution in the thickness of flat sections exposed on one face h ≥ 200 mm



R-30 - R240