

HSE

**Fire resistance of
concrete enclosures**

Work Packages 5-8

HSE

Fire resistance of concrete enclosures

Work Packages 5-8

Work Package 5 and 6: Heat transfer modelling in response to two of the HSE design fires, Work Package 7: Look-up Tables, Work Package 8: Spalling guidance

October 2005

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Job number 116718

Job title	Fire resistance of concrete enclosures	Job number	116718
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Document title	Work Packages 5-8	File reference	
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Document ref					
Revision	Date	Filename	0002Report work packages 5-8 Draft 1.doc		
Draft 1	20/06/05	Description	First draft		
		Prepared by	Checked by	Approved by	
		Name	Susan Lamont	Barbara Lane	Barbara Lane
		Signature			
Issue	24/06/05	Filename	0003Report work packages 5,7 and 8 issue.doc		
		Description	Includes comment from BL		
		Prepared by	Checked by	Approved by	
		Name	Susan Lamont	Barbara Lane	Barbara Lane
Rev A	26/08/05	Filename	0006Report work package 5-8 26th Aug 05 Rev A.doc		
		Description	Include additional runs and client comments		
		Prepared by	Checked by	Approved by	
		Name	Susan Lamont	Barbara Lane	Barbara Lane
Rev B	02/09/05	Filename	0007Report work package 5-8 2nd Sept 05 Rev B.doc		
		Description	Incorporate client comments and additional work for cooling phase of fire etc		
		Prepared by	Checked by	Approved by	
		Name	Susan Lamont	Barbara Lane	Barbara Lane
Rev B	02/09/05	Signature			

Issue Document Verification with Document

Job title Fire resistance of concrete enclosures Job number 116718

Document title Work Packages 5-8 File reference

Document ref

Revision	Date	Filename	0009Report Work package 5-8 Rev C Oct 2005.doc		
Rev C	05/10/05	Description			
			Prepared by	Checked by	Approved by
		Name	Susan Lamont	Barbara Lane	Barbara Lane
		Signature			
		Filename			
		Description	Issued to MSSN Group Specification Representatives for comment.		
			Prepared by	Checked by	Approved by
		Name			
		Signature			
		Filename			
		Description			
			Prepared by	Checked by	Approved by
		Name			
		Signature			
		Filename			
		Description			
			Prepared by	Checked by	Approved by
		Name			
		Signature			

Issue Document Verification with Document

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APPENDICES

Appendix A

Flowchart showing hierarchy of folders and files in Database

Appendix B

Designer's guide

1 Executive summary

This report describes the output from the final 4 work packages (5-8) of this project. The intent is to present the assumptions and validation for the Design Guide detailed in Appendix B of this report which is the final output of this work.

The scope of Work Packages 5-7 is to model heat transfer through a range of concrete wall thicknesses for 2 of the HSE provided design fires and generate design look-up tables from the results. The scope of Work Package 8 is to provide design guidance to limit spalling of ordinary strength concrete walls in a hydrocarbon fire.

The design guide in Appendix B follows a flow chart which has been created to allow designers to establish the spalling risk to a particular concrete wall from the risk categories created in Work Package 2 and then guide them to the appropriate look-up table. The look-up table then allows the designer to determine whether for a particular wall thickness, design fire, concrete moisture content and concrete type the wall passes the failure criterion of 140°C on the unexposed face of the wall. This is the failure criterion adopted for insulation in BS 476 for standard fire resistance testing and is considered to be current best practice.

The following summarises the data used to create the Tables:

Heat transfer analyses to a range of concrete walls varying in thickness from 0.5-1.5m have been carried out using the design fires (Fire A and Fire C as described in the letter from the HSE of 12th April 2005) in order to develop these look-up tables. The variables tested and constants used in the heat transfer modelling were as per the conclusions of the sensitivity analyses of Work Package 3 and 4.

Therefore, three initial wall thicknesses with varying spalling rates during the 2 design fires resulted in 15 number wall thicknesses to be tested, in order to generate a useful data base.

In addition four concrete types taken from Work Package 1 and 2 were tested and two concrete moisture contents of 0% or 17%.

All of these variables were chosen to ensure the most conservative results could be obtained and the typical concrete of interest to the HSE could be captured.

In each analysis run (heat transfer from the fire through the specific make-up of concrete) only one variable of concrete type, moisture content, design fire or wall thickness was changed (a parametric study). Each run provided temperature-time data through the depth of the wall thicknesses (heat transfers from the fire side to the unexposed side) and therefore allowed an unexposed wall temperature check against the pass/fail criterion of 140°C.

The results of these analyses have been added to the database, the layout and hierarchy of which is described in Appendix A of this report.

Failure was observed for six scenarios when the thinnest wall (500mm thick) had a high risk spalling category and was exposed to a 60 minute hydrocarbon fire.

It was of concern to the HSE that heat would continue to pass through the wall during the cooling phase of the fire and after the fire has burnt out. Consequently, some of the scenarios tested were repeated with design fires including a cooling phase. The maximum wall thickness tested with cooling was 320mm as this case showed that for 0% moisture, the concrete type with highest thermal diffusivity (Concrete type IV) and the hottest/longest fire (Fire C) the temperature on the unexposed face of the wall did not change in the cooling phase of the fire. It can therefore be assumed that for wall thicknesses > 320mm plus the concrete types and fire exposures considered here the results for temperature on the unexposed face of the wall are valid without including the cooling phase of the fire.

In some cases the wall therefore failed the test criterion of 140°C during cooling or when the fire had burnt out despite having passed at the end of the heating phase of the fire. A further 11 failures were therefore predicted when the cooling phase was incorporated in the study.

As the thinner wall sections are more sensitive to fire and at the request of the HSE, further wall thicknesses were investigated of 120mm, 150mm and 220mm in order to enhance the data within the look-up tables for wall thicknesses < 320mm.

The design flow chart and associated look-up tables, now allow designers to determine if a particular arrangement of wall design passes the failure criterion set out by this project

The design guide should be used with a full understanding of the limitations of the method as listed in Section 10 of this report.

2 Introduction

This report describes the heat transfer analyses carried out under work package 5 of this project, on a range of wall thicknesses, assuming the two fire exposures as provided by the HSE on 12th April 2005.

The variables and constants assumed in the heat transfer models tested were as per the conclusions of Work Package 3&4.

The results of the heat transfer analyses are used to generate look-up tables, for a particular concrete material, wall thickness and moisture content that indicate whether or not the wall assembly will pass the failure criterion of a temperature rise limit of 140°C on the unexposed face of the wall. The check is calculated at the end of the HSE provided fire exposure and as heat continues to pass through the concrete during cooling and after the fire has burnt out.

In order for the look-up tables to be used by a designer, various decisions relating to the specific wall assembly must be made. Therefore the first step in the process is to use a specially prepared flowchart. The flowchart guides the designer through a series of questions and tables to define the thickness of the wall after spalling and then indicates which pass/fail look-up table that should be read to check the adequacy of their design against the agreed failure criterion.

This process is summarised in the Designer's guide presented in Appendix B of this report which is the final outcome of this work.

3 Heat transfer analysis - Constants

The constant values proposed by Work Package 4 and adopted by the heat transfer analyses in Work Package 5 are as follows:

1. Convection coefficient on the unexposed face = 10W/m²K

Varying convection coefficient on the unexposed face of the wall had almost no impact on the temperature of the unexposed face of the wall in Work Package 4. The value of 10W/m²K is within the range for natural convection, which is 5-50W/m²K (Drysdale 1999). EN 1991-1-2 recommends a slightly lower value of between 4-9W/m²K. A value of 10W/m²K was taken because it is close to the values suggested by EN 1991-1-2 which is considered best practice at this time.

2. Convection coefficient on the exposed face = 50W/m²K

This is the value defined by EN 1991-1-2 for hydrocarbon type fire exposures and the sensitivity analyses in work package 4 have shown that using a higher value has little impact on the resulting temperature of the unheated side of the concrete wall. Hence the use of this currently accepted best practice value.

3. Resultant emissivity on the unexposed face = 0.6

Resultant emissivity has been shown by work package 4 to have little effect on the unexposed face unless the wall is thinner than 200mm. A value of 0.6 is quoted by Drysdale (1998) as the emissivity value associated with concrete. Hence the use of this currently accepted best practice value.

4. Resultant emissivity on the exposed face = 0.8

This is the value defined by EN 1991-1-2 and the sensitivity analyses in work package 4 have shown that using a higher value has little impact on the concrete wall temperature. Using lower values does result in lower concrete temperatures but resultant emissivity in

this case can be expected to be close to 1.0 because of the black smoke in a hydrocarbon fire. Hence the use of this currently accepted best practice value.

5. Temperature range for evaporation of water = 100-200°C

The evaporation range has been shown to not affect the temperature of the concrete unless it is close to 100°C. EN 1992-1-2 recommends 100-200°C and so will be used here, as it is considered best practice at this time.

4 Heat transfer analysis - variables

The variables used in the heat transfer calculations from the respective design fires through the range of concrete walls are as follows:

- The concrete material properties (density, conductivity and specific heat).
- Moisture content
- Wall thickness
- Spalling

This is justified as follows.

4.1 Moisture content

A moisture content of either 0% or 17% has been analysed in the heat transfer studies of Work Package 5. A value of 0% is conservative for design in all cases because the presence of moisture slightly reduces the concrete wall temperature.

17% is the upper bound requested to be tested by the HSE because this was tested in the sensitivity analyses of work package 4 and found to be significant.

4.2 Wall Thicknesses

The three basic wall thicknesses tested in Work Package 5 are 0.5, 1.0 and 1.5m. This range of wall thickness was agreed with the HSE at a project review on the 10th January 2005.

However, the actual wall thickness to be tested in the heat transfer analyses is the final thickness after all spalling has occurred. In other words on application of heat it is already assumed the wall is at its thinnest as if all spalling (as calculated from the risk categories of Work Package 2) had occurred. This has been an assumption all through this project.

After considering spalling rates of 3mm/min or 7mm/min (described in Work Package 2) with fire durations of 30 or 60 minutes (as defined by Fire A and Fire C) the 12 different wall thickness listed in Table 1 were generated and were therefore assessed in the heat transfer analysis of Work Package 5.

Base wall thickness (mm)	Thickness after a 30 minute fire of 3mm/min spalling (mm)	Thickness after a 30 minute fire of 7mm/min spalling (mm)	Thickness after a 60 minute fire of 3mm/min spalling (mm)	Thickness after a 60 minute fire of 7mm/min spalling (mm)
500	410	290	320	80
1000	910	790	820	580
1500	1410	1290	1320	1080

Table 1 Range of wall thicknesses before and after spalling assessed by Work Package 5.

4.3 Concrete types

Four concrete types were analysed in Work Package 5.

These were selected from “Concrete properties.xls” under Work Package 1 of the database. In order to make the concrete type selection, the thermal diffusivity of the concrete materials was calculated. Thermal diffusivity is a measure of how rapidly heat will travel through the concrete and is defined as follows:

$$\text{Thermal diffusivity} = \frac{k}{\rho c}$$

Where,

k = thermal conductivity (W/mK)

ρ = density (kg/m³)

c = specific heat (J/kgK)

Figure 1 shows thermal diffusivity with increasing concrete temperature for a range of different concretes.

The data for all three material properties is not always available for every concrete, and this is reflected in “Concrete properties.xls”. Consequently, for example, the material “Siliceous 2”, “Granite” and “Basalt”, as presented in Figure 1, are theoretical concretes considering density, specific heat and conductivity from a range of measurements taken on different siliceous, granite or basalt concretes respectively by different researchers.

It is likely that this type of approach was also used to develop the Eurocode curves for siliceous and calcareous type concretes also plotted in Figure 1 of this report.

The 4 materials therefore chosen as input to the heat transfer models in Work Package 5 are as follows:

- **Concrete I:** Eurocode 2 calcareous because it is one of the lower bounds for thermal diffusivity for normal weight concrete. i.e it allows slow heat transfer but is still conservative for design of walls with Basalt type concretes.
- **Concrete II:** Eurocode 2 siliceous because it is a recognised concrete model in the mid-range of thermal diffusivity for normal weight concrete. Siliceous aggregates are also commonly used.
- **Concrete III:** Siliceous 2 because based on the data in work package 2, a higher value of thermal diffusivity is possible with siliceous type concretes than the EC 2 model for concrete III suggests.
- **Concrete IV:** Quartz because based on the material from Work package 1 and 2 it is the upper bound for thermal diffusivity of normal weight concrete. i.e it allows most heat transfer.

The thermal diffusivity against temperature plot for the 4 concrete types chosen is shown in Figure 2.

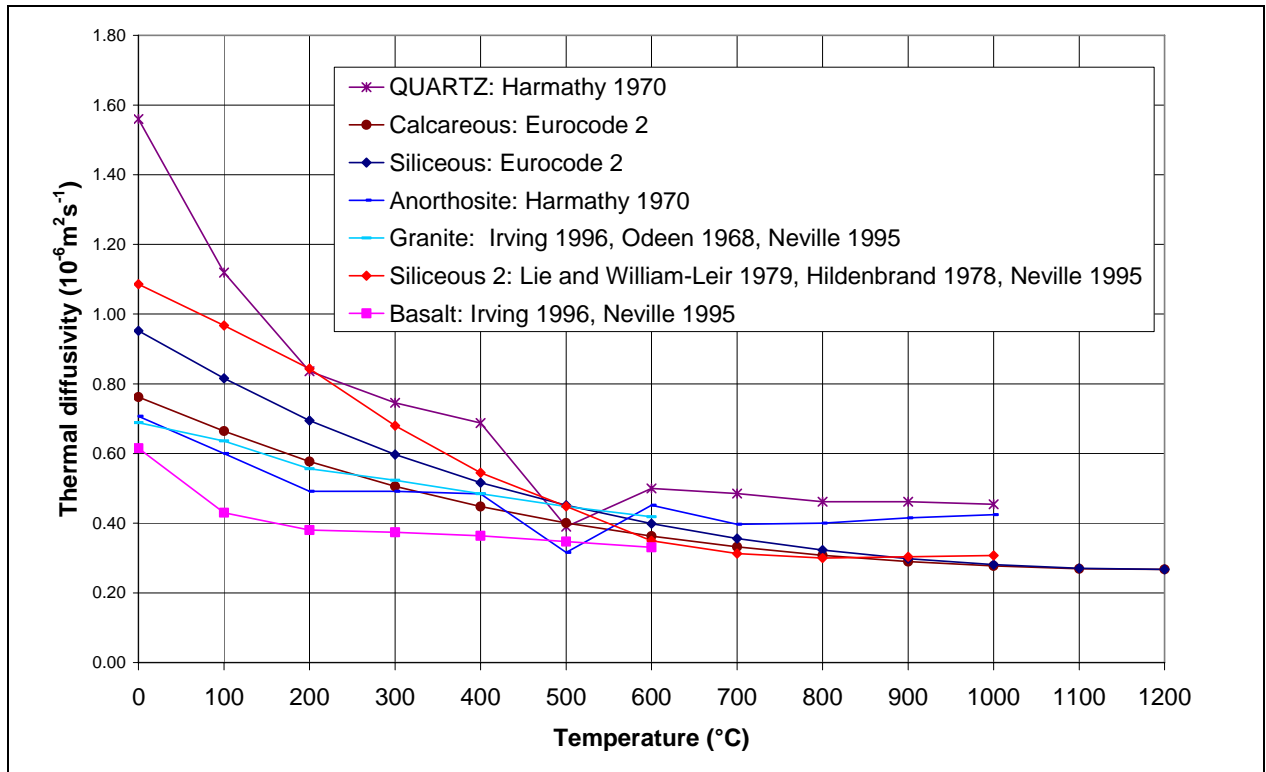


Figure 1 Thermal diffusivity of several concrete material types

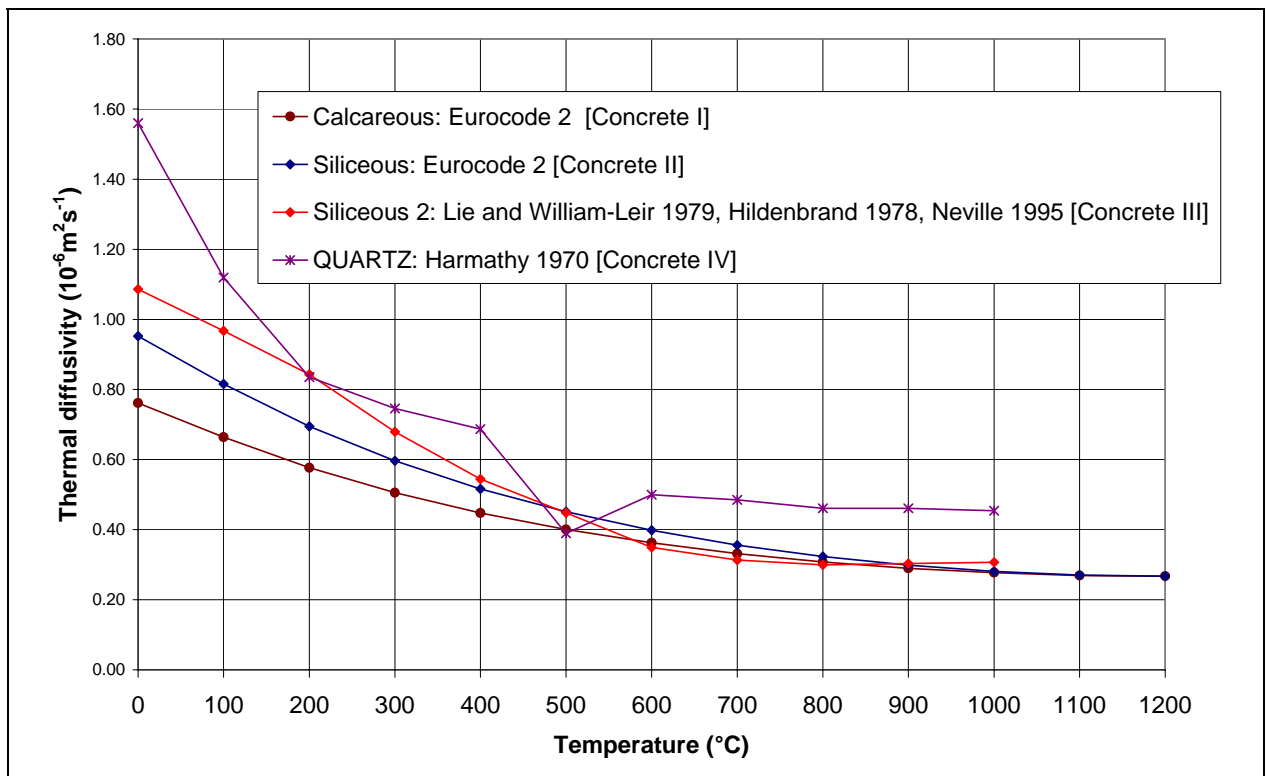


Figure 2 Four concrete types used in the heat transfer assessment for the look-up tables.

5 Heat transfer analysis - Design fires

Three design fires have been provided by the HSE. These are described in Table 2.

As agreed with the HSE on 28th April 2005, Fire A and Fire C have been taken as input to the heat transfer modelling work to generate the final look-up tables.

The site specific fire (Fire B) has been tested on a site specific case only (see Section 12 of this report).

Fire Ref.	Description	Surface Emissive Power (kW/m ²)	Burn Time* (mins)	Convective Gas Temperature (K)
A	Best estimate	23	30	1073
B	Site specific	86	60	1073
C	Worst case	120	60	1473

Table 2 The three design fires.

*Burn time is the duration of the fully developed phase of the fire i.e. the cooling phase is not included.

5.1 The cooling phase of the fire

Initially, the heat transfer analyses through the walls were carried out for the duration of the fire exposure up to but excluding the decay phase of the fire.

This meant the heat transfer analysis was terminated after 30 minutes of Fire A and 60 minutes of Fire C. This approach is in line with current design practice and standard furnace testing. However, in reality heat would continue to dissipate through the wall in the decay or cooling phase of the fire and when the fire has completely burnt out.

The design fires with cooling are illustrated in Figure 3.

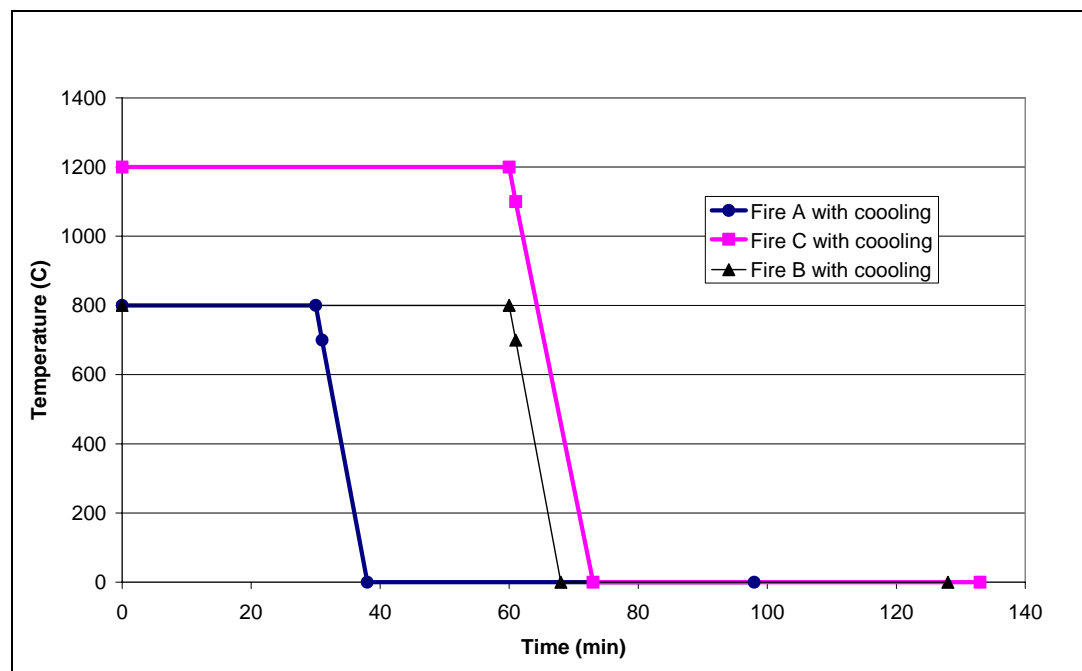


Figure 3 Design fires with cooling phase

The maximum wall thickness tested with cooling was 320mm as this case showed that for 0% moisture, the concrete type with highest thermal diffusivity (Concrete type IV) and the hottest/longest fire (Fire C) the temperature on the unexposed face of the wall did not

change in the cooling phase of the fire. It can therefore be assumed that for wall thicknesses > 320mm plus the concrete types and fire exposures considered here the results for temperature on the unexposed face of the wall are valid without including the cooling phase of the fire.

For the thinner wall thicknesses only, the heat transfer analyses were repeated for each of Fire A and Fire C including a cooling phase at a rate of 100°C per minute and thereafter a temperature of 0°C for 1 hour (see Figure 3).

The results are presented in the look-up tables of Section 7 of this report.

6 Spreadsheets in database: Work Package 5

The spreadsheets (Results Fire A.xls, Results Fire C.xls) generated for the database under Work Package 5 have been formatted to allow their use as an additional design tool in combination with the look-up tables. A designer can determine the exact values of temperature on the unheated side from this database, in order to make alternative judgements or decisions, not part of the presented set of look-up tables.

The spreadsheets include concrete material properties for the 4 concrete types studied and temperature-time plots generated at various points through the depth of each wall.

An example of the output in the database is shown in Figure 4.

Figure 4 shows a plot of the temperature versus time relationship through the thickness of a concrete wall at different thicknesses through the wall for the 0% and 17% moisture case respectively.

6.1 Data for wall thicknesses < 320mm

The heat transfer analyses have shown that the temperature on the unexposed face of the wall only significantly increases if the wall thickness after spalling is less than 320mm. Spalled wall thicknesses of 120mm, 150mm and 220mm were analysed for the 0% moisture case to further populate the design tables at these thicknesses.

<h1 style="margin: 0;">ARUP</h1>	Job No.	Sheet No.	Rev.
	116718	n/a	C
	Member/Location	n/a	
	Drq. Ref.	n/a	
Job Title	HSE - Work package 5		
Calculation	Concrete IV: QUARTZ-Harmathy 1970		
Made by	AB	Date	10/05/2005 Chd. SL

<p>Input Data for Fire C:</p> <p>Burn time: 60 min</p> <p>Surface emissive power: 120 kW/m²</p> <p>Convective gas temperature: 1200 °C</p> <p>Wall properties:</p> <p>Assessed concrete wall thickness: 80mm</p> <p>Original Wall Thickness: 500 mm</p> <p>Spalling Rate: 7 mm/min</p> <p>Moisture Content (MC): Varying: 0% or 17%</p> <p>Evaporation range: 100-200 °C</p>	<p>Concrete Properties:</p> <p>Conductivity: As specified for Concrete type</p> <p>Density: As specified for Concrete type</p> <p>Specific Heat: As specified for Concrete type</p> <p>Heat transfer data:</p> <p>Emissivity (exposed): 0.8</p> <p>Emissivity (unexposed): 0.6</p> <p>Convection (exposed): 50 W/m²K</p> <p>Convection (unexposed): 10 W/m²K</p>
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<p>Results form heat transfer calculation:</p> <p>0% Moisture Content</p> <table border="1" style="width: 100%; text-align: center;"> <caption>Temperatures at varying depth in concrete (°C)</caption> <thead> <tr> <th>Time (min)</th> <th>Exposed Surface</th> <th>27mm</th> <th>54mm</th> <th>Unexposed surface</th> </tr> </thead> <tbody> <tr><td>0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>10</td><td>1116.2</td><td>339.1</td><td>108.9</td><td>54.3</td></tr> <tr><td>20</td><td>1139.3</td><td>491.6</td><td>230.3</td><td>148.7</td></tr> <tr><td>30</td><td>1150.0</td><td>581.4</td><td>319.3</td><td>219.7</td></tr> <tr><td>40</td><td>1158.1</td><td>660.3</td><td>392.4</td><td>275.2</td></tr> <tr><td>50</td><td>1163.6</td><td>717.8</td><td>446.9</td><td>316.3</td></tr> <tr><td>60</td><td>1167.5</td><td>759.8</td><td>485.3</td><td>343.8</td></tr> </tbody> </table>	Time (min)	Exposed Surface	27mm	54mm	Unexposed surface	0	0.0	0.0	0.0	0.0	10	1116.2	339.1	108.9	54.3	20	1139.3	491.6	230.3	148.7	30	1150.0	581.4	319.3	219.7	40	1158.1	660.3	392.4	275.2	50	1163.6	717.8	446.9	316.3	60	1167.5	759.8	485.3	343.8	<p>17% Moisture Content</p> <table border="1" style="width: 100%; text-align: center;"> <caption>Temperatures at varying depth in concrete (°C)</caption> <thead> <tr> <th>Time (min)</th> <th>Exposed Surface</th> <th>27mm</th> <th>54mm</th> <th>Unexposed surface</th> </tr> </thead> <tbody> <tr><td>0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>10</td><td>1091.7</td><td>168.6</td><td>64.1</td><td>34.5</td></tr> <tr><td>20</td><td>1123.9</td><td>388.0</td><td>116.2</td><td>84.5</td></tr> <tr><td>30</td><td>1139.6</td><td>490.6</td><td>157.0</td><td>105.1</td></tr> <tr><td>40</td><td>1146.2</td><td>543.2</td><td>194.7</td><td>120.4</td></tr> <tr><td>50</td><td>1152.3</td><td>599.2</td><td>289.9</td><td>148.4</td></tr> <tr><td>60</td><td>1157.9</td><td>655.8</td><td>352.1</td><td>186.1</td></tr> </tbody> </table>	Time (min)	Exposed Surface	27mm	54mm	Unexposed surface	0	0.0	0.0	0.0	0.0	10	1091.7	168.6	64.1	34.5	20	1123.9	388.0	116.2	84.5	30	1139.6	490.6	157.0	105.1	40	1146.2	543.2	194.7	120.4	50	1152.3	599.2	289.9	148.4	60	1157.9	655.8	352.1	186.1
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<p>Data from heat transfer calculations:</p> <table border="1" style="width: 100%; text-align: center;"> <thead> <tr> <th></th> <th>Exposed</th> <th>27mm</th> <th>54mm</th> <th>Unexposed</th> </tr> </thead> <tbody> <tr><td>0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>1</td><td>8.6</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>1</td><td>16.9</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>2</td><td>25.1</td><td>0.1</td><td>0.0</td><td>0.0</td></tr> <tr><td>3</td><td>33.2</td><td>0.1</td><td>0.0</td><td>0.0</td></tr> <tr><td>4</td><td>41.0</td><td>0.2</td><td>0.0</td><td>0.0</td></tr> <tr><td>4</td><td>48.7</td><td>0.3</td><td>0.0</td><td>0.0</td></tr> <tr><td>5</td><td>56.3</td><td>0.4</td><td>0.0</td><td>0.0</td></tr> <tr><td>6</td><td>63.7</td><td>0.5</td><td>0.0</td><td>0.0</td></tr> <tr><td>7</td><td>71.0</td><td>0.6</td><td>0.0</td><td>0.0</td></tr> </tbody> </table>		Exposed	27mm	54mm	Unexposed	0	0.0	0.0	0.0	0.0	1	8.6	0.0	0.0	0.0	1	16.9	0.0	0.0	0.0	2	25.1	0.1	0.0	0.0	3	33.2	0.1	0.0	0.0	4	41.0	0.2	0.0	0.0	4	48.7	0.3	0.0	0.0	5	56.3	0.4	0.0	0.0	6	63.7	0.5	0.0	0.0	7	71.0	0.6	0.0	0.0	<p>Data from heat transfer calculations:</p> <table border="1" style="width: 100%; text-align: center;"> <thead> <tr> <th></th> <th>Exposed</th> <th>27mm</th> <th>54mm</th> <th>Unexposed</th> </tr> </thead> <tbody> <tr><td>0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>1</td><td>8.6</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>1</td><td>16.9</td><td>0.0</td><td>0.0</td><td>0.0</td></tr> <tr><td>2</td><td>25.1</td><td>0.1</td><td>0.0</td><td>0.0</td></tr> <tr><td>3</td><td>33.2</td><td>0.1</td><td>0.0</td><td>0.0</td></tr> <tr><td>4</td><td>41.0</td><td>0.2</td><td>0.0</td><td>0.0</td></tr> <tr><td>4</td><td>48.7</td><td>0.3</td><td>0.0</td><td>0.0</td></tr> <tr><td>5</td><td>56.3</td><td>0.4</td><td>0.0</td><td>0.0</td></tr> <tr><td>6</td><td>63.7</td><td>0.5</td><td>0.0</td><td>0.0</td></tr> <tr><td>7</td><td>71.0</td><td>0.6</td><td>0.0</td><td>0.0</td></tr> </tbody> </table>		Exposed	27mm	54mm	Unexposed	0	0.0	0.0	0.0	0.0	1	8.6	0.0	0.0	0.0	1	16.9	0.0	0.0	0.0	2	25.1	0.1	0.0	0.0	3	33.2	0.1	0.0	0.0	4	41.0	0.2	0.0	0.0	4	48.7	0.3	0.0	0.0	5	56.3	0.4	0.0	0.0	6	63.7	0.5	0.0	0.0	7	71.0	0.6	0.0	0.0
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Figure 4 Example of output from work package 5 in database. The 17% moisture case shows a change in gradient between 100-200°C at 27mm into the wall (red line). This is the delay in heating caused by latent heat of evaporation as the free moisture in the concrete evaporates during heating between 100-200°C.

7 Work package 7: Look-up tables

Four look-up tables (see Tables A-D) have been produced for each HSE fire and a moisture content of 0% or 17% to summarise the results in the database for work package 5. Note these results include those walls that failed when thermal lag in the cooling phase of the fire was included.

The cells of Tables A-D include the actual temperature achieved on the unheated side of the wall and a simple pass or fail, pass being written as "ok" and fail highlighted in blue. The pass/fail results in the tables relate to the failure criterion of a limit to 140°C temperature rise on the unexposed face of the wall.

Out of the 144 scenarios tested ignoring the cooling phase of the fires in the heat transfer analyses, six failures were predicted.

This equates to 4% of the total scenarios tested. In all failed cases the unspalled thickness of wall was 500mm, reduced to 80mm after spalling at a rate of 7mm/min over 60minutes.

Out of the new scenarios tested an additional 11 failures have been predicted. In all failed cases the spalled thickness of wall was <220mm.

It is important to note that this could be significant if there are a number of walls of existing structures with an unspalled thickness of 500mm and they are in a high risk spalling category.

Fire A, Moisture Content 0%										
Original Thickness (mm)	Spalled Thickness (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
	80	yes	155.2	FAIL	176.0	FAIL	204.7	FAIL	215.1	FAIL
	120	yes	82.6	ok	97.6	ok	118.0	ok	130.6	ok
	150	yes	53.5	ok	66.7	ok	82.5	ok	95.0	ok
	220	yes	12.3	ok	20.3	ok	29.3	ok	43.6	ok
500	290	yes	2.5	ok	5.0	ok	7.9	ok	16.1	ok
500	410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	790	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	910	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1290	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table A Look-up table for Hydrocarbon Fire A and 0% moisture content. Thermal diff = Thermal diffusivity and is a measure of how rapidly heat will travel through the concrete related to density, specific heat and conductivity of the concrete. It is defined in Section 4.3 of this report.

Fire A, Moisture Content 17%										
Original Thickness (mm)	Spalled Thickness (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
500	290	no	0.0	ok	0.0	ok	0.0	ok	0.2	ok
500	410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	790	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	910	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1290	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table B Look-up table for Hydrocarbon Fire A and 17% moisture content.

Fire C, Moisture Content 0%										
Original Thickness (mm)	Thickness after spalling (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
500	80	yes	291.0	FAIL	312.2	FAIL	354.9	FAIL	365.0	FAIL
	120	yes	175.2	FAIL	196.0	FAIL	237.5	FAIL	246.8	FAIL
	150	yes	122.9	ok	142.3	FAIL	178.8	FAIL	187.5	FAIL
	220	yes	38.5	ok	55.3	ok	77.3	ok	94.7	ok
500	320	yes	*	ok	*	ok	*	ok	29.9	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	580	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	820	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1080	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1320	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table C Look-up table for Hydrocarbon Fire C and 0% moisture content. *Note the maximum temperature on the unexposed face of the wall was not calculated for the wall of spalled thickness 320mm including the cooling phase of the fire for Concrete Types I-III because they are known to pass when Concrete type IV passes.*

Fire C, Moisture Content 17%										
Original Thickness (mm)	Thickness after spalling (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
500	80	no	114.6	ok	130.0	ok	168.6	FAIL	186.1	FAIL
500	320	no	0.2	ok	0.4	ok	0.8	ok	2.4	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	580	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	820	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1080	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1320	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table D Look-up table for Hydrocarbon Fire C and 17% moisture content.

8 Thickness of wall remaining below 400°C

At the request of the HSE Tables E-H list the thickness of the fire exposed walls that did not exceed 400°C at any point in the design fire. At 400°C almost 100% of concrete strength and 50% of concrete stiffness is retained. This information may be used in structural stability checks of the walls. Structural design in fire is not part of this project therefore this is not included in the design guide in Appendix B.

The results show that for the thicker walls (>320mm) which readily passed the thermal criterion, the depth of the concrete with lower strength and significant degradation in stiffness (temperatures in excess of 400°C) is generally 50mm. However for the thinner post-spalled sections, the depth of thermal degradation could extend to the full section depth of 80mm.

Fire A, Moisture Content 0%, Thickness of wall < 400°C (mm)						
Original Thickness (mm)	Spalled Thickness (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76	Concrete II Aggregate=siliceous 0.76<Therm diff<0.95	Concrete III Aggregate =siliceous 0.95<Therm diff<1.1	Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6
	80	yes	55	55	55	55
	120	yes	95	95	95	95
	150	yes	125	125	125	125
	220	yes	195	195	195	195
	290	yes	265	265	265	265
500	290	no	265	265	265	265
500	410	no	385	385	385	385
500	500	no	475	475	475	475
1000	790	no	765	765	765	765
1000	910	no	885	885	885	885
1000	1000	no	975	975	975	975
1500	1290	no	1265	1265	1265	1265
1500	1410	no	1385	1385	1385	1385
1500	1500	no	1475	1475	1475	1475

Table E Thickness of concrete wall that has remained below 400°C for the duration of design fire A and a moisture content of 0%.

Fire A, Moisture Content 17%, thickness of wall < 400°C (mm)						
Original Thickness (mm)	Spalled Thickness (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76	Concrete II Aggregate=siliceous 0.76<Therm diff<0.95	Concrete III Aggregate =siliceous 0.95<Therm diff<1.1	Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6
500	290	no	265	265	265	265
500	410	no	385	385	385	385
500	500	no	475	475	475	475
1000	790	no	765	765	765	765
1000	910	no	885	885	885	885
1000	1000	no	975	975	975	975
1500	1290	no	1265	1265	1265	1265
1500	1410	no	1385	1385	1385	1385
1500	1500	no	1475	1475	1475	1475

Table F Thickness of concrete wall that has remained below 400°C for the duration of design fire A and a moisture content of 17%.

Fire C, Moisture Content 0%, Thickness of wall < 400°C						
Original Thickness (mm)	Thickness after spalling (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76	Concrete II Aggregate=siliceous 0.76<Therm diff<0.95	Concrete III Aggregate =siliceous 0.95<Therm diff<1.1	Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6
	80	yes	20	20	0	0
	120	yes	70	70	45	45
	150	yes	100	100	75	75
	220	yes	195	195	170	170
	320	yes				245
500	80	no	20	20	10	10
500	320	no	270	270	245	245
500	500	no	450	450	425	425
1000	580	no	530	505	505	505
1000	820	no	770	770	745	745
1000	1000	no	950	950	925	925
1500	1080	no	1030	1030	1005	1005
1500	1320	no	1270	1270	1270	1270
1500	1500	no	1450	1450	1425	1425

Table G Thickness of concrete wall that has remained below 400°C for the duration of design fire C and a moisture content of 0%.

Fire C, Moisture Content 17%, Thickness of wall < 400°C (mm)						
Original Thickness (mm)	Thickness after spalling (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76	Concrete II Aggregate=siliceous 0.76<Therm diff<0.95	Concrete III Aggregate =siliceous 0.95<Therm diff<1.1	Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6
500	80	no	30	30	30	30
500	320	no	270	270	270	270
500	500	no	450	450	450	450
1000	580	no	530	530	530	530
1000	820	no	770	770	770	770
1000	1000	no	950	950	950	950
1500	1080	no	1030	1030	1030	1030
1500	1320	no	1270	1270	1270	1270
1500	1500	no	1450	1450	1450	1450

Table H Thickness of concrete wall that has remained below 400°C for the duration of design fire C and a moisture content of 17%.

9 Design guide

The full design guide is presented in Appendix B of this report.

The proposed design process to determine the most applicable look-up table, can be summarised by the flow chart in Figure 5.

To aid understanding of this process a design example is provided below.

9.1 Important information

It should be noted that both design fires, Fires A and C, are hydrocarbon type fires. The look-up tables are only appropriate for these fire scenarios.

The HSE needs to provide guidance on which Design Fire is appropriate for different enclosures. This guidance should be added to this design guide before the guide is made available for use.

If the moisture content of the concrete is not known, in order to be conservative the designer should assume the worst case scenario for spalling i.e. >3% and the worst case scenario for heat transfer i.e. 0%.

Alternatively two checks could be carried out assuming 0% moisture or >3% moisture to establish the worst case scenario without being overly conservative.

If the material properties of the concrete (density, specific heat and conductivity) are not known and a thermal diffusivity cannot be calculated then the concrete type (I-IV) should be chosen based on the aggregate. For example if the aggregate is Calcareous then assume Concrete I. If the aggregate is siliceous but not quartz then assume concrete III.

9.2 Design example

The design process can be summarised by the following example, assuming these characteristics:

- Ordinary Strength Concrete (OSC) wall of 500mm thick
- The fire exposure is hydrocarbon Fire A,
- The concrete contains 2% moisture,
- The wall contains no rebar therefore cover > 40mm,
- The concrete will have a siliceous aggregate,
- The number of sides expected to be exposed to fire =1,
- The wall is restrained
- The concrete has low thermal expansion properties
- The wall is unloaded.
- Thermal diffusivity >1.0x10⁻⁶ for siliceous type concrete

The designer is prompted by the flow chart to choose a design fire and a concrete type.

In this example:

Fire A (30minutes duration, 23kW/m²)

Concrete Type IV because the thermal diffusivity > 1.0x10⁻⁶.

The designer is then asked to establish the thickness of wall after spalling. To do this the designer must first categorise the spalling risk of the chosen concrete type. This is achieved by (A) calculating the total spalling risk from Table 3, based on the characteristics of the concrete and the wall design, then (B) reading the appropriate category of spalling rate from Table 4.

(A) To arrive at a “total spalling risk” value for a particular concrete, all of the relevant individual “risk” values from Table 3 are added together. The value of “total risk” will then fit into the range for each of the categories in Table 4.

In this example:

OSC: hydrocarbon fire, 2% moisture, no rebar, cover > 40mm, siliceous aggregate, sides exposed =1, section size >200m, restrained, low thermal expansion, unloaded:

= 1+5+1+3+3+3+1+1+3+1 + 1=23 ⇒ Risk Category C

(B) The designer must multiply the spalling rate associated with the particular risk category by the chosen fire duration. This will give a value of total spalled material.

For this example:

Category C = 3mm/min spalling rate.

Fire A has a duration of 30 minutes therefore the thickness of wall that can be expected to spall is 30 x 3 =90mm.

The total spalled material thickness should then be subtracted from the original wall thickness.

For this example:

The residual wall thickness = 500-90=410mm.

Once this reduced wall thickness and the level of moisture expected in the concrete wall is known the designer is directed to one of the Tables A-D by the flow chart.

Tables A-D show whether or not the various wall thicknesses and concrete types pass the failure criterion of not exceeding a temperature rise of 140°C on the unexposed face of the wall.

In this case Table A is suitable because the example considers Fire A and a moisture content less than 17%. From look-up Table A for a moisture content of <17% and spalled thickness of 410mm, the design passes the failure criterion including the decay phase of the fire for all concrete types I-IV.

Table 3 Risk factors for each variable known to affect spalling of concrete (see report for Work Package 2 of this project)

	RISK
Design Strength >55Mpa	Not quantified
Design Strength ≤55Mpa	1
Hydrocarbon fire	5
Standard fire (BS 476)	1
Moisture content >3%	5
Moisture content ≤3%	1
No Reinforcement	3
Reinforcement included	1
Cover ≥ 40mm	3
Cover <40mm	1
Siliceous aggregate	3
Calcareous aggregate	1
No. of sides exposed >1	3
No. of sides exposed = 1	1
Section size <200mm	3
Section size ≥ 200mm	1
Restrained	3
Unrestrained	1
Thermal expansion ≥ 10 x 10 ⁻⁶	3
Thermal expansion < 10 x 10 ⁻⁶	1
Loaded in compression	3
Unloaded	1

Table 4 Spalling categories and associated spalling levels (*key factors = properties of the concrete or the boundary conditions that are known to promote spalling e.g. aggregate type, section thickness etc) (see report for work package 2 of this project)

Category	Risk of spalling	Value of Total Risk	Key factors	Spalling level
A	Very low	≤11	Ordinary strength, NWC, Unloaded, Unrestrained, Standard fire exposure, Reinforced, moisture <3%, one side exposure	Zero or minimal
B	Low	12-20	Ordinary strength, NWC, restrained, Standard fire exposure Significant number of key variables* likely to promote spalling	Up to the level of the reinforcement
C	Med	21-28	Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure :Small number of key variables* likely to promote spalling	3mm/min
D	High	29-37	Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure Significant number of key variables* likely to promote spalling	7mm/min
E	Very high	>37	High strength (Design strength >55Mpa), standard hydrocarbon fire exposure.	Unquantifiable

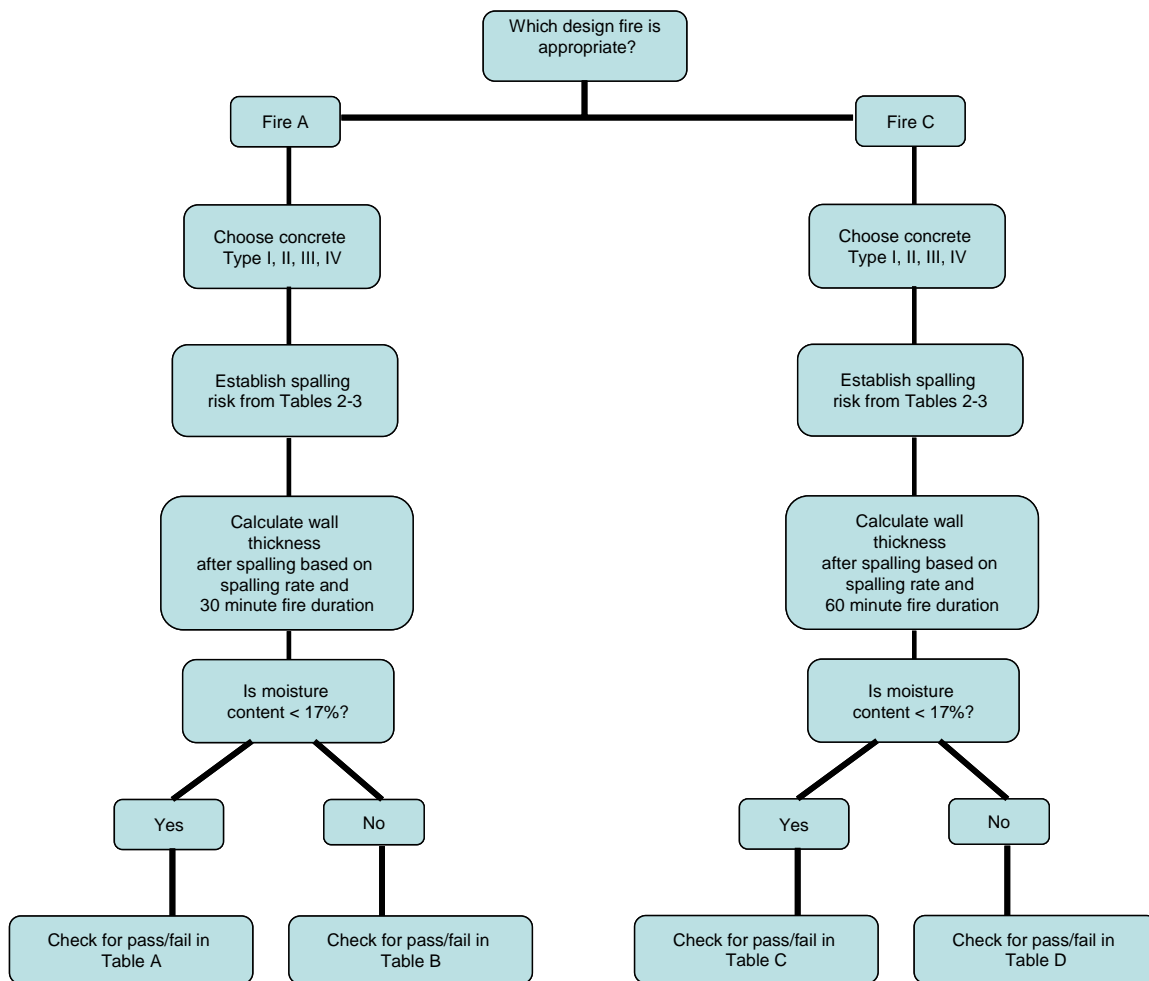


Figure 5 Flowchart outlining the design steps

10 Limitations of design guide

This project has considered 1D heat transfer through a range of wall thicknesses only. The exact dimensions or construction of a typical enclosure is not known. Consequently the following limitations should be considered when applying the results of this project to design.

- The presence of shielding windows in the thickness of the walls has been ignored by the heat transfer calculations which form the basis of this report and the associated design guide. However, some of the walls which will be tested with the design guide will have these windows passing through their thickness. It is understood that the thickness of the shielding windows generally equals the thickness of the wall therefore the face of the window is flush with the face of the wall. If the window system is determined to be equivalent to or better than the concrete it too can be incorporated in the assessment proposed in this work. Otherwise it must not be included.
- The presence of discontinuities in the concrete wall has also not been considered quantitatively by the heat transfer analyses. When the concrete walls are constructed the concrete is poured in sections which results in discontinuities between wall pours. It is understood that these discontinuities are generally very small cracks as would be expected in any other concrete structure that was poured in several stages.
 - The advantage for some of the structures of interest to the HSE is that the wall discontinuities are stepped in order to prevent a radiation shine path

through the wall. In addition the discontinuity is understood to be tied together with water bars, in the depth of the wall, made from continuous extruded rubber. It is proposed that because the crack is thin and only a construction joint that this is not of concern.

- However, in some instances the HSE have advised that the stepped discontinuities consist of a 25mm gap which are filled with flexcell (a proprietary preformed rigid cane fibre board product, containing durable asphalt) or a lead wool to create an expansion joint. Asphalt melts at about 150°C although the exact properties of flexcell are not known. Lead melts at about 320°C. The flexcell or lead is therefore likely to melt in a fire leaving an exposed edge which could experience greater spalling than the continuous portion of the wall because fire will be able to heat the wall on 2 sides. A 2D heat transfer analysis would then be required where fire exposure on 2 sides of the wall was considered. This has not been considered by the heat transfer analyses of this study therefore the look-up tables would underestimate the temperatures for fire exposure on 2 sides.
- Structural stability of the wall thickness has not been quantified. The stability of the wall after spalling should be considered as part of the overall design as a separate exercise. Eurocode 2 gives a range of methods to calculate structural stability in concrete at high temperature. The strength properties of different concretes derived from testing were listed in the database in spreadsheets under Work Package 1.
- The effect of thermal curvature as a result of the temperature gradient through the wall should also be considered as part of the structural stability check. The strain associated with thermal bowing can be simply calculated by $\left(\frac{T_1 - T_2}{d}\right)\alpha$ where T_1 and T_2 are the exposed and unexposed wall temperature, d is the wall thickness and α the thermal expansion coefficient of the concrete. This is an approximation because the temperature through concrete is not linear. How this strain affects the deformed shape of the wall depends on the fixity of the wall boundaries. The thermal expansion properties of different concretes derived from testing were listed in the database under Work Package 1.
- The heat transfer models and the spalling categories defined are based on the research material available in the public domain at the time this project was carried out and the assumptions in the reports for Work Packages 1-4. We recommend that these be reviewed as the technology for concrete in fire improves.

11 Advice for designers in the event of a fail rating

If the failure criterion is exceeded, for proposed construction this means the designer can alter the concrete assembly design, to develop a “pass” system.

However if this is determined for an existing structure, this may pose significant problems if remedial works are not practicable.

As such a more detailed investigation of the wall system can be carried out, using the data on which the look-up tables are based.

This is because the look-up tables represent the conservative result of all the assumptions made in this project. Should any conservative assumption not be deemed relevant to the wall enclosure under review, the designer could then determine an alternative pass/fail system.

To assist in this approach the following conservatisms are identified for information purposes:

- In the context of this project for ordinary strength concrete exposed to the design fires the spalling rates of 3mm/min and 7mm/min for medium and high risk of spalling respectively as defined by this project are considered to be high but based on current knowledge of spalling.
- In general most spalling will occur during the growth phase of the fire when the rate of change of temperature is high therefore assuming that spalling will occur for the entire duration of the heating phase of the fire is probably also conservative.
- The heat transfer studies assumed that all spalled material was lost at time zero which means the wall temperatures predicted are higher than they might be in reality as spalling varies with time.
- Almost all structural elements are restrained by adjacent structure but the extent to which they are restrained will vary. If the wall is external and not heavily restrained then this means less spalling will occur.
- Columns are most certainly loaded in compression whereas walls may not be, or may be in compression as a result of bending only. If the load ratio of the wall is low (~0.2-0.3) i.e. the compressive stress is low compared to the capacity it could be argued that the wall is not significantly loaded.
- The failure criterion of 140°C is based on the BS476 standard test for insulation and may or may not be appropriate for the materials stored on the other side of the wall. A temperature rise of 140°C may be too high in some cases resulting in ignition of fire load on the unexposed face or it may be too low, and this should be considered on a case by case basis.

The designer could question each of the assumptions above especially if failure is only by a few °C say up to 160°C or if the spalling risk as defined by this project is close to the cut-off point between 2 spalling categories.

Conversely if a wall only just passes and there is material on the unexposed face of the wall that has a lower ignition temperature than 140°C the designer should ensure all of their assumptions are indeed conservative.

12 The site specific wall and associated design fire

As part of this project the HSE requested that a site specific wall be considered in response to a particular design fire (Fire B).

It is understood that the wall is a reinforced concrete structure with no openings or shielding windows. The results of the site specific case and associated design fire can be described as follows:

12.1 Step 1 - The fire exposure

The design fire has a surface emissive power of 86kW/m^2 with a burn time of 60 minutes and a maximum temperature of 1073K (800°C). The design fire includes an assumed cooling period and 60 minutes at 0°C is described by Figure 3.

12.2 Step 2 - The concrete type

The aggregate of the concrete wall is made up from siliceous fines and coarse limestone aggregate. The specific values of conductivity and specific heat are unknown for the concrete therefore the exact thermal diffusivity can not be calculated but Concrete I has been assumed on the basis that limestone is a calcareous aggregate.

12.3 Step 3 -Defining the spalling risk category

The following wall characteristics have been provided by the HSE. It should be noted that the thermal expansion of the concrete was not measured but taken by the HSE from Neville (1995) for calcareous concrete as $6-8 \times 10^{-6}$. The wall is understood to be restrained by return walls, reinforced concrete foundations and roof. The wall is loaded by hydrostatic conditions on the inside therefore is loaded in bending and subjected to compression and tension forces.

Concrete wall characteristic	Risk factor from Table 3
Strength: 30 N/mm^2	1
Hydrocarbon fire exposure	5
Moisture content > 3%	5
Reinforced	1
Cover > 40mm	3
Calcareous aggregate	1
1 side exposure	1
Section size > 200mm	1
Restrained	3
Thermal expansion < 10×10^{-6}	1
Loaded in compression	3
Total	25

The sum of all the risk factors is 25 leading to a “medium” risk of spalling and Category C from Table 4.

12.4 Spalled thickness

Category C is associated with a spalling rate of 3mm/min. The duration of the heating phase of Fire B is 60 minutes.

Therefore the total spalling is:

$$60 \times 3 = 180 \text{mm}$$

and the wall thickness after spalling is:

$$1372 - 180 = 1192 \text{mm}$$

12.5 Temperature on the unexposed surface of the wall

The 1192mm wall and associated material properties was analysed in response to the site specific fire and the results of the heat transfer are presented in Figure 6.

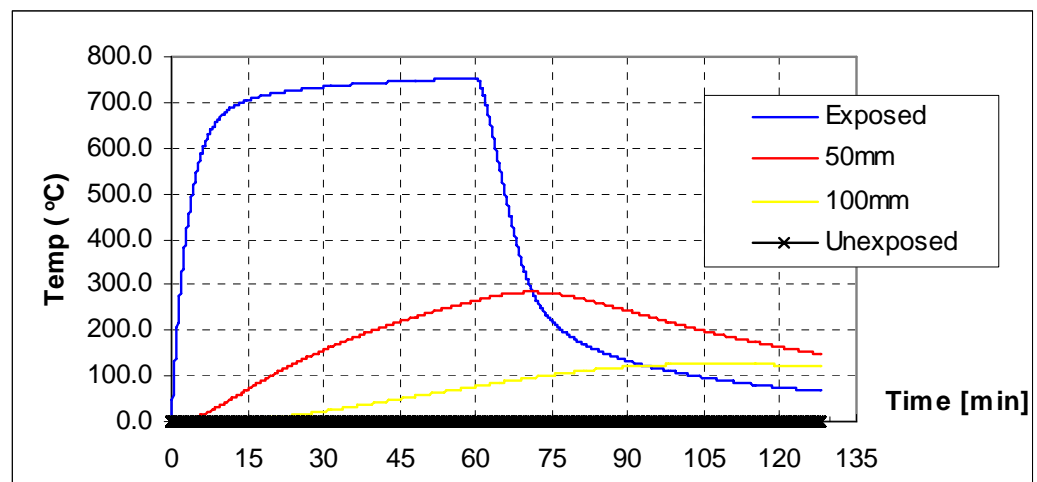


Figure 6 Heat transfer results from the site specific case and associated fire.

The temperature of the wall on the unexposed face did not exceed ambient during the design fire, therefore the wall passes the failure criterion of limiting the temperature rise on the unexposed side to 140°C.

Furthermore, 1167mm of the wall thickness remained below 400°C for the duration of the fire including cooling phase.

13 Work package 8: Spalling guidance

In terms of good design practice to limit spalling in new construction the variables which generate a high risk of spalling as described in Table 3 should be minimised wherever possible.

The ideal combination of these variables to limit spalling is:

- Concrete design strength $\leq 55\text{Mpa}$.
- Moisture content $\leq 3\%$. Note this level of moisture cannot be achieved in external structures.
- Reinforcement included.
- Cover $< 40\text{mm}$.
- Calcareous aggregate.
- No. of sides exposed = 1.
- Section size $\geq 200\text{mm}$.
- Unrestrained.
- Thermal expansion of the concrete material $< 10 \times 10e^{-6}$. Calcareous aggregates have thermal expansion coefficients $< 10 \times 10e^{-6}$.
- Unloaded.

In addition to designing the concrete wall itself to meet the best combination of variables to limit spalling there are three standardised protective methods of limiting or preventing spalling in design as follows:

- The inclusion of a sacrificial mesh.
- Passive fire protection applied to the concrete surface.
- The inclusion of polypropylene fibres in the concrete mix.

13.1 Inclusion of a sacrificial mesh

The British standard BS 8110 Part 2 and Eurocode 2 recommend the inclusion of a steel sacrificial mesh the intent of which is to delay spalling beyond the line of the sacrificial mesh. The success of this approach is unknown because there is evidence that spalling will occur beyond the line of the mesh. However, spalling can be expected to be slower with the mesh than without.

13.2 Application of passive fire protection

The application of passive fire protection to the face of the concrete wall is the only known approach to limit or prevent spalling effectively because the concrete surface is not directly exposed to heat. However this approach is also the most expensive solution and is entirely reliant on the fire protection remaining in place throughout the fire. It is also the only approach to limit spalling in an existing enclosure because it can be retrofitted to the wall.

Suitable materials include;

Cementitious sprays, thermally insulating board, proprietary products used in the lining of tunnels.

In the case of the board and cementitious spray type products their suitability in an external environment will need to be considered as well as their response to hydrocarbon type fires. The fixings and stickability of these products are essential to ensure their good performance.

13.3 Addition of polypropylene fibres

Adding polypropylene fibres to the concrete mix to limit spalling was developed for High Strength Concretes (HSC). It is generally considered overly conservative for traditional Ordinary Strength Concrete (OSC) structures.

However if spalling could not be tolerated by a design then this is one method of significantly limiting spalling. Guidance on the amount of fibres to be added to an OSC concrete mix is scarce because the technology was developed for High Strength Concrete (HSC).

From a literature review of up to 28 research papers and reports (Arup 2005) where concrete with polypropylene fibres had been tested in fire the following can be summarised:

- The amount of PPF added to the concrete mixes tested ranged from 0.9 to 6 kg/m³.
- The range of concrete strength tested varied from 30 MPa to 114 MPa therefore some OSC has been tested.
- Six of the tests reviewed were for tunnel fire designs.
- Two of the tests focused on offshore installations.
- Both standard hydrocarbon and cellulosic fires were tested.

It is well documented in all of the reports/papers reviewed that spalling of high strength concrete is significantly reduced by adding polypropylene fibres to the concrete mix.

The cube compressive strength of the concrete is reported in some of the papers to be reduced by adding polypropylene fibres. "Effect of PPF on Performance in Fire" by N. Clayton 2000, suggests that the loss of cube strength is approximately 2 % per kg/m³ fibre.

A general trend in the conclusions is that 1 kg polypropylene fibre per m³ concrete is sufficient to prevent or largely reduce spalling of high strength concrete in fire.

Eurocode 2 recommends 2.0kg/m³ of PPF should be added to concrete to limit spalling - this applies to both HSC and OSC. There is no substantial justification for this value of fibres as far as we are aware. Very often tests are carried out on a project by project basis to show that they are effective in limiting spalling.

The British Board of Agrément who approve technical issues for construction recommend fibre doses for crack control etc but do not recommend a specific quantity to prevent spalling. They simply state the following:

20.1 The results of tests indicate that when concrete containing the product is subjected to fire, the structural integrity will be the same as for the plain concrete. The potential for explosive spalling will be reduced.

20.2 Fire will destroy fibres located close to the surface, resulting in an increase in porosity of the concrete.

Tests on a recent Arup project has shown that for HSC in a hydrocarbon fire, 1.0kg/m³ of fibres will be effective in limiting spalling which seems to agree with the general trend observed from the literature review. This amount of fibres should be conservative for OSC also but this has not been quantified.

This advice should be reviewed as the technology improves in the future.

14 Conclusion

The heat transfer analysis work carried out in work package 5 with the HSE hydrocarbon fire exposures, Fire A and Fire C, has shown that for most of the wall thicknesses requested by the HSE to form part of this analysis, the failure criterion of limiting the temperature rise on the unexposed side below 140°C was not exceeded.

Out of the 144 scenarios tested, ignoring the cooling phase of the fire, six failures have been predicted of which all cases had an unspalled wall thickness of 500mm, reduced to 80mm after spalling at a rate of 7mm/min over 60minutes.

When cooling is included a further 11 failures have been predicted. In all failed cases the spalled thickness of wall was <220mm.

The design flow chart and associated look-up tables produced as a result of the analysis, now allows designers to determine if a particular arrangement of wall design passes the failure criterion as formed the basis of this project

The design guide should be used with a full understanding of the limitations of the method as listed in Section 10 of this report.

In addition, suggestions have been given in Section 13 of this report on measures known to limit spalling effects in fire.

15 References

- 1) Arup Fire, Fire resistance of concrete enclosures. Work Package 1: data collection and Work Package 2: spalling categories.
- 2) Arup Fire, Fire resistance of concrete enclosures. Work Package 3: Upper and lower bound solution and Work Package 4: Sensitivity study.
- 3) Arup Fire, Fire resistance of concrete enclosures. Database – Spreadsheets under Work Package 1.
- 4) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 3.
- 5) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 4.
- 6) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 5.
- 7) The British Board of Agreement, Technical approvers for construction.
<http://www.bbacerts.co.uk/>
- 8) Drysdale, D. *Introduction to Fire Dynamics*, Wiley 1998.
- 9) ENV 1992-1-2 (1996), Eurocode 2 Design of concrete structures, Part 1.2 General rules – Structural fire design.
- 10) Arup literature review of polypropylene fibres. Internal report 2005.
- 11) Neville A.M. *Properties of concrete*, Longman Group Ltd 4th Edition, 1995.

Appendix A

**Flowchart showing
hierarchy of folders and
files in Database**

A1 Hierarchy of folders and files in Database

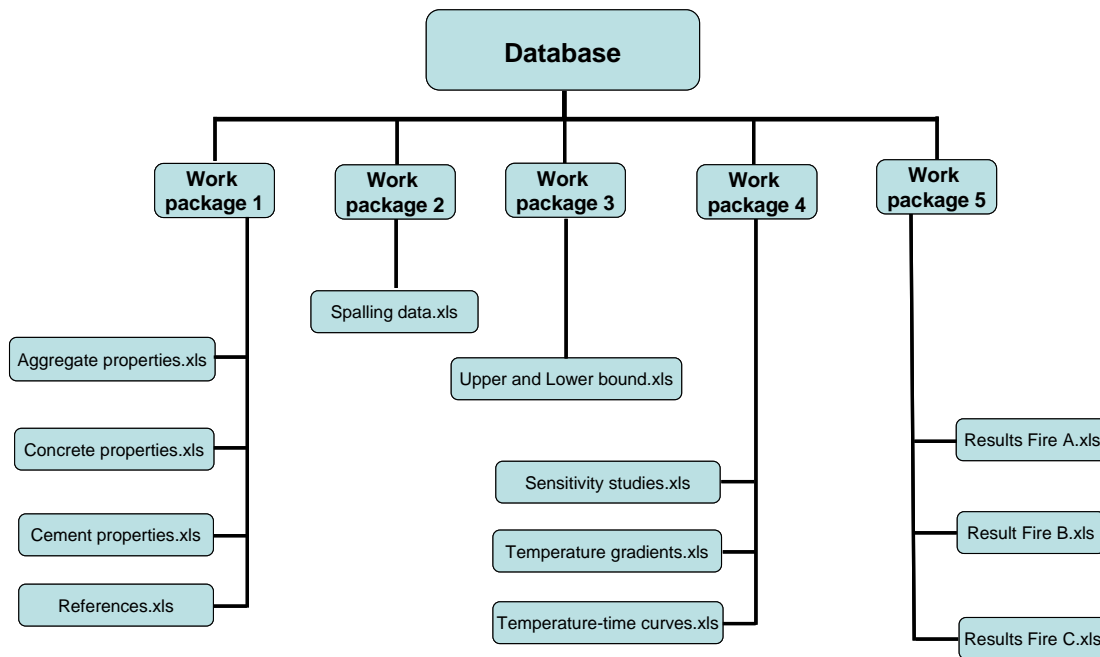


Figure A1 Flowchart showing hierarchy of folders and files in the database to be read in conjunction with Table A1 which describes the content of each excel file.

File name	Contents
Aggregate properties.xls	Values of conductivity, thermal expansion, specific heat, strength, moisture content and density at various temperatures for various aggregates.
Concrete properties.xls	Values of conductivity, thermal expansion, specific heat, strength, moisture content and density at various temperatures for various concretes.
Cement properties.xls	Values of conductivity, thermal expansion, specific heat, strength, moisture content and density at various temperatures for cement.
References.xls	List of literature referenced by this project.
Spalling data.xls	Guidance on spalling in literature, record of spalling in past fire tests etc.
Upper and lower bound.xls	Results of Work Package 3 showing the temperature on the unexposed face of the wall for the upper and lower bound case.
Sensitivity studies.xls	Results of Work Package 4 showing the sensitivities of the temperature on the unexposed face of the wall to each variable affecting heat transfer.
Temperature gradients.xls	Results of Work Package 4 showing the sensitivities of the gradient through the wall to each variable affecting heat transfer.
Temperature-time curves.xls	Results of Work Package 4 showing the sensitivities of the temperature time curves at various depths in the wall to each variable affecting heat transfer.
Results Fire A.xls	Heat transfer results in the form of temperature-time curves at various depths through the walls for Fire A.
Result Fire B.xls	Heat transfer results in the form of temperature-time curves at various depths through the site specific wall for Fire B.
Results Fire C.xls	Heat transfer results in the form of temperature-time curves at various depths through the walls for Fire C.

Table A1 The content of each excel file listed in Figure A1

Appendix B

Designer's guide

B1 Design guide

The result of the work carried out in the project "Fire resistance of concrete enclosures" is a series of look-up tables and a simple flow chart which can be used to assess whether or not an Ordinary Strength Concrete (OSC) wall will pass failure criterion of limiting the temperature rise on the unexposed face below 140°C, when the opposite face is exposed to one of the two HSE specified hydrocarbon design fires (Fire A or Fire C). A temperature rise of 140°C on the unexposed face of the wall is the failure criterion adopted for insulation in BS 476 for standard fire resistance tests and is considered to be current best practice.

The design process is given in the flow chart in Figure B1 and described in a series of steps in the following sections.

B1.1 Step 1 – Choose a design fire

The designer is prompted to choose a relevant design fire from Table B1. The temperature-time history of each design basis fire is shown in Figure B2. Note guidance required on this from HSE.

E.g.: Fire A (30minutes duration, 23kW/m²)

B1.2 Step 2 – Choose the appropriate concrete type I-IV

The range of concrete types appropriate for use are characterised by their thermal diffusivity. Thermal diffusivity is a measure of how rapidly heat will travel through the concrete and is defined as follows:

$$\text{Thermal diffusivity} = \frac{k}{\rho c}$$

Where,

k = thermal conductivity (W/mK)

ρ = density (kg/m³)

c = specific heat (J/kgK)

Figure B3 shows thermal diffusivity with increasing concrete temperature for the range of 4 OSC types appropriate for use with this design guide. These concrete types were chosen for the following reasons:

- **Concrete I(thermal diffusivity at 20°C <0.76 x10⁻⁶):** Eurocode 2 calcareous because it is one of the lower bounds for thermal diffusivity for normal weight concrete. i.e it allows slow heat transfer but is still conservative for design of walls with Basalt, granite and anorthosite type concretes.
- **Concrete II (0.76 x10⁻⁶<thermal diffusivity at 20°C<0.95 x10⁻⁶):** Eurocode 2 siliceous because it is a recognised concrete model in the mid-range of thermal diffusivity for normal weight concrete. Siliceous aggregates are also commonly used.
- **Concrete III(0.95 x10⁻⁶<thermal diffusivity at 20°C <1.1x10⁻⁶):** "Siliceous 2" because based on the data gathered in this project a higher value of thermal diffusivity is possible with siliceous type concretes than the EC 2 model for concrete II suggests.
- **Concrete IV(1.1 x10⁻⁶<thermal diffusivity at 20°C <1.6 x10⁻⁶):** Quartz because based on the material from Work package 1 and 2 it is the upper bound for thermal diffusivity of normal weight concrete. i.e it allows most heat transfer.

The thermal diffusivity value at 20°C should be calculated for the concrete under consideration and the concrete type (I-IV) selected based on this value. If the material properties of the concrete (density, specific heat and conductivity) are not known and a thermal diffusivity cannot be calculated then the concrete type (I-IV) should be chosen based on the aggregate because this drives the value

of the thermal diffusivity. For example if the aggregate is Calcareous then assume Concrete I. If the aggregate is Siliceous but not quartz then concrete III should be assumed.

B1.3 Step 3 – Calculate the spalling risk category

To categorise the spalling risk of the chosen concrete type the designer should

- calculate the total spalling risk from Table B2, based on the characteristics of the concrete and the wall design, then
- read the appropriate category of spalling rate from Table B3.

To arrive at a "total spalling risk" value (A) for a particular concrete, all of the relevant individual "risk" values from Table B2 are added together. The value of "total risk" will then fit into the range for each of the categories in Table B3.

E.g.: for OSC: hydrocarbon fire, 2% moisture, no rebar, cover > 40mm, siliceous aggregate, sides exposed =1, section size >200m, restrained, low thermal expansion, unloaded:
= 1+5+1+3+3+3+1+1+3+1 + 1=23 ⇒ Risk Category C (Table B3)

B1.4 Step 4 – Calculate final wall thickness after spalling

The designer must multiply the spalling rate associated with the particular risk category by the chosen fire duration. This will give a value of total spalled material.

E.g.: Category C = 3mm/min spalling rate.

Fire A has a duration of 30 minutes therefore the thickness of wall that can be expected to spall is 30 x 3 =90mm.

The total spalled material thickness should then be subtracted from the original wall thickness.

E.g.: The residual wall thickness = 500-90=410mm.

B1.5 Step 5 – Check design against pass/fail criterion in the look-up table

Once this reduced wall thickness and the level of moisture expected in the concrete wall is known the designer is directed to one of the Tables A-D by the flow chart.

Tables A-D contain the pass/fail results for various wall thicknesses and concrete types for a failure criterion of 140°C on the unexposed face of the wall.

If the moisture content of the concrete is not known and in order to be conservative the designer could assume the worst case scenario for spalling i.e. >3% and the worst case scenario for heat transfer i.e. 0%. Alternatively two checks could be carried out assuming 0% moisture or >3% moisture.

E.g. Table A is suitable for Fire A and a moisture content less than 17%.

From look-up Table A for a moisture content of <17% and spalled thickness of 410mm the design passes the failure criterion for all concrete types I-IV.

B2 Limitations of design guide

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- The presence of shielding windows in the thickness of the walls has been ignored by the heat transfer calculations which form the basis of this report and the associated design guide.

However, some of the walls which will be tested with the design guide will have these windows passing through their thickness. It is understood that the thickness of the shielding windows generally equals the thickness of the wall therefore the face of the window is flush with the face of the wall. If the window system is determined to be equivalent to or better than the concrete it too can be incorporated in the assessment proposed in this work. Otherwise it must not be included.

- The presence of discontinuities in the concrete wall has also not been considered quantitatively by the heat transfer analyses. When the concrete walls are constructed the concrete is poured in sections which results in discontinuities between wall pours. It is understood that these discontinuities are generally very small cracks as would be expected in any other concrete structure that was poured in several stages.
- The advantage for some of the structures of interest to the HSE is that the wall discontinuities are stepped in order to prevent a radiation shine path through the wall. In addition the discontinuity is understood to be tied together with water bars, in the depth of the wall, made from continuous extruded rubber. It is proposed that because the crack is thin and only a construction joint that this is not of concern.
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- Structural stability of the wall thickness has not been quantified. The stability of the wall after spalling should be considered as part of the overall design as a separate exercise. Eurocode 2 gives a range of methods to calculate structural stability in concrete at high temperature. The strength properties of different concretes derived from testing were listed in the database of Work Package 2.
- The effect of thermal curvature as a result of the temperature gradient through the wall should also be considered as part of the structural stability check. The strain associated with thermal bowing can be simply calculated by $\left(\frac{T_1 - T_2}{d}\right)\alpha$ where T_1 and T_2 are the exposed and unexposed wall temperature (°C), d is the wall thickness (mm) and α the thermal expansion coefficient of the concrete. This is an approximation because the temperature through concrete is not linear. How this strain affects the deformed shape of the wall depends on the fixity of the wall boundaries. The thermal expansion properties of different concretes derived from testing were listed in the database of Work Package 2.
- The heat transfer models and the spalling categories defined are based on the research material available in the public domain at the time this project was carried out and the assumptions in the reports for Work Packages 1-4. We recommend that these be reviewed as the technology for concrete in fire improves.

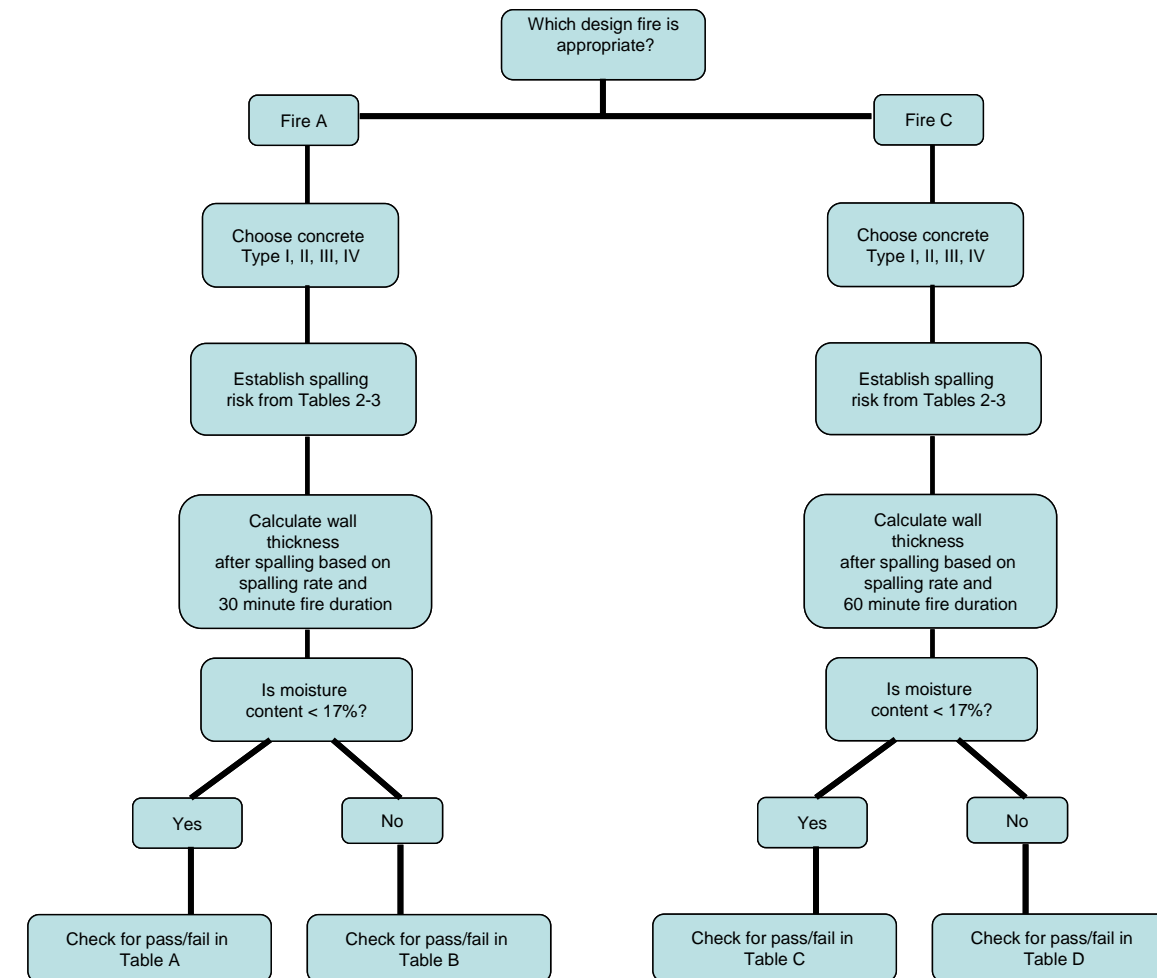


Figure B1 Design process

Table B1 Description of design fires

Fire Ref.	Description	Surface Emissive Power (kW/m ²)	Burn Time* (mins)	Convective Gas Temperature (°K)
A	Best estimate	23	30	1073
C	Worst case	120	60	1473

*Burn time is the duration of the fully developed phase of the fire i.e. the cooling phase is not included.

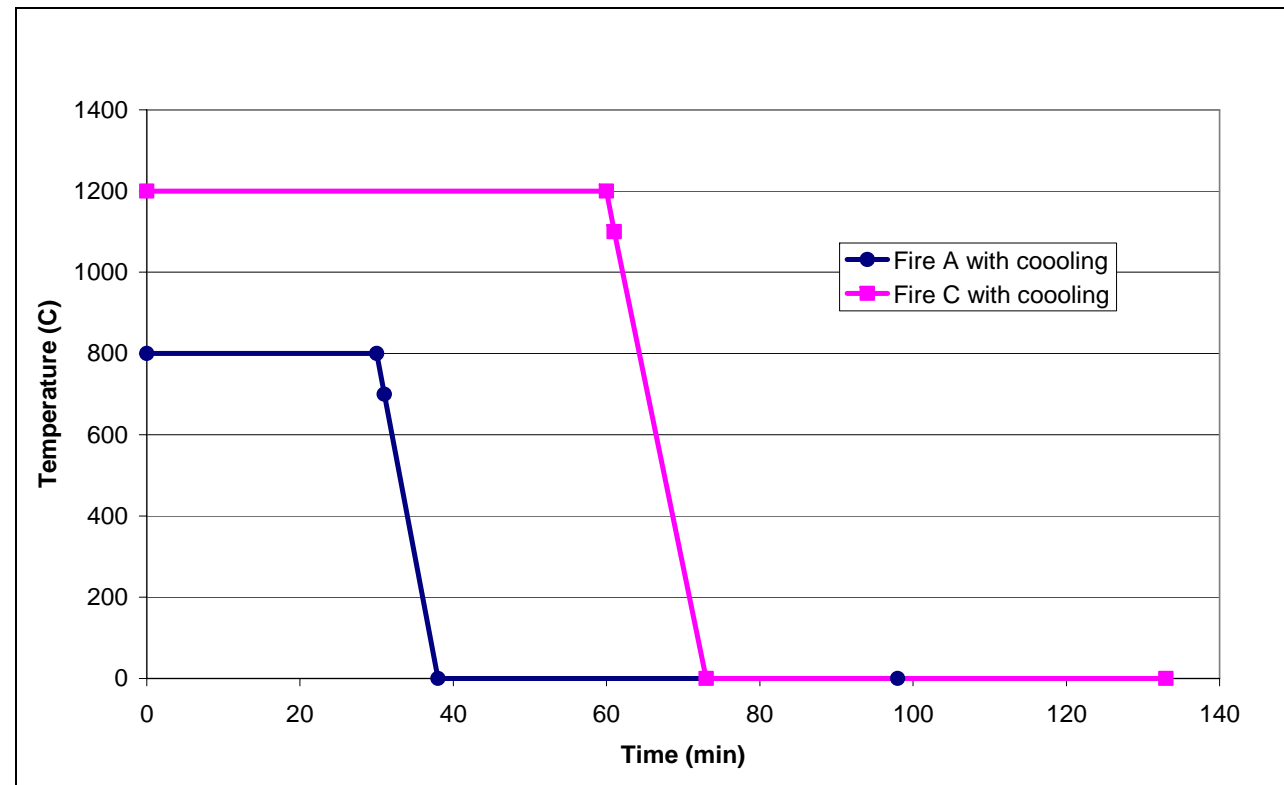


Figure B2 Temperature time curves for each design fire including a cooling phase and time for heat transfer through the concrete after the fire has burnt out.

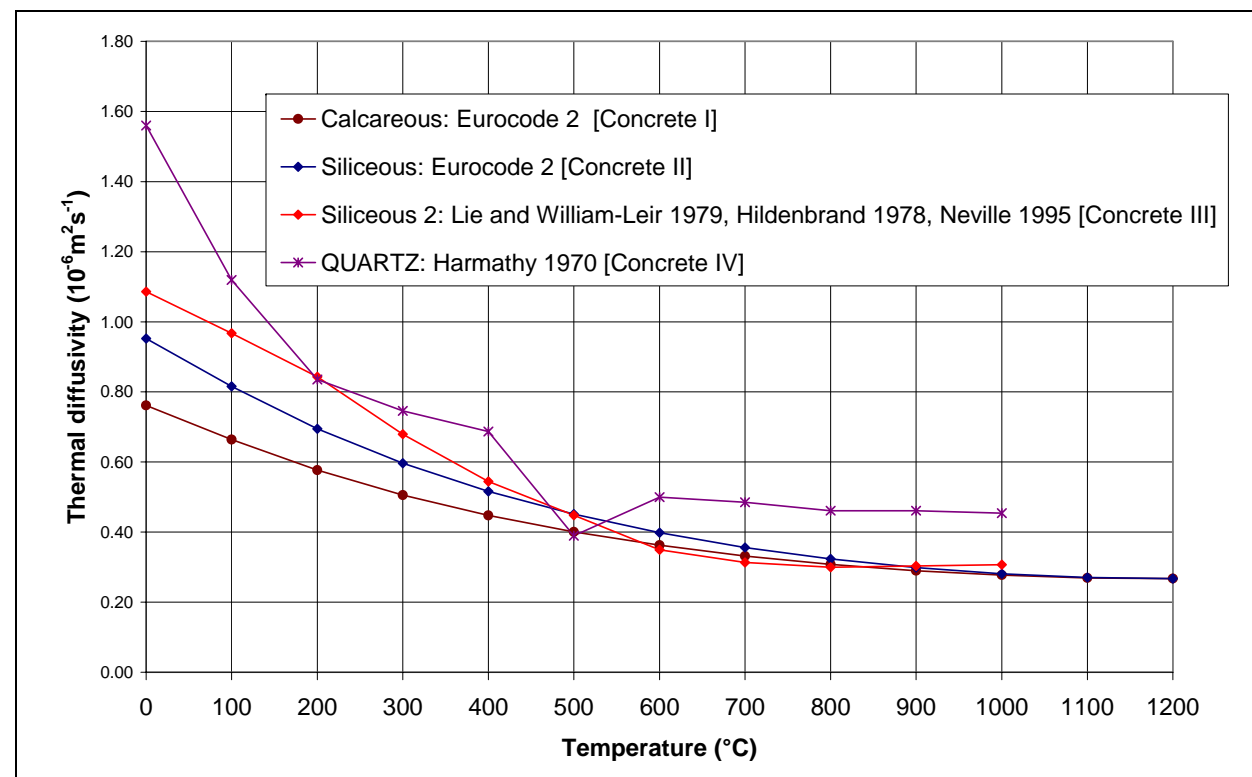


Figure B3 The range of four concrete types appropriate to the design guide.

Table B2 Risk factors for each variable known to affect spalling of concrete (see report for Work Package 2 of this project)

	RISK
Design Strength >55Mpa	Not quantified
Design Strength ≤55Mpa	1
Hydrocarbon fire	5
Standard fire (BS 476)	1
Moisture content >3%	5
Moisture content ≤3%	1
No Reinforcement	3
Reinforcement included	1
Cover ≥ 40mm	3
Cover <40mm	1
Siliceous aggregate	3
Calcareous aggregate	1
No. of sides exposed >1	3
No. of sides exposed = 1	1
Section size <200mm	3
Section size ≥ 200mm	1
Restrained	3
Unrestrained	1
Thermal expansion ≥ 10 x 10 ⁻⁶	3
Thermal expansion < 10 x 10 ⁻⁶	1
Loaded in compression	3
Unloaded	1

Table B3 Spalling categories and associated spalling levels (*key factors = properties of the concrete or the boundary conditions that are known to promote spalling e.g. aggregate type, section thickness etc) (see report for work package 2 of this project)

Category	Risk of spalling	Value of Total Risk	Key factors	Spalling level
A	Very low	≤11	Ordinary strength, NWC, Unloaded, Unrestrained, Standard fire exposure, Reinforced, moisture <3%, one side exposure	Zero or minimal
B	Low	12-20	Ordinary strength, NWC, restrained, Standard fire exposure. Significant number of key variables* likely to promote spalling	Up to the level of the reinforcement
C	Med	21-28	Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure :Small number of key variables* likely to promote spalling	3mm/min
D	High	29-37	Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure Significant number of key variables* likely to promote spalling	7mm/min
E	Very high	>37	High strength (Design strength >55Mpa), standard hydrocarbon fire exposure.	Unquantifiable

Fire A, Moisture Content 0%										
Original Thickness (mm)	Spalled Thickness (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
	80	yes	155.2	FAIL	176.0	FAIL	204.7	FAIL	215.1	FAIL
	120	yes	82.6	ok	97.6	ok	118.0	ok	130.6	ok
	150	yes	53.5	ok	66.7	ok	82.5	ok	95.0	ok
	220	yes	12.3	ok	20.3	ok	29.3	ok	43.6	ok
500	290	yes	2.5	ok	5.0	ok	7.9	ok	16.1	ok
500	410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	790	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	910	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1290	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table A Look-up table for Hydrocarbon Fire A, 0% moisture content. Note Thermal diff = Thermal diffusivity ($\times 10^{-6}$).

Fire A, Moisture Content 17%										
Original Thickness (mm)	Spalled Thickness (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
500	290	no	0.0	ok	0.0	ok	0.0	ok	0.2	ok
500	410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	790	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	910	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1290	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1410	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table B Look-up table for Hydrocarbon Fire A, 17% moisture content. Note Thermal diff = Thermal diffusivity ($\times 10^{-6}$).

Fire C, Moisture Content 0%										
Original Thickness (mm)	Thickness after spalling (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
500	80	yes	291.0	FAIL	312.2	FAIL	354.9	FAIL	365.0	FAIL
	120	yes	175.2	FAIL	196.0	FAIL	237.5	FAIL	246.8	FAIL
	150	yes	122.9	ok	142.3	FAIL	178.8	FAIL	187.5	FAIL
	220	yes	38.5	ok	55.3	ok	77.3	ok	94.7	ok
500	320	yes	*	ok	*	ok	*	ok	29.9	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	580	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	820	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1080	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1320	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table C Look-up table for Hydrocarbon Fire C, 0% moisture content. Note Thermal diff = Thermal diffusivity ($\times 10^{-6}$). Note the maximum temperature on the unexposed face of the wall was not calculated for the wall of spalled thickness 320mm including the cooling phase of the fire for Concrete Types I-III because they are known to pass when Concrete type IV passes.

Fire C, Moisture Content 17%										
Original Thickness (mm)	Thickness after spalling (mm)	Cooling phase of fire included?	Concrete I Aggregate=calcareous Therm diff<0.76		Concrete II Aggregate=siliceous 0.76<Therm diff<0.95		Concrete III Aggregate =siliceous 0.95<Therm diff<1.1		Concrete IV Aggregate=Quartz 1.1<Therm diff<1.6	
			Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result	Maximum temperature unexposed face of wall (°C)	Pass/fail result
500	80	no	114.6	ok	130.0	ok	168.6	FAIL	186.1	FAIL
500	320	no	0.2	ok	0.4	ok	0.8	ok	2.4	ok
500	500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	580	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	820	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1000	1000	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1080	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1320	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok
1500	1500	no	0.0	ok	0.0	ok	0.0	ok	0.0	ok

Table D Look-up table for Hydrocarbon Fire C, 17% moisture content. Note Thermal diff = Thermal diffusivity ($\times 10^{-6}$).

B3 References

- 1) Arup Fire, Fire resistance of concrete enclosures. Work Package 1: data collection and Work Package 2: spalling categories.
- 2) Arup Fire, Fire resistance of concrete enclosures. Work Package 3: Upper and lower bound solution and Work Package 4: Sensitivity study.
- 3) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 1.
- 4) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 3.
- 5) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 4.
- 6) Arup Fire, Fire resistance of concrete enclosures. Database - Spreadsheets under Work Package 5.
- 7) ENV 1992-1-2 (1996), Eurocode 2 Design of concrete structures, Part 1.2 General rules – Structural fire design