Efectis Nederland BV

Efectis Nederland BV
Centre for Fire Safety
Lange Kleiweg 5
P.O. Box 1090
2280 CB Rijswijk

www.efectis.nl

T +31 15 276 34 80
F +31 15 276 30 25
E nederland@efectis.nl

Efectis Nederland report

2008-Efectis-R1046

Investigation of concrete cracking due to fire in scaled immersed tunnel elements

Date	April 2009
Author(s)	P.G.R. Scholten, B.Sc. A.J. Breunese, M.Sc. Dr. C. Both, M.Sc.
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Contents

1 Investigation

An investigation of fire in immersed scaled tunnel elements.

2 Sponsor

Efectis Nederland BV
Lange Kleiweg 5
2288 GH Rijswijk
The Netherlands

3 Tested elements

3.1 Production of the elements

The elements were produced at the Betonfabriek Vrijenban in Delft, the Netherlands. After the casting the minimum curing time of the elements before testing was 90 days.

The elements were cast at the following dates, in order of the fire tests:
element 0: 08-02-2008
element 6: 10-03-2008
element 10: 29-03-2008
element 8: 14-03-2008
element 2: 21-02-2008
element 9: 19-03-2008
element 5: 04-03-2008
element 7: 12-03-2008

3.2 Concrete composition

For the fire tests thirteen elements of concrete C28/35 were cast: four without polypropylene fibre, three with polypropylene fibre Fibermesh 150, Ø 32 µm length = 12 mm, three with polypropylene fibre of Adfil Confiber 23, Ø 18 µm with a length of 6 mm and three with polypropylene fibres of Adfil Confiber 23, Ø 18 µm with a length of 12 mm.

All fibres were dosed in 3 kg per m^3 concrete.
The choices of which elements to test, were partly made during the testing programme, depending on the results. Not all elements were tested.

Table 3.1 Overview of the tested elements

Element	Test date	Fibre ∅, l	Ceiling and wall protection	High/low fire curve	Load	Cubic strength [N/mm^2]
0	07-03-2008	-	-	high	-	n.a.
6	18-06-2008	18 µm/6 mm	X	high	-	38.6
10	20-06-2008	32 µm/12 mm	X	high	-	46.0
8	23-06-2008	18 µm/12 mm	-	high	-	34.3
6 upside down	27-06-2008	18 µm/6 mm	X	high	perpendicular to tube	38.6
2	03-07-2008	-	-	high	-	47.4
9	04-07-2008	18 µm/12 mm	-	low	-	37.7
5	08-08-2008	18 µm/6 mm	-	low	perpendicular to tube	47.3
7	12-08-2008	18 µm/6 mm	-	low	in line with tube	41.3

3.3 Size

All elements were scale models, approximately 1:10, with two tubes of 1000 x 500 mm w x h with straight corners and a length of 1500 mm. Only the first specimen 0 had a length of 2000 mm.

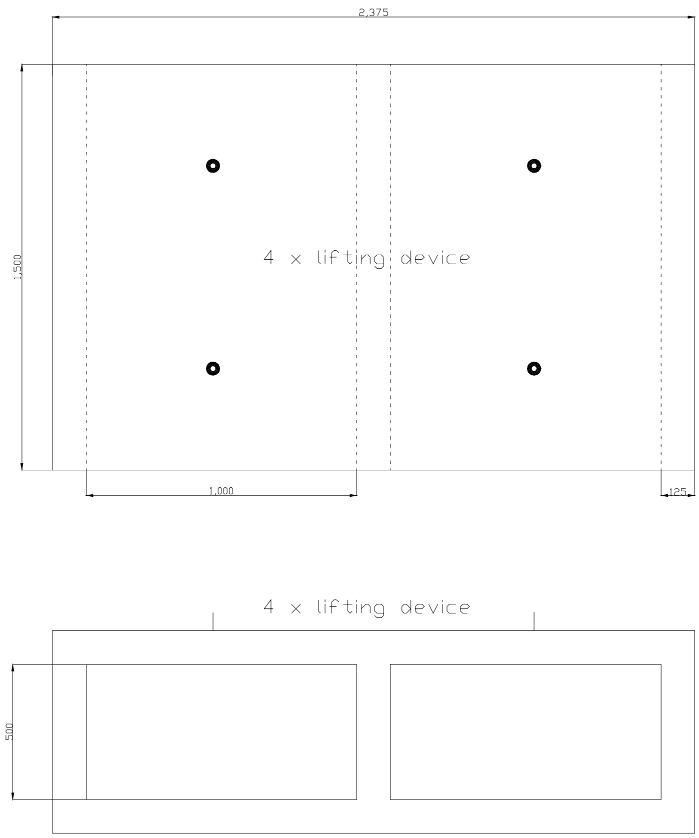

Figure 3.1 Dimensions of the elements

The steel reinforcement consisted of two nets Ø 12-150 mm with a cover of 35 mm on both sides, see Figure 3.2

Figure 3.2 Mould for the casting the elements with the reinforcement in place

4 Protection of the elements

Ten elements were tested without fire protection on the ceiling. Three elements were protected with Promatect-H® 15 mm thick boards on the ceiling to simulate the practical situation. The upper 10 cm of the walls were protected with Promatect-H® 15 mm thick lining. The Promatect-H® lining 15 mm was fixed with Fischer FNA II 6 x 30/5 anchors.

All floors of the elements were protected with 2 x 20 mm thick Promatect-H® to simulate the insulating effect of the concrete filling layer below the road surface.

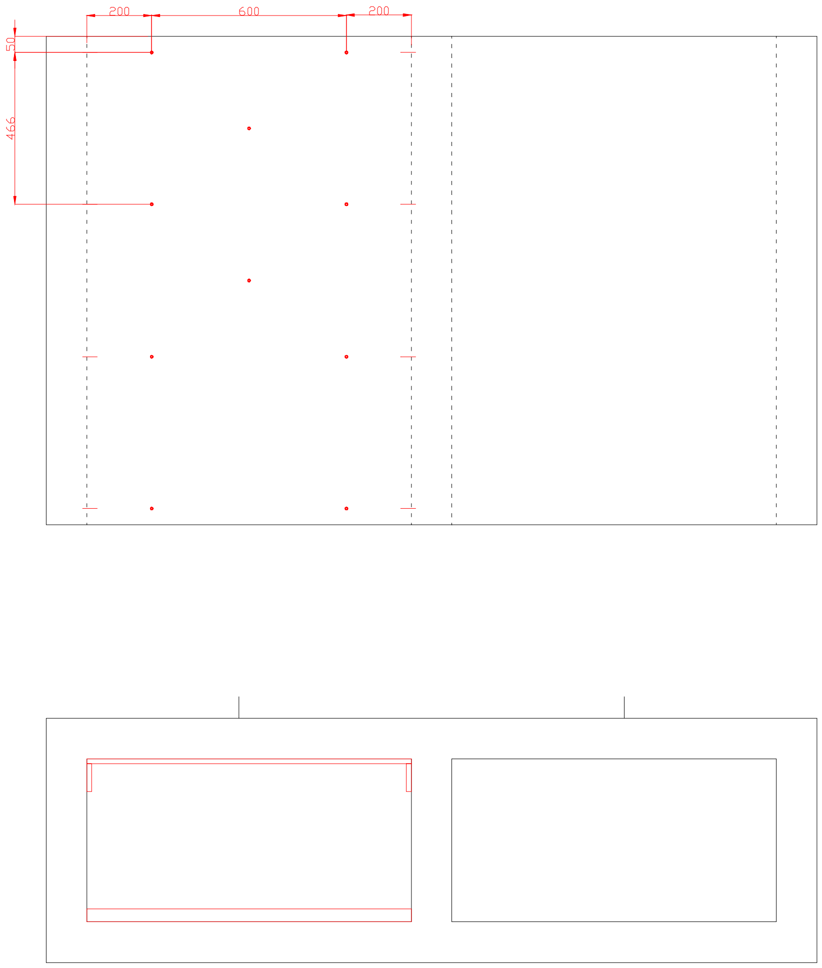

Figure 4.1 Locations of the Promatect-H® lining on the ceiling and walls and its fixation locations

5 Location and date of the fire tests

The investigation took place at the laboratory of Efectis Nederland BV, Rijswijk, The Netherlands.
Fire test dates:
element 0: 07-03-2008
element 6: 18-06-2008
element 10: 20-06-2008
element 8: 23-06-2008
element 6: 27-06-2008
element 2: 03-07-2008
element 9: 04-07-2008
element 5: 08-08-2008
element 7: 12-08-2008

5.1 Density and equilibrium moisture content[1]

Concrete specimen 2
- Density : 2285 kg/m^3
- Moisture content : 4.2 %

Concrete specimen 5
- Density : 2188 kg/m^3
- Moisture content : 4.8 %

Concrete specimen 6
- Density : 2084 kg/m^3
- Moisture content : 4.6 %

Concrete specimen 7
- Density : 2150 kg/m^3
- Moisture content : 4.1 %

Concrete specimen 8
- Density : 2105 kg/m^3
- Moisture content : 4.9 %

Concrete specimen 9
- Density : 2143 kg/m^3
- Moisture content : 5.3 %

Concrete specimen 10
- Density : 2189 kg/m^3
- Moisture content : specimen was no longer available to determine the content

Promatect-H® 15 mm
- Density : 960 kg/m^3
- Moisture content : 1.4 %

[1] Moisture content determined after drying 86 days at 105°C

5.2 Fire test

5.2.1 Conditions and test situation

The elements were installed in the horizontal furnace on a concrete slab of 150 mm thickness, see Figure 5.1. One tunnel tube of the elements was in line with one ore two burners of the furnace to simulate fire in one of the tubes. A block of aerated concrete was placed directly before the burners to improve hot air circulation inside the tunnel tube, rather than having the burners blow directly towards each other.

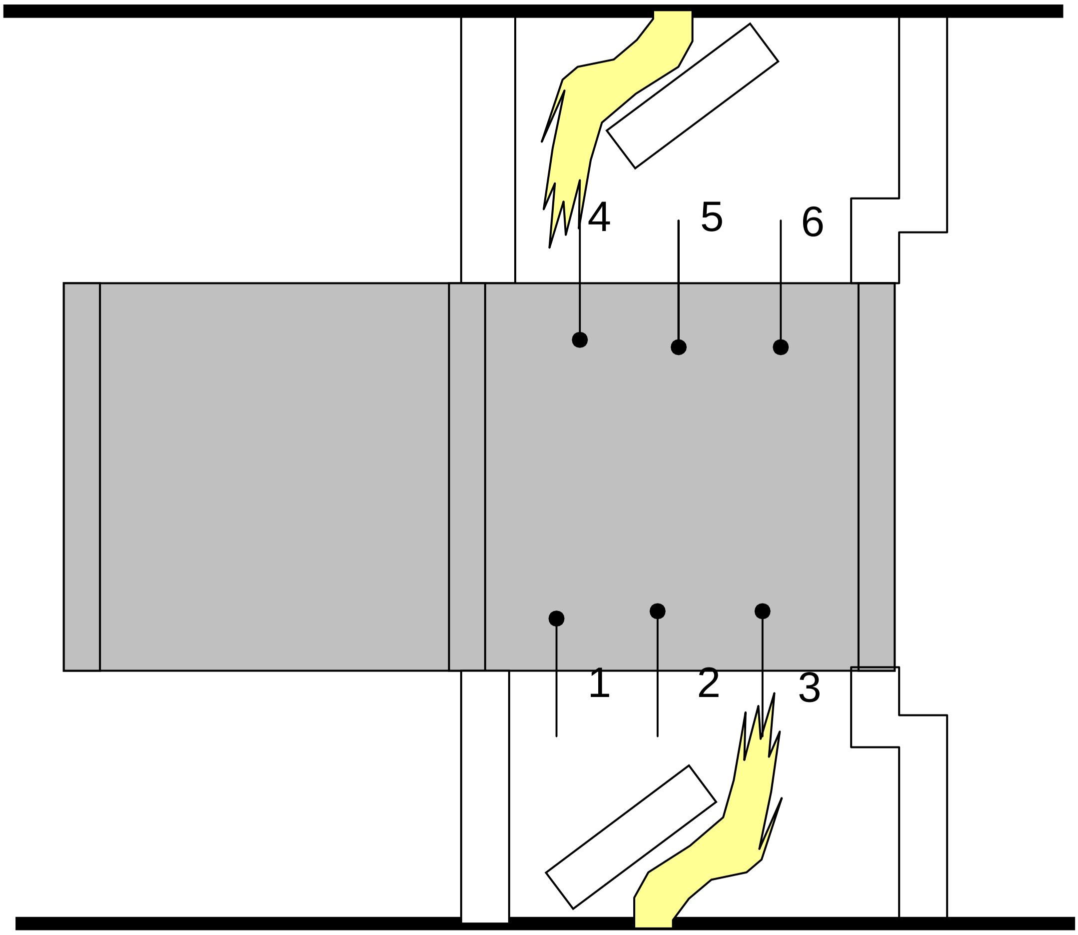

Figure 5.1 Schematic top view of the test set up in the horizontal furnace. The scaled tunnel element is placed in the centre. Around it, an aerated autoclaved concrete compartment was built to create a compartment of the heated tube, the furnace walls, the gas burners and furnace exhaust holes.

Figure 5.2 Top view of the test set up in the horizontal furnace.

5.2.2 Load

Three elements were subjected to a vertical load during the fire test to simulate the static ground and water pressure that is normally present on immersed tunnel elements.
Concrete blocks with a total weight of 7560 kg were placed on top of the heated tunnel tube.
On elements 5 and 6 the load was laid perpendicular to the tubes. To make the observations of concrete cracking still possible the concrete blocks were concentrated in two rows. When the roof of the element would sag the concrete blocks would rest on the wall of the element.

On element 7 it was laid in line with the tube. When the roof of this element would sag the load would still be present on the roof just like in the situation in practice.

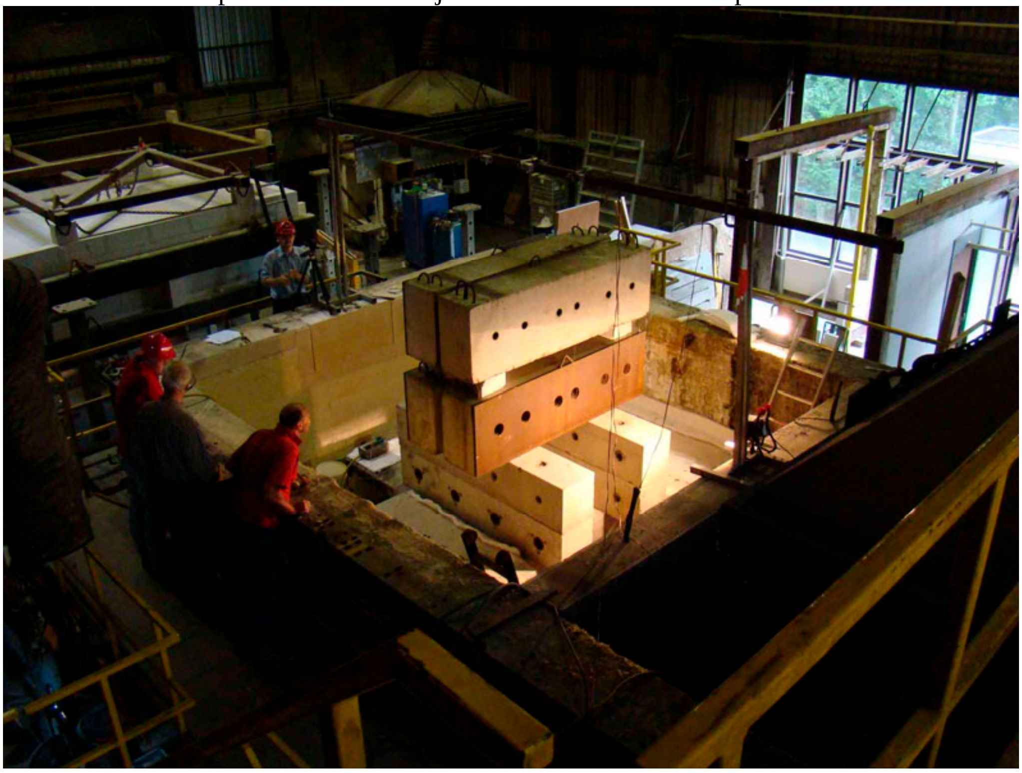

Figure 5.3 Load perpendicular to element tube

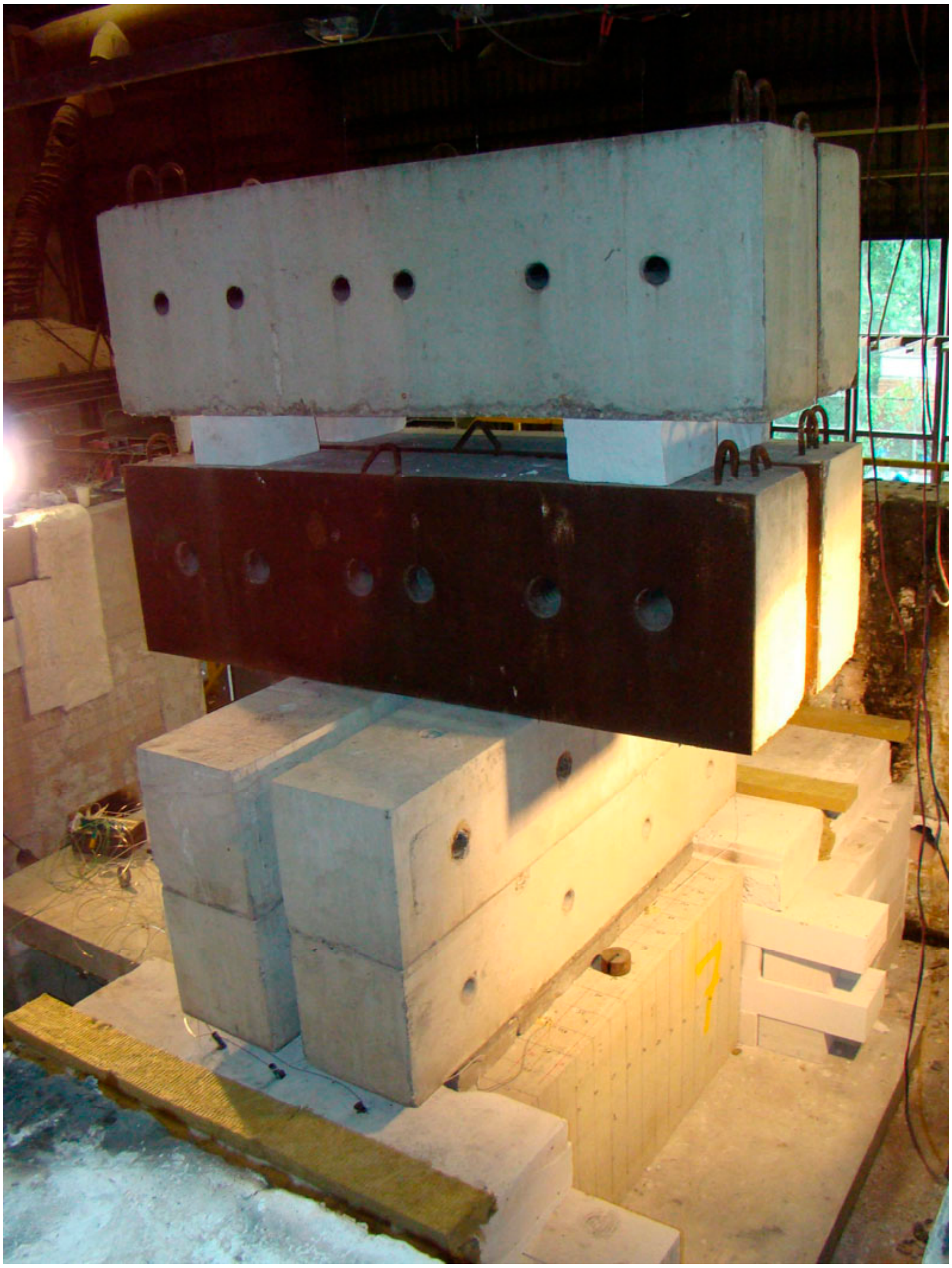

Figure 5.4 Load in line with the element tube

5.2.3 Measurements

During the test the following measurements were made:
- Gas temperatures inside the scaled tunnel element;
- Displacement of the heated tube at the middle wall, centre of the heated tube and the outer wall;
- Cold surface temperatures on top of the element;
- Temperatures of the interface when Promatect-H® 15 mm thick lining was used on the ceiling.

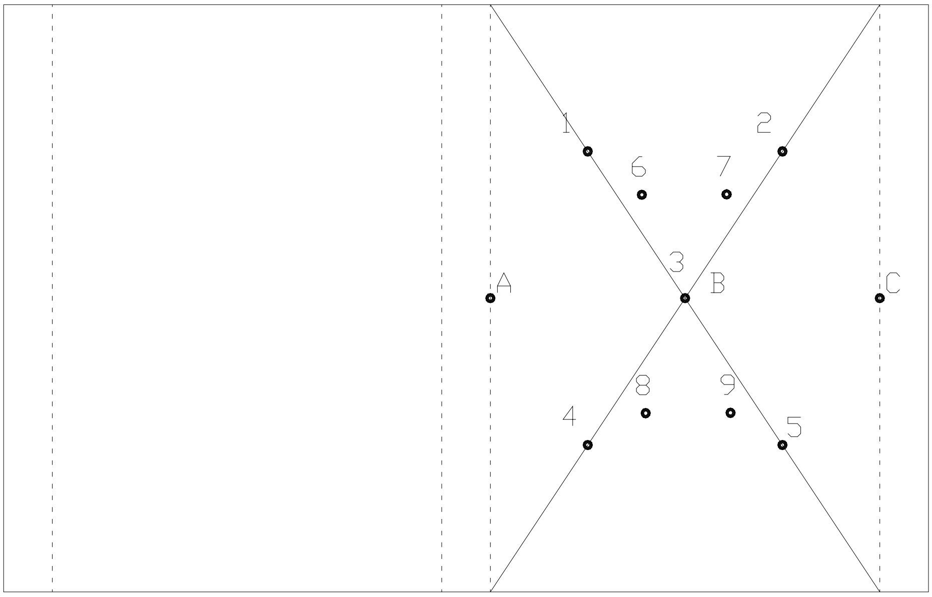

Figure 5.5 Overview of the thermocouples on the cold surface, 1 to 5, the interface temperature 6 to 9 and the displacement measurement locations A, B and C

6 Observations during the fire tests

Observations were made during the tests regarding the appearance of cracking. The X and Y coordinates refer to the grid that was drawn onto the upper and side surfaces of the elements.
Horizontal cracks are in the direction of the X direction and perpendicular to the element tube and vertical cracks are in the Y direction and in line with the element tube. Cracks on the side of the elements are called horizontal when they are parallel to ground level and vertical when perpendicular to it.

Table 6.1 Observations specimen 0 tested on 07-03-2008

Time [min]	Observation
0	Start of heating.
5	Spalling at low volume is audible
10	Loud spalling is audible
12	Crack above the middle wall is visible. No water is coming from it
15	Spalling has stopped Water is coming form the heated tube and is covering the non heated tube as well
30	End of heating. No new cracks are formed

Table 6.2 Observations specimen 6 tested on 18-06-2008

Time [min]	Observation
0	Start of heating.
11’ 55”	First cracks appear in side surface. These cracks are only visible when the element is observed very closely.
12’ 45”	Crack in upper surface above the middle wall, Y = 70 – 150
14’ 10”	The crack in the side of the element has an width of approximately 0.1 mm
14’ 35”	Crack in the upper surface above the side wall, X = 90
16’ 40”	Crack above the middle wall, X = 0 grows in the Y direction form Y = 70 to Y = 30
17’ 25”	Water comes from cracks in the side surface. Vertical cracks appear in this surface as well
19’ 55”	A horizontal crack above the side wall, Y = 70
20’ 40”	Vertical crack at X =45, width < 0.1 mm, Y = 100-120
21’00”	Vertical crack at X = 90, Y = 130-150
23’ 30”	New vertical crack at side surface Y = 65
28’ 00”	A slanted crack X = 10-30, Y = 120-140
29’ 00”	Crack X = 60, Y = 100-150
30’ 00”	A slanted crack X = 60-80, Y = 40-60
30’ 45”	At Y = 55 and Y = 110 horizontal cracks continue at the side surface
31’ 00”	More and more water is coming out of the cracks from the side surface, approximately until 10 cm under the upper side
33’ 20”	Crack X = 30-10, Y = 50-70
	The maximum width of all cracks < 0.1 mm
36’ 10”	At Y = 65 a cracks continues at the side surface
37’ 05”	Water is coming from crack at X = 75, Y = 55
37’ 05”	Crack X = 10, Y = 130-150
38’ 30”	At the side surface several horizontal cracks connects the present vertical cracks
41’ 15”	A vertical crack at X = 60, Y = 0-30
42’ 15”	At Y = 85 a cracks continues at the side surface
44’ 10”	At the side surface a vertical crack appears at Y = 35
45’ 10”	A horizontal crack at half the height, Y = 120-150, is approximately 0.5 mm wide
45’ 10”	A several locations water is present, at thermocouple 5, at X = 30, Y = 40-50
54’ 55”	A vertical crack at X = 50
56’ 00”	A vertical crack at X = 30, Y = 100-140
56’ 45”	At X = 10 the crack grows and connects itself with the slanted crack
57’ 05”	A slanted crack X = 80-100, Y = 130-150
62’ 50”	More and more wet spots appear on the upper surface
62’ 50”	A horizontal crack at X = 80, Y = 50 towards the corner appears, idem at X = 90
72’ 30”	Water on upper surface is clearly following the path of several vertical cracks
74’ 00”	The side surface dries

75’ 30”	The whet vertical crack at X = 60 spans the total length of the element
75’ 30”	At the crack at X = 0 above the middle wall no water is present
77’ 00”	The crack width at the upper surface are in the range 0.15 to 0.20 mm
82’ 45”	At X = 0, Y = 80 a horizontal crack is present across the middle wall towards the non heated tube
82’ 45”	At the side surface is a crack at Y = 150 is present with a width of approximately 1 mm
87’ 30”	Water is present at X = 0, Y = 30-70
91’ 45”	Crack at X = 0 is approximately 0.2 mm wide. Also a new crack is present across the middle wall
95’ 45	The crack at the side surface below the “6” is approximately 0.5 mm. The “6” is the elements number.
96’ 15”	More horizontal cracks X > 80 in the direction of the corner between Y = 70 and 110
96’ 30”	Vertical crack X = 75, Y 110-130
97’ 00”	Slanted crack X = 30-40, Y = 50-60
98’ 30”	Water is present at crack at X = 0, Y > 80
102’ 00”	Right side, X > 40, of the element is drying while the left side is getting wetter and wetter.
109’ 45	End of heating

Table 6.3 Observations specimen 10, tested on 20-06-2008

Time [min]	Observation
0	Start of heating.
8’ 50”	Crack at X = 100, Y = 0-40
9’ 20”	
10’ 10”	Water is coming from cracks at the side surface
10’ 55”	Crack at X = 20, Y = 0-50
11’ 20”	Crack at X =80, Y = 40-80
11’ 40”	Crack at X = 90-60, Y = 60-15
14’	
33	The non heated tube is moving 23 mm upwards
45’ 00”	Crack continues from the upper surface to the side surface at Y = 50, 80 and 90
54’ 00”	Crack at X =30, Y = 0-50
65’ 00”	End of heating

Table 6.4 Observations specimen 8 tested on 23-06-2008

Time [min]	Observation
0	Start of heating.
5’ 20”	Cracks at side surface and X = 100
6’ 00”	Crack [1] X = 0
7’ 00”	Crack [2] X = 50, Y >120
8’ 00”	Crack [1] width = 0.2 mm Crack [2] width = 0.1 mm
11’ 00”	Water is coming from crack X = 30, Y < 30
11’ 40”	Water is coming from crack X = 60-70, Y < 40
13’ 30”	Cracking pattern in Y direction, Y < 50, also in 2 cracks in Y direction Y > 110
14’ 20”	Cracking pattern in X direction at Y = 70-75
15’ 10”	Width crack [1] 0.3 -0.4 mm
17’ 00”	X = 95, Y < 50 width = 0.2 mm X = 95, Y > 120 width = 0.1 mm
24’ 00”	X = 0, Y = 105 width is 0.4 mm
35’ 00”	X = 0, Y = 105 width is 0.3-0.4 mm
36’ 00”	X = 0, Y = 70 width is 0.4 mm
58’ 00”	X = 0, Y = 70 width is 0.6 mm X = 30, Y = 100 width is 0.1 mm
64	End of heating

Table 6.5 Observations specimen 6, loaded, tested on 27-06-2008

Time [min]	Observation
0	Start of heating.
1	Due to the load on the element no close by observations are being made
30	Along the side surface water is coming from cracks
35	A small crack is visible in the upper surface along X = 0. This crack is to thin to photograph.
57	Some water is coming from cracks at X = 100, Y = 100-90, X = 70, Y = 60-50 and X = 10-35, Y = 70-45
61	Crack at X = 60-70, Y = 80
64	A dry crack is visible at X = 100, Y = 70-50
76	Water is coming from crack at X = 0, Y = 60
90	Water is no longer coming from cracks at the side surface. Most cracks are dry.
93	End of heating

Table 6.6 Observations specimen 2, tested on 03-07-2008

Time [min]	Observation
0	Start of heating.
5’ 10”	Vertical crack at X = 90, Y = 10-110 bending towards X = 70 and Y = 140
5’ 40”	Vertical crack at X = 0, Y = 80-140
5’ 50”	Vertical crack at X = 0, Y = 0-70 [1] Vertical crack at X = 65, Y = 0-30 Vertical crack at X = 45, Y = 0-30
6’ 20”	Crack at X = 65-90, Y = 30-60
7’ 15”	The crack at X = 0 has a width of 0.4 mm
7’ 40”	A horizontal cracking pattern develops at Y = 80 and 100
8’ 05”	The crack at X = 0 has a width of 0.4 mm
9’ 05”	Water is coming from the element at Y = 0 and Y = 150 and crack [1]
10’ 30”	Water is coming from the element at Y = 130 and Y = 10
13’ 20”	Water is coming from the element at Y = 95 and Y = 40. The side surface is still dry.
14’ 15”	Water is coming from horizontal cracks at Y = 80, Y = 65 and Y = 50
17’ 40”	The crack at X = 90 has a width of 0.4 - 0.5 - 0.4 - 0.3 mm on increasing Y values
18’ 00”	The crack at X = 50, 60, 30 has a width of 0.3 mm, all at high Y values The crack at X = 0 has a width of 0.8 mm at high Y values and 0.4 m at lower Y values
19’ 10”	Horizontal cracks in the upper surface continue to the unheated surface of the unheated element tube
19’ 30”	The crack at X = 50 Y = 30 has a width of 0.2 mm
19’ 50”	A large crack is present along the total length of the side surface; it is approximately 10 cm under the upper surface. Water is coming from it. [2] The width of this crack is 0.5, 0.7, 0.5 mm at increasing Y values
21’ 05”	Vertical crack in the side surface
26’ 30”	The width of the crack at X = 0 is 0.9 mm at Y = 100 and 0.5 mm at Y = 60
38’ 00”	End of heating
± 40	The width of the crack at X = 0 is 0.9 mm at Y = 100

[1] At approximately X = 75 the displacement measurement apparatus is blocking the view, but most probably it is the same crack as observed at the time 5’ 40”.
[2] Only observed now, but likely to be present before this time.

Table 6.7 Observations specimen 9, tested on 04-07-2008

Time [min]	Observation
0	Start of heating.
7’ 00”	Crack at X = 0, Y = 0, width 0.05 mm
7’ 30”	Crack at X = 0, Y = 0-100, width 0.1 mm
10’ 00”	Crack at X = 90, Y = 100
12’ 00”	Crack at X = 90, Y = 0-100, approximate width of 0.05 to 0.1 mm
15’ 00”	Crack at the side surface at X = 0, approximate width of 0.1 to 0.15 mm Crack at X = 0, Y = 105, width 0.15 mm
22’ 00”	Crack at X = 60-70, Y = 60, horizontal cracks
23’ 00”	Water s coming from cracks at X = 20, 55 and 70
29’ 00”	Crack at X = 0, Y = 105, width of 0.2 mm Crack at X = 20, Y = 70-130 Crack at X = 30-20, Y = 50
31’ 00”	Crack at X = 60-90, Y = 100
37’ 00”	Water is coming from crack at X = 60, Y = 60-140
38’ 00”	Crack at X = 0, Y = 105, width of 0.25 mm
43’00”	Water is coming from cracks at X = 90 and 100, Y = 120-110
47’ 00”	Crack at side surface at X = 0, Y = 70, width of 0.3 mm Water is coming from cracks in the side surface
50’ 00”	Crack at X = 0, Y = 105, width of 0.3 mm
70’ 00”	Crack at X = 0, Y = 105, width of 0.3 mm
71’ 30”	End of heating

Table 6.8 Observations specimen 5 loaded, tested on 08-08-2008

Time [min]	Observation
0	Start of heating.
15’ 00”	Crack at X = 50-105, Y = 0.
20’ 00”	Crack at X = 50-105, Y = 90
30’ 00”	Water is coming from cracks underneath load at X = 30, 45, 60 and 90, Y = no more than 50
64’ 00”	Water is coming from cracks up to Y = 150
65’ 00”	End of heating

Table 6.9 Observations specimen 7 loaded, tested on 12-08-2008

Time [min]	Observation
0	Start of heating.
6’ 00”	No water is visible so the assumption is that there are no cracks present in the element yet
14’ 00”	Crack above middle wall at X =0 , Y = 0-80
20’ 00”	Crack above middle wall at X = 0, Y = 0-110
30’ 00”	Crack above middle wall at X =0, Y = 0-150
35’ 00”	Vertical crack in side surface at Y = 50
38’ 00”	A horizontal/vertical cracking pattern develops
40’ 00”	The crack at Y = 50 seems to continue at the side surface
42’ 00”	Crack above the middle wall has a width of approximately 0.3 mm
68’ 00”	Crack above the middle wall has a width of approximately 0.4 mm
75’ 00”	End of heating

On the photographs of this element it can be seen that the grid orientation is deviating from the observations given here. This is done in order to have all observations are given in relation to the same grid orientation.

P.G.R. Scholten, B.Sc.   A. J. Breunese, M.Sc.   Dr. C. Both, M.Sc.

A Test results element 0

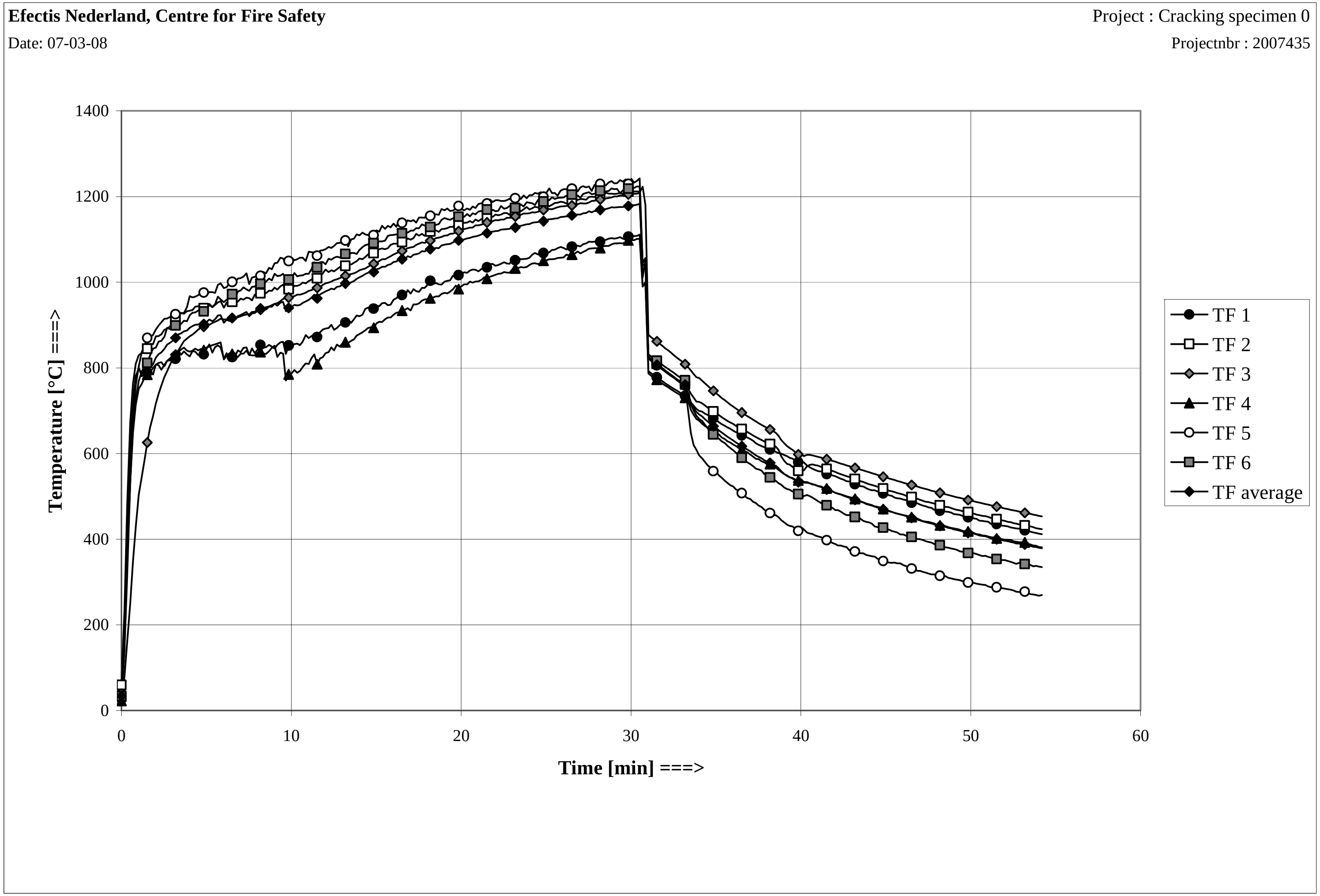

Figure A1 Furnace temperature

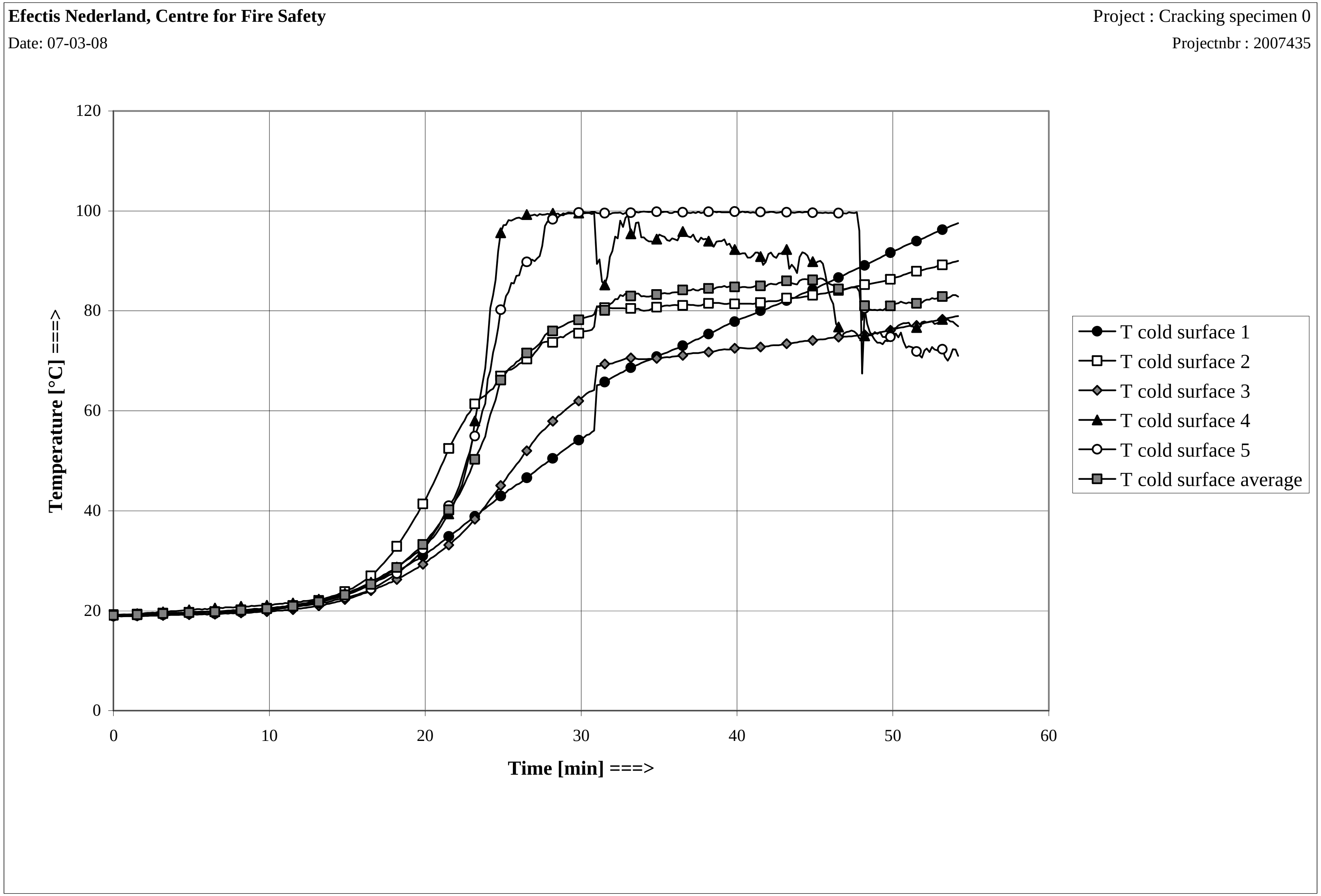

Figure A2 Cold surface temperatures

Figure A3 Element 0 after 10 minutes of heating

Figure A4 Element 0 after 13 minutes of heating

Figure A5 Element 0 after 14 minutes of heating

Figure A6 Element 0 after 29 minutes of heating

Figure A7 Element 0 after 29 minutes of heating

Figure A8 Element 0 after 56 minutes of heating

Figure A9 Element 0 cracking pattern on upper and side surface

Figure A10 Element 0 spalling on the inside of the element

B Test results element 6

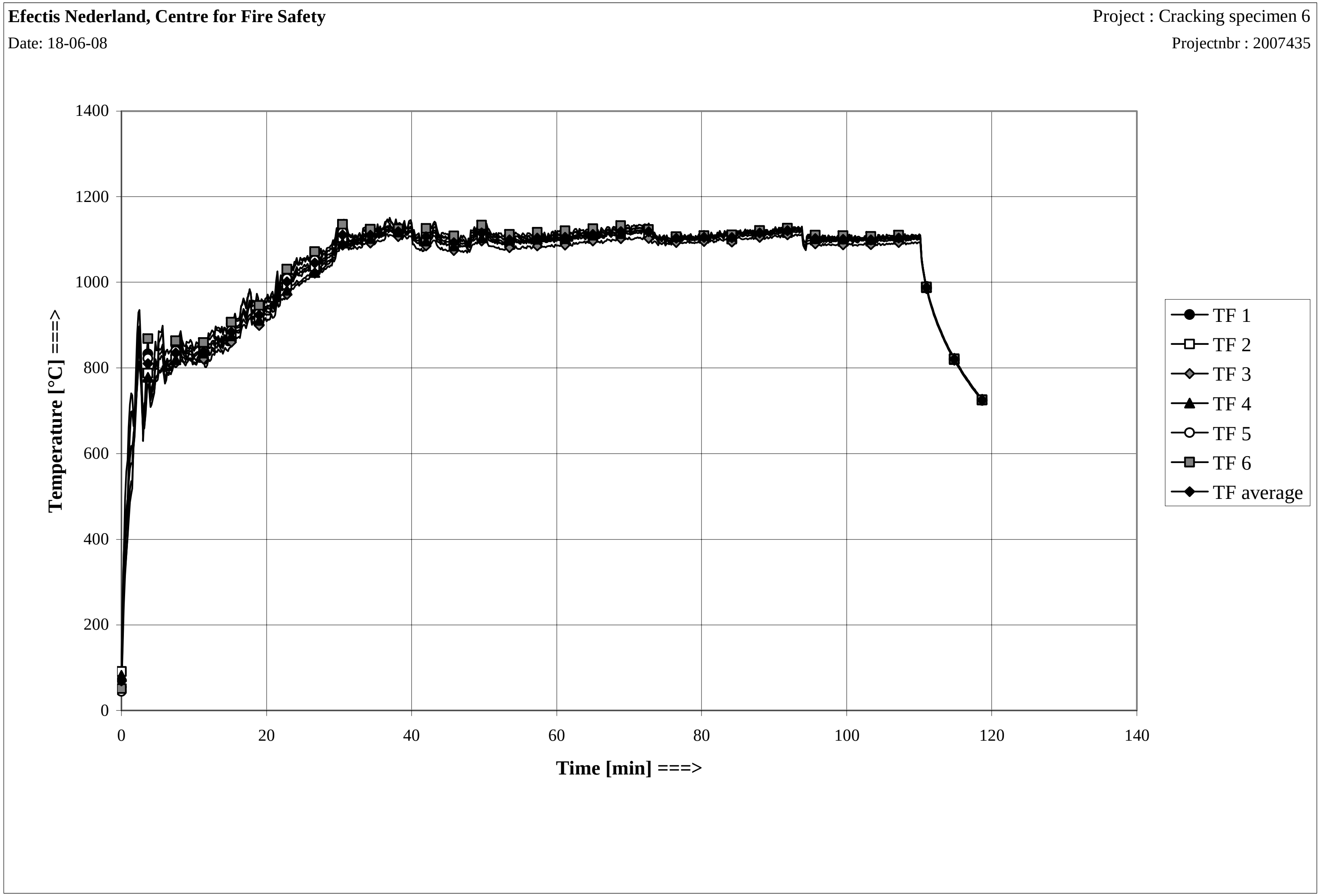

Figure B1 Furnace temperature

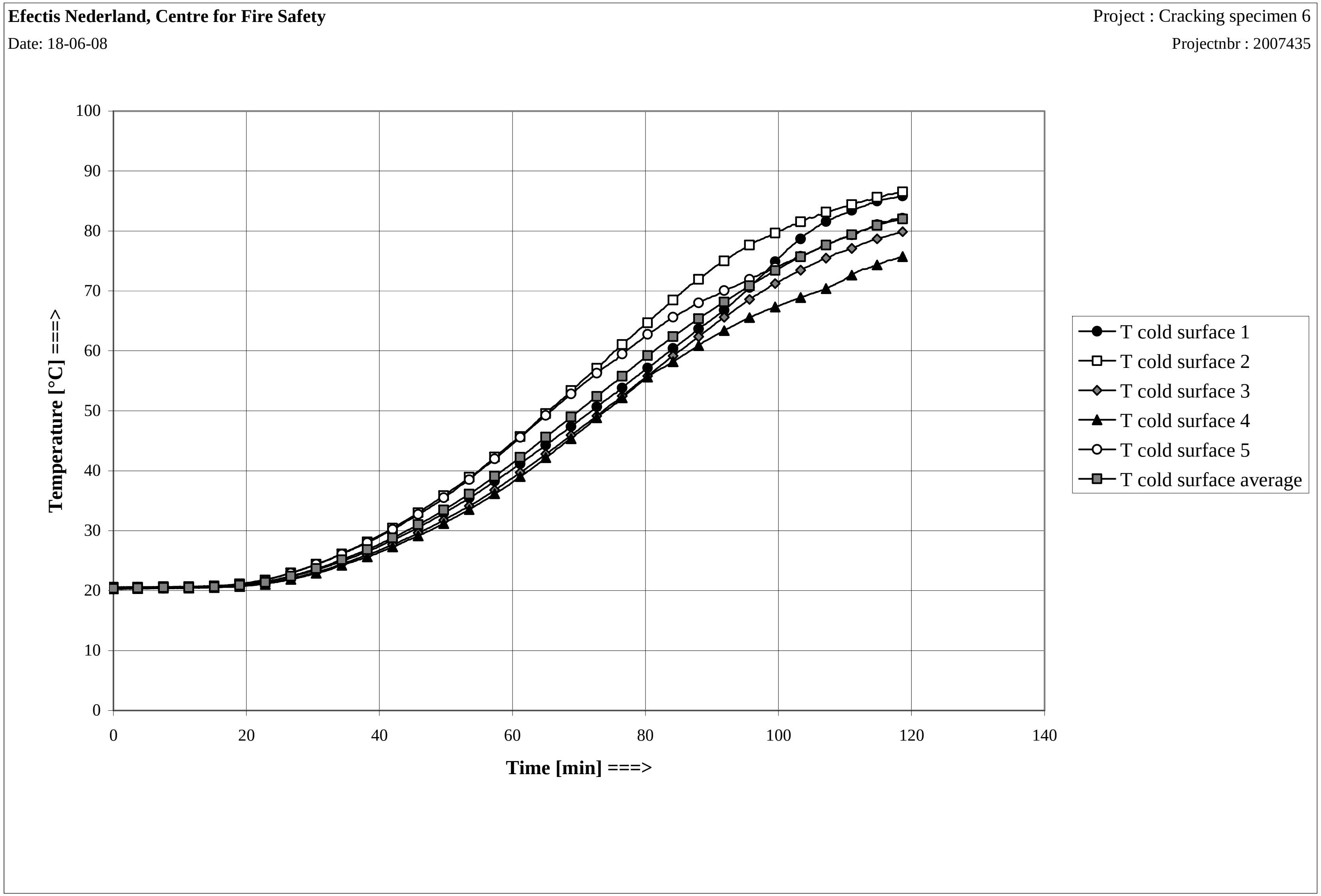

Figure B2 Cold surface temperatures

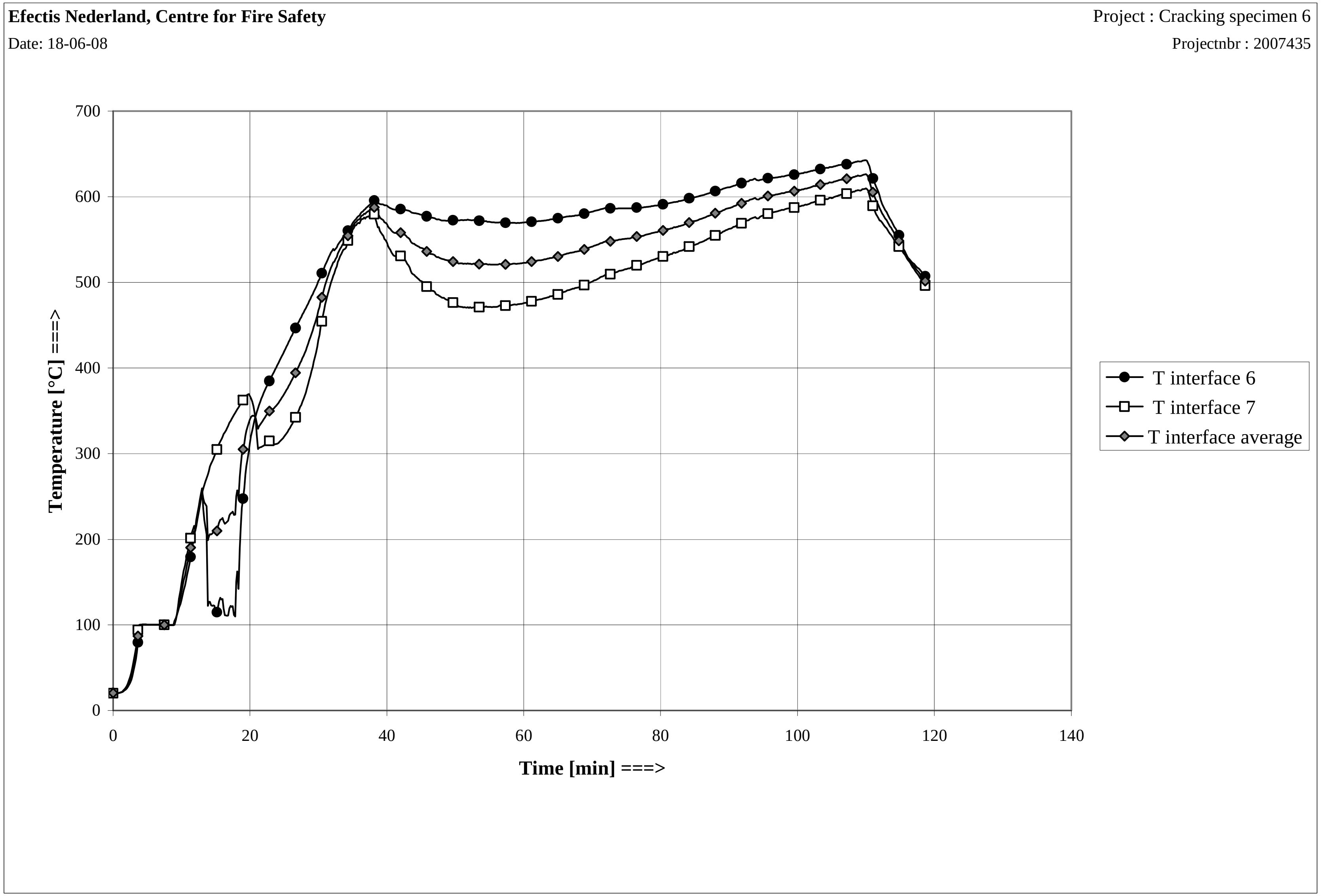

Figure B3 Interface temperatures

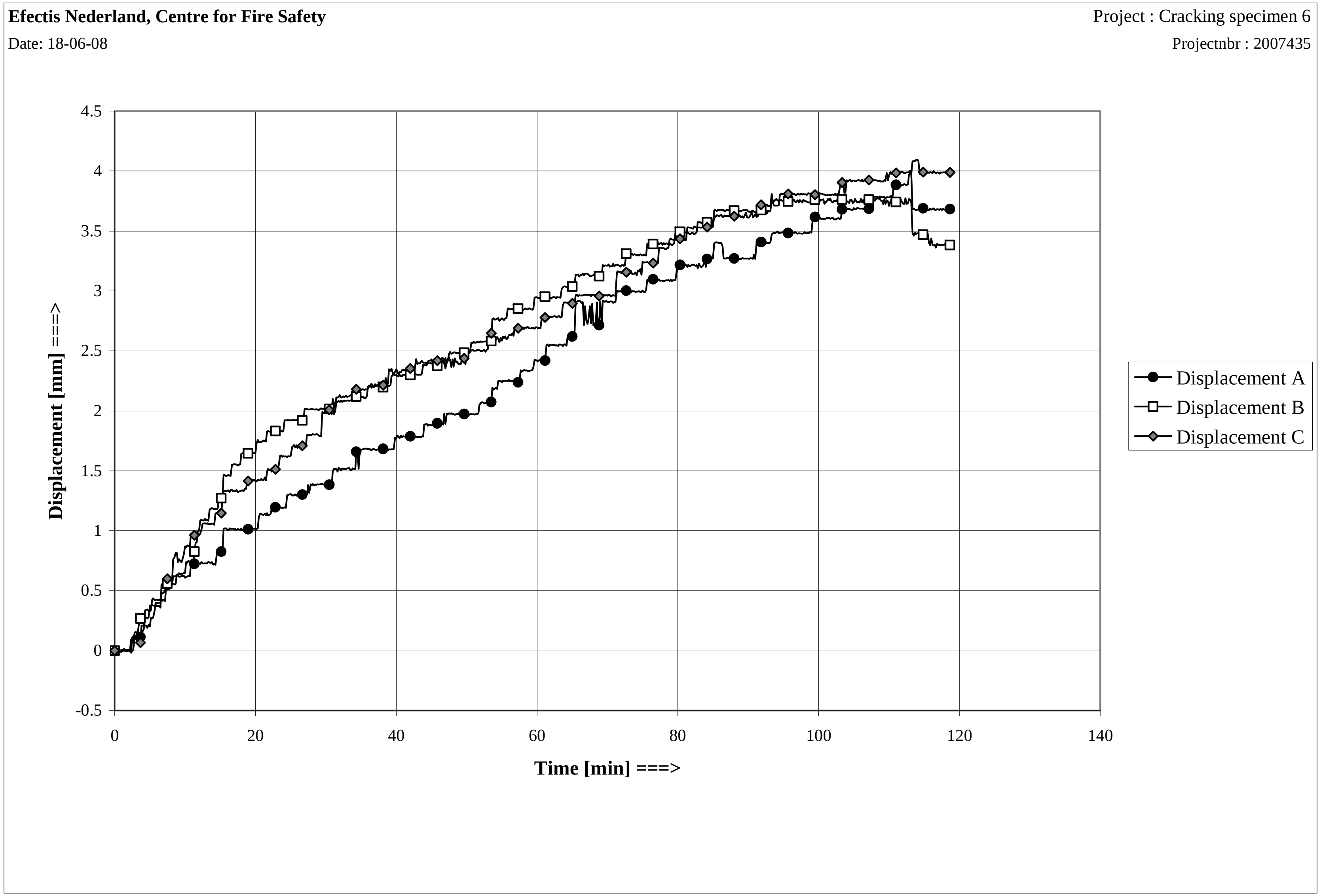

Figure B3 Displacements of the cold surface

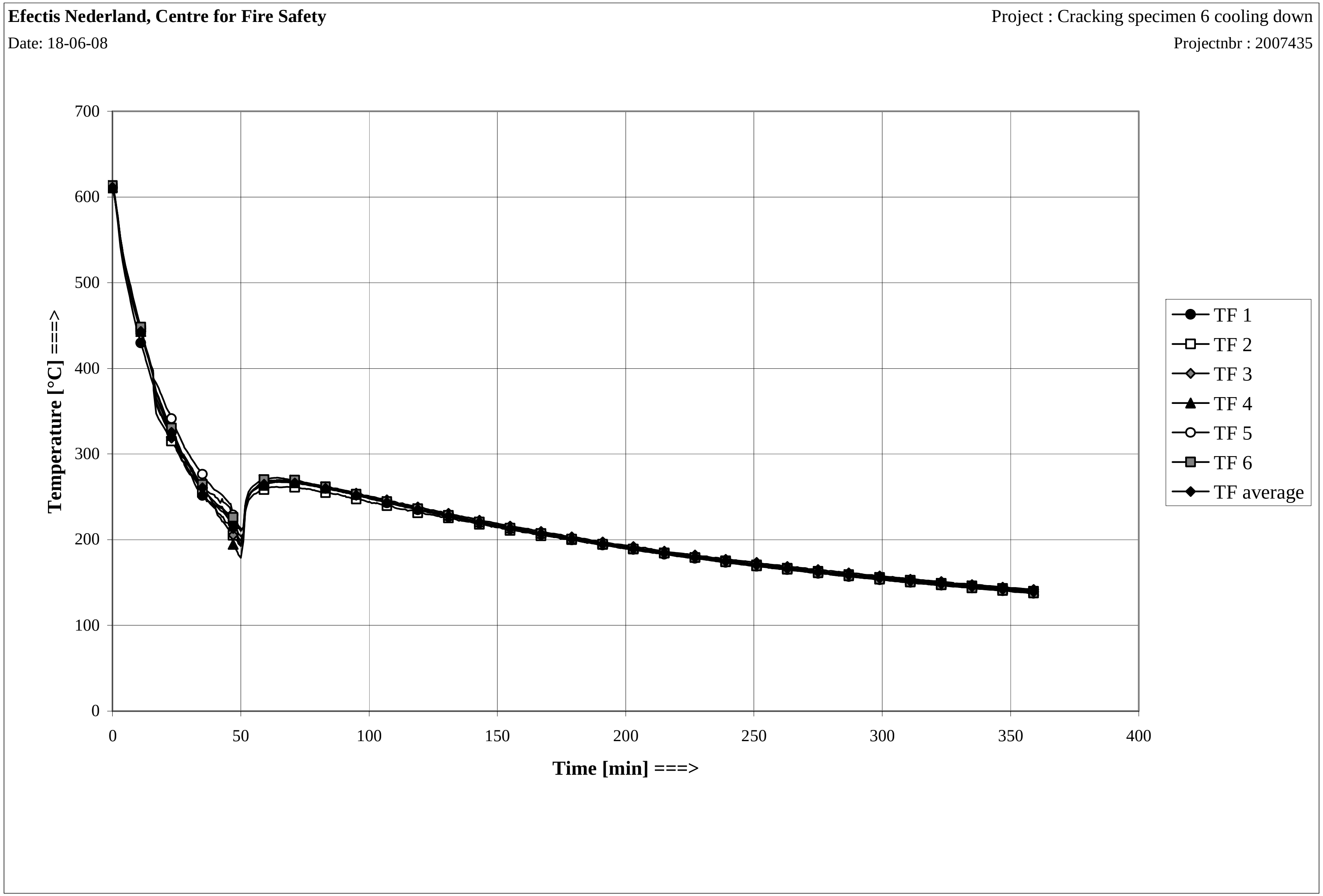

Figure B4 Furnace temperature during cooling down

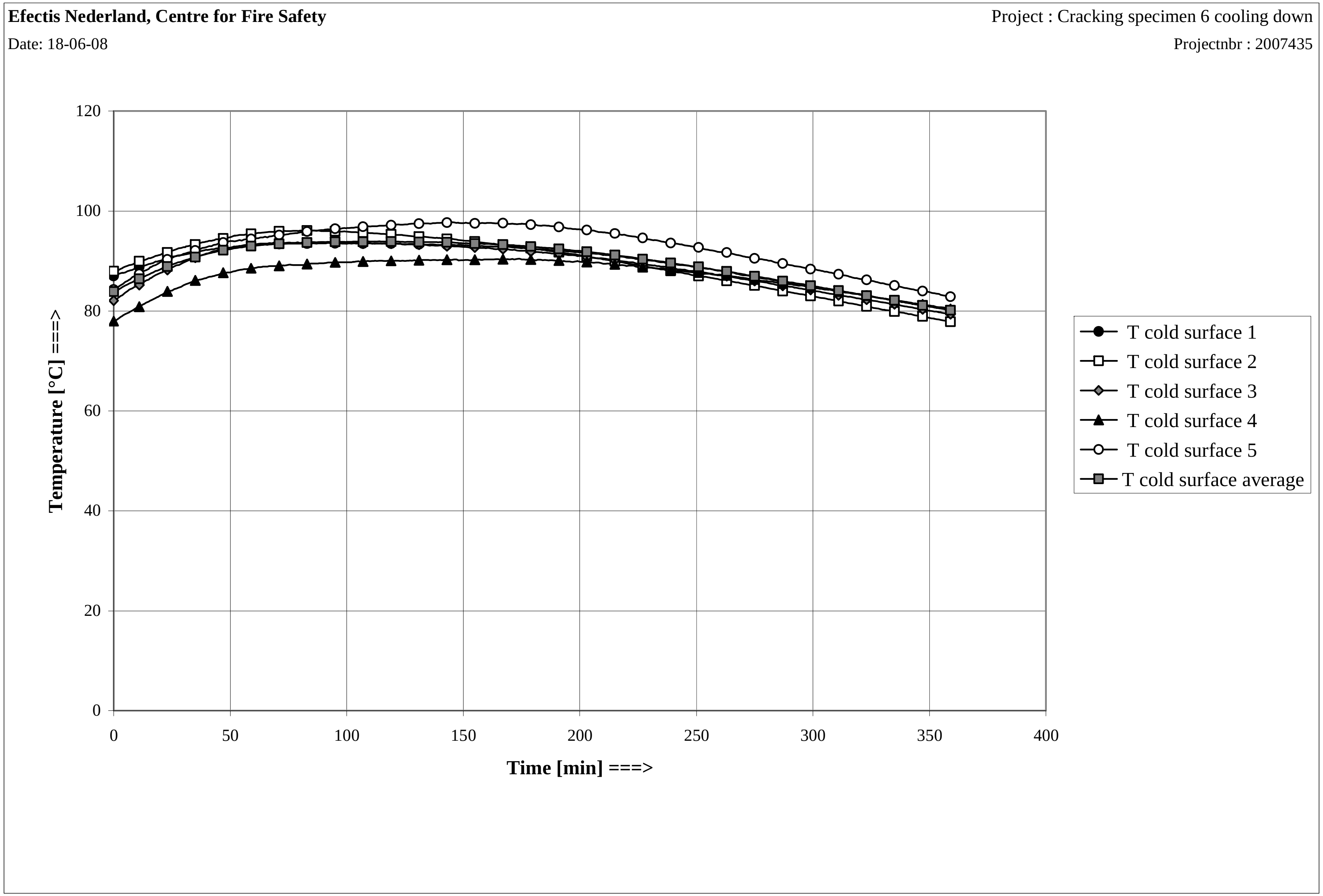

Figure B5 Cold surface temperatures during cooling down

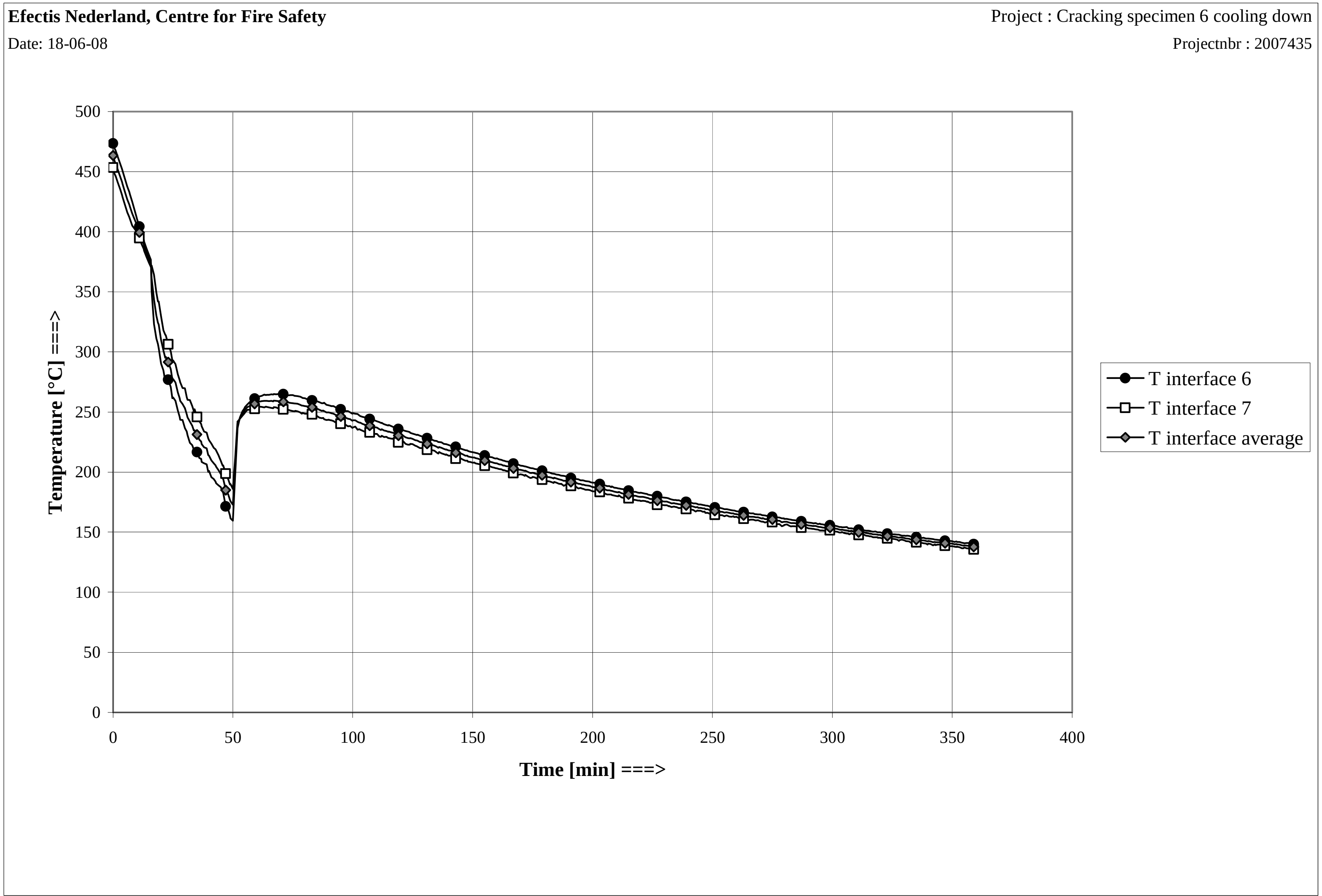

Figure B6 Interface temperatures during cooling down

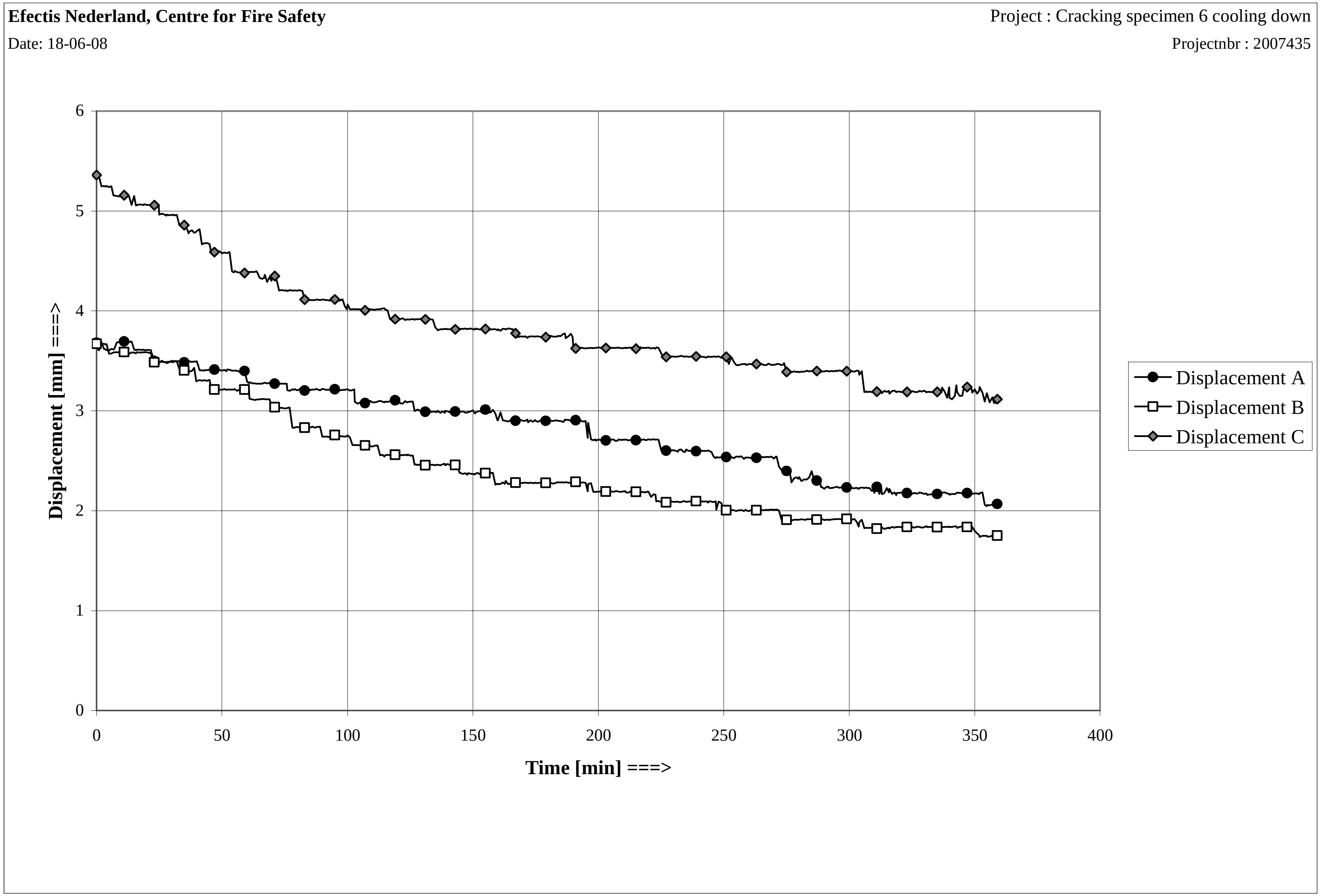

Figure B7 Displacements during cooling down

Figure B8 Overview of the test set up

Figure B9 Element 6 after 14 minutes of heating

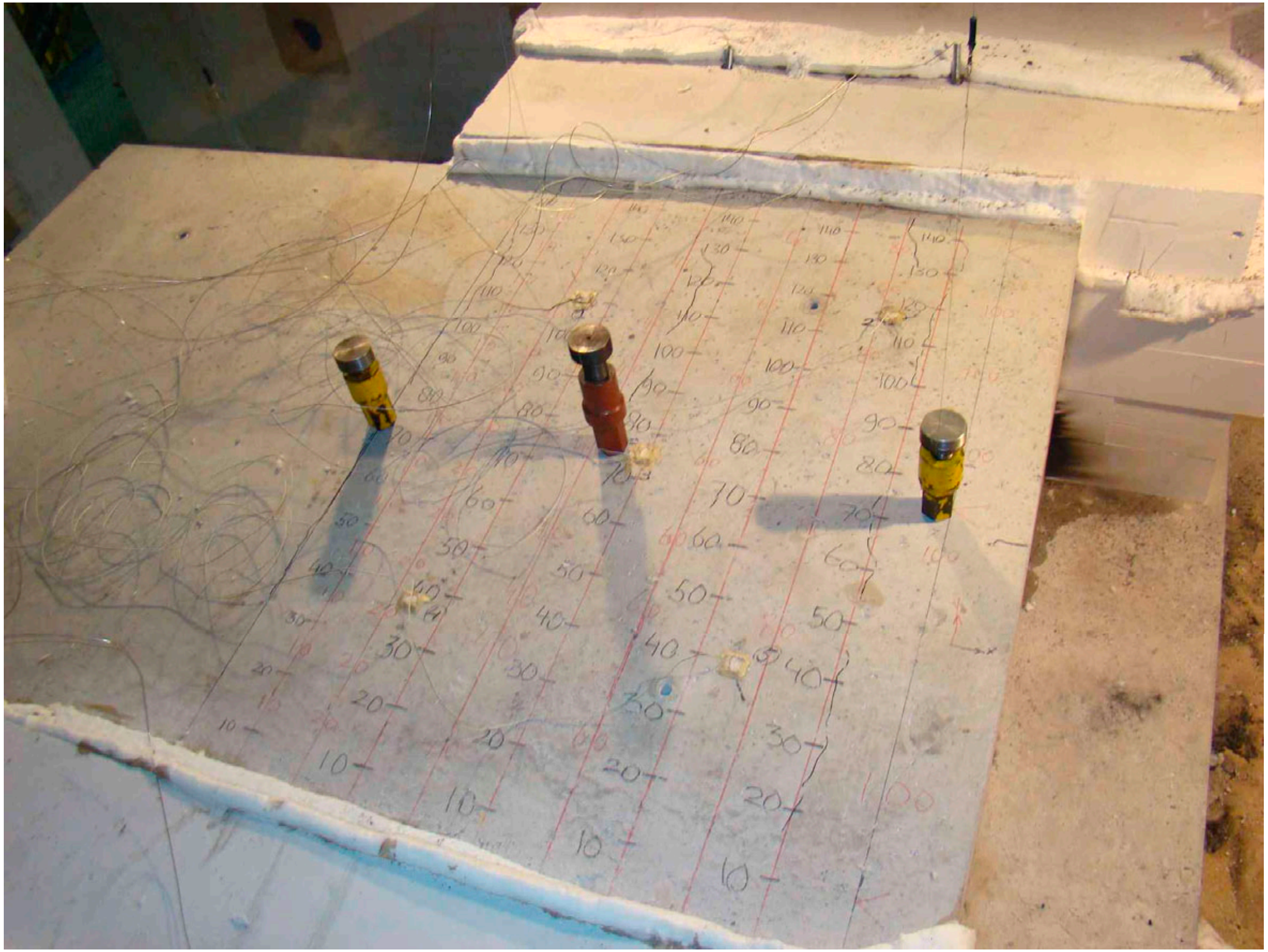

Figure B10 Element 6 after 21 minutes of heating

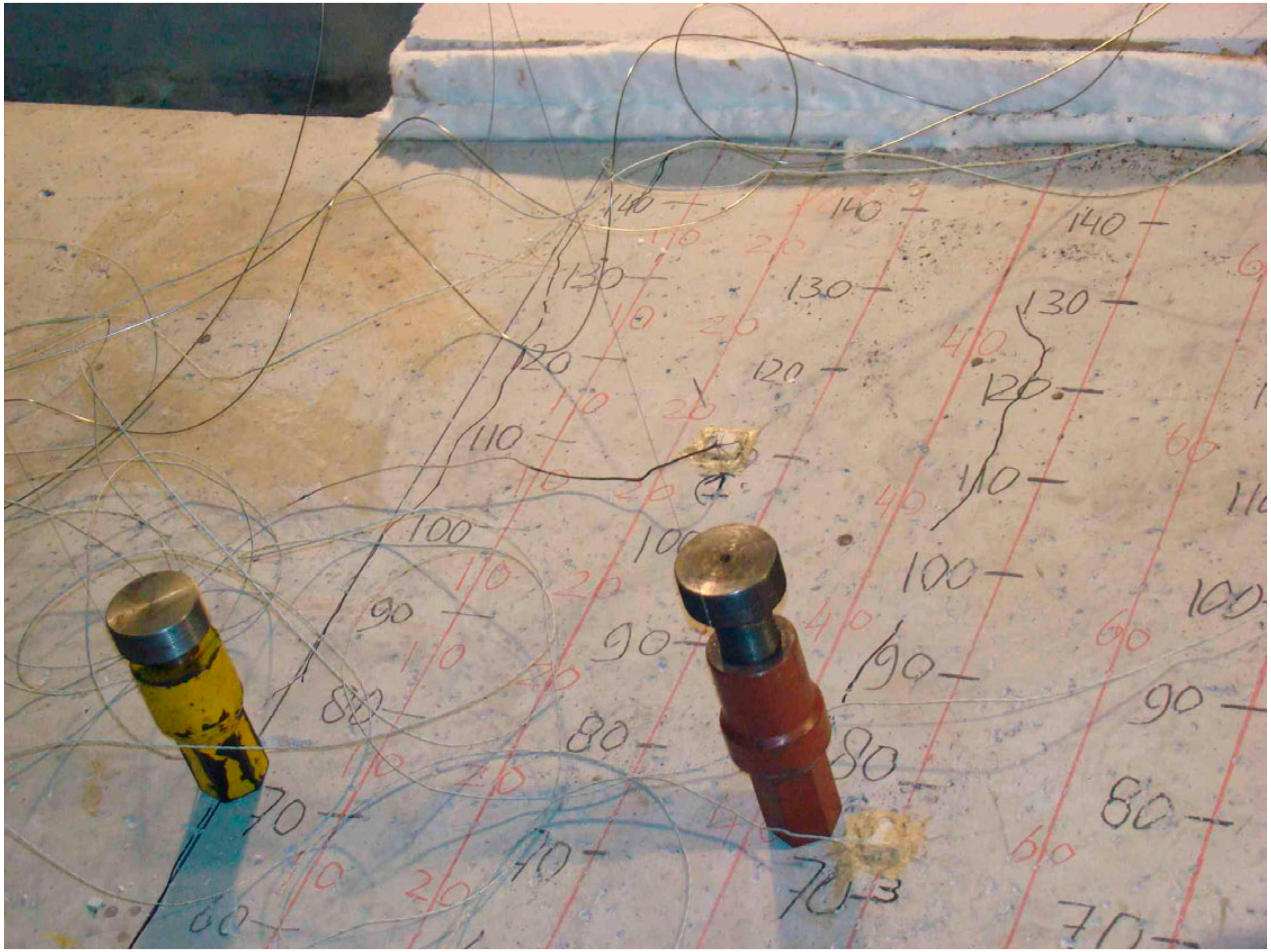

Figure B11 Element 6 after 21 minutes of heating, upper left corner detail

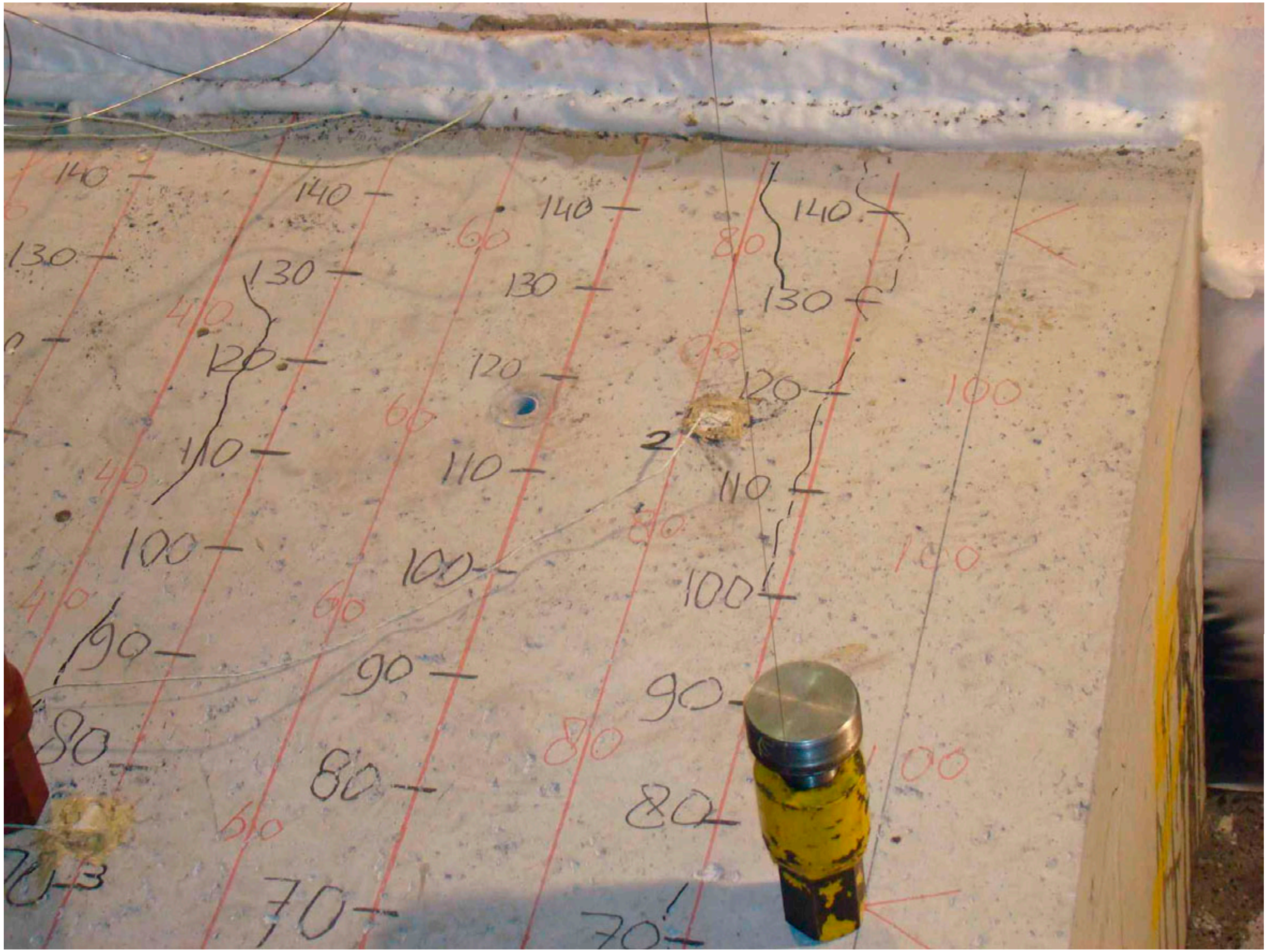

Figure B12 Element 6 after 21 minutes of heating, upper right corner detail

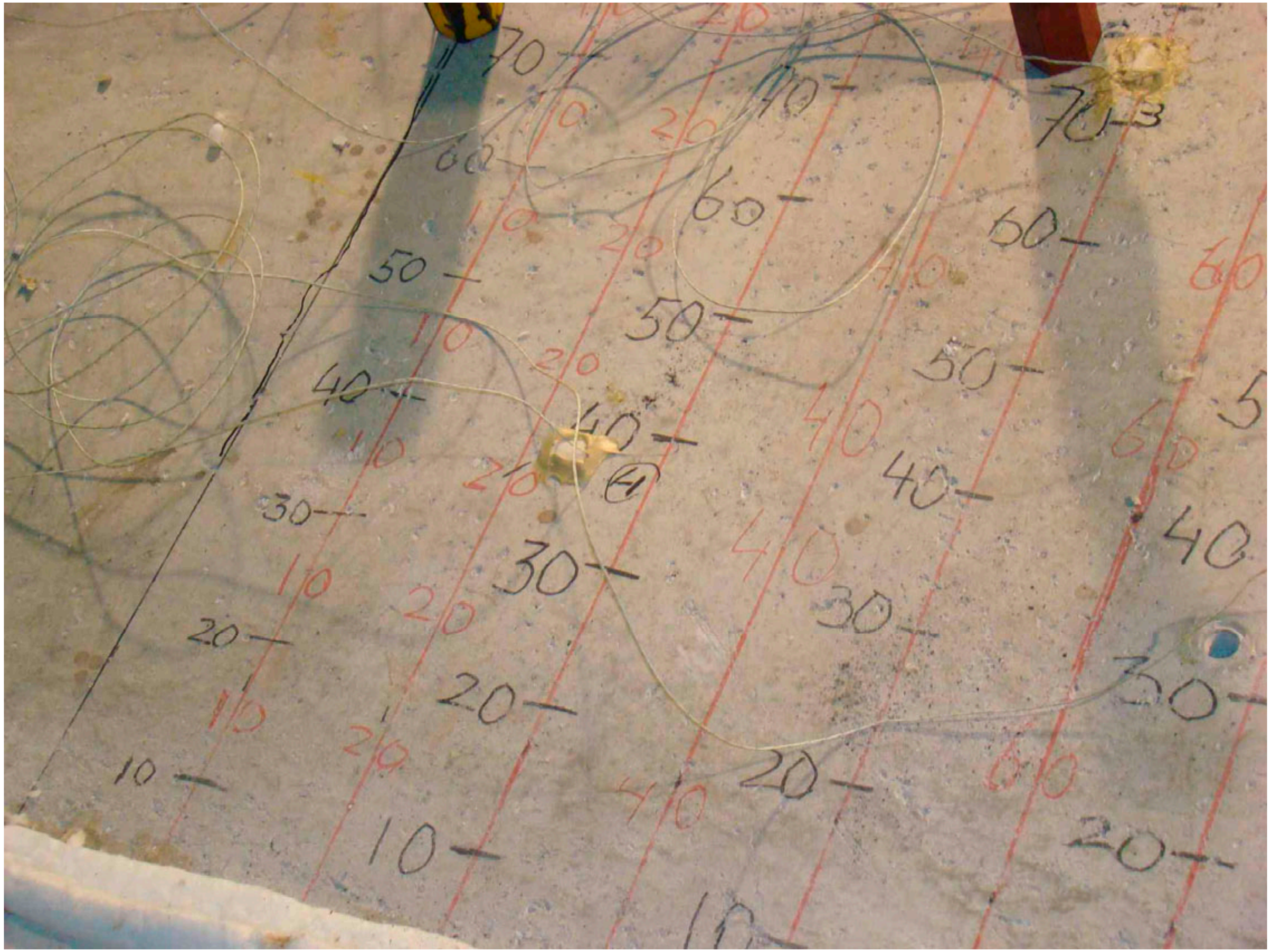

Figure B13 Element 6 after 21 minutes of heating, lower left corner detail

Figure B14 Element 6 after 21 minutes of heating, lower right corner detail

Figure B15 Element 6 after 27 minutes of heating

Figure B16 Element 6 after 40 minutes of heating

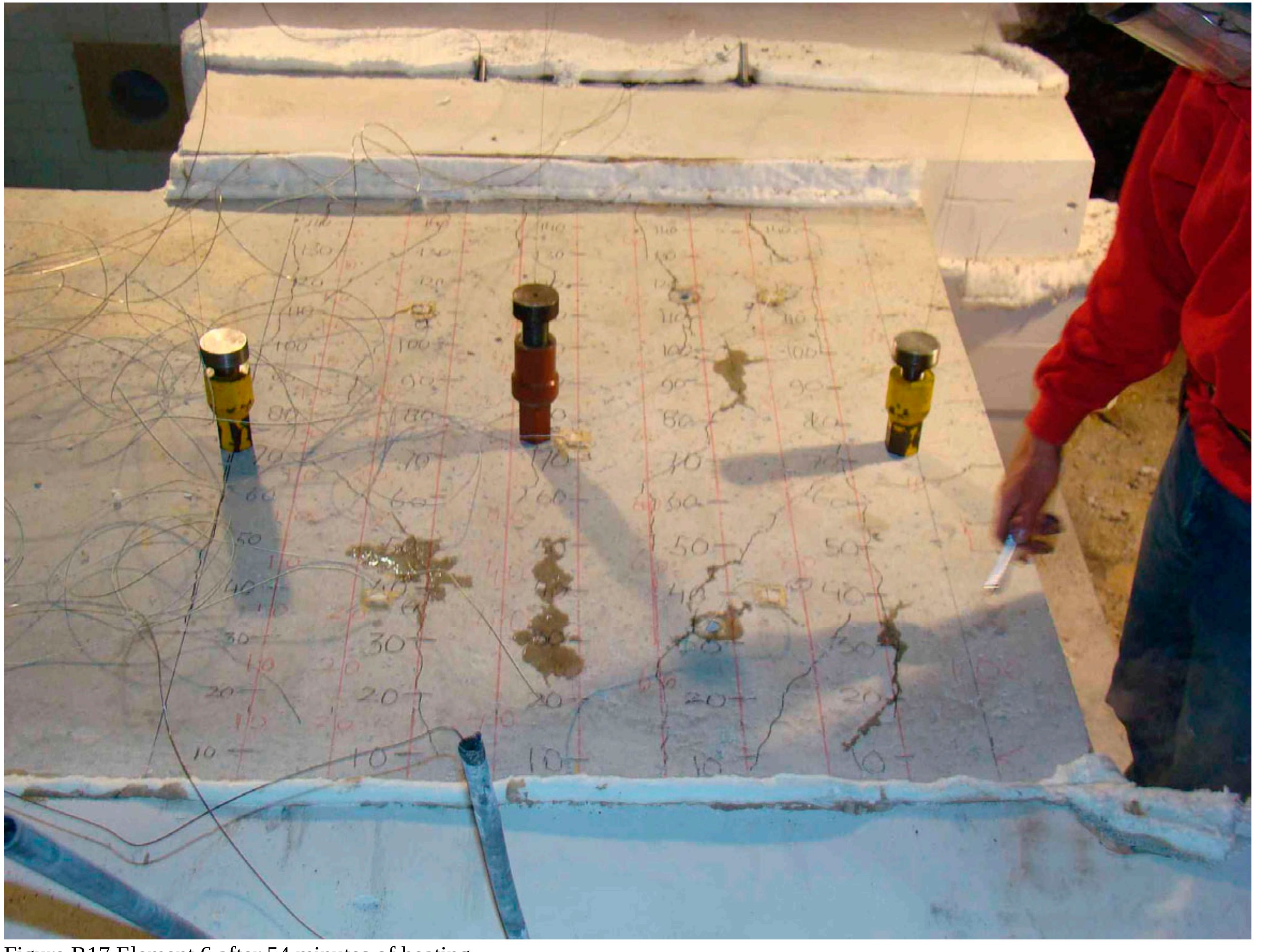

Figure B17 Element 6 after 54 minutes of heating

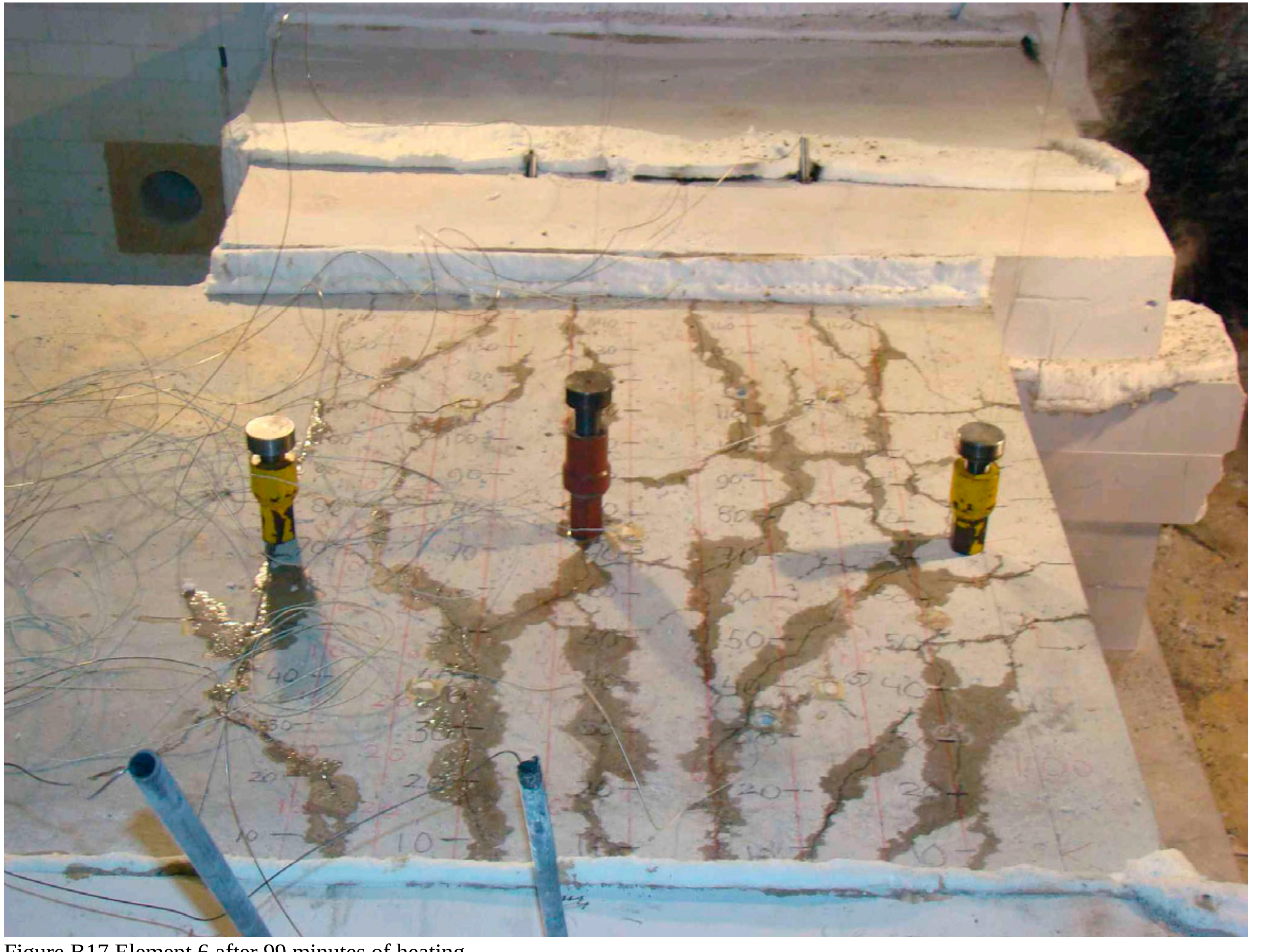

Figure B17 Element 6 after 99 minutes of heating

C Test results element 10

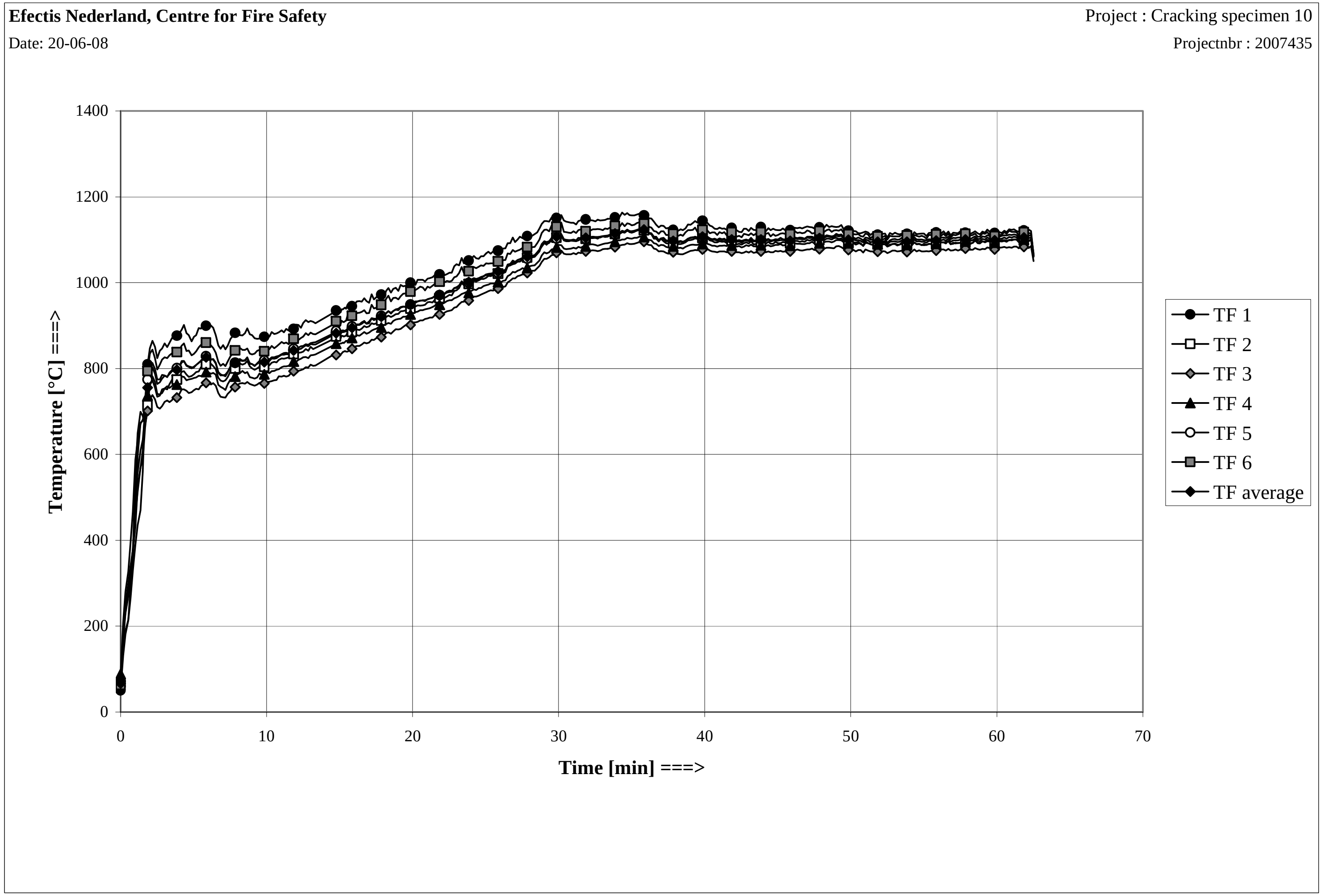

Figure C1 Furnace temperature

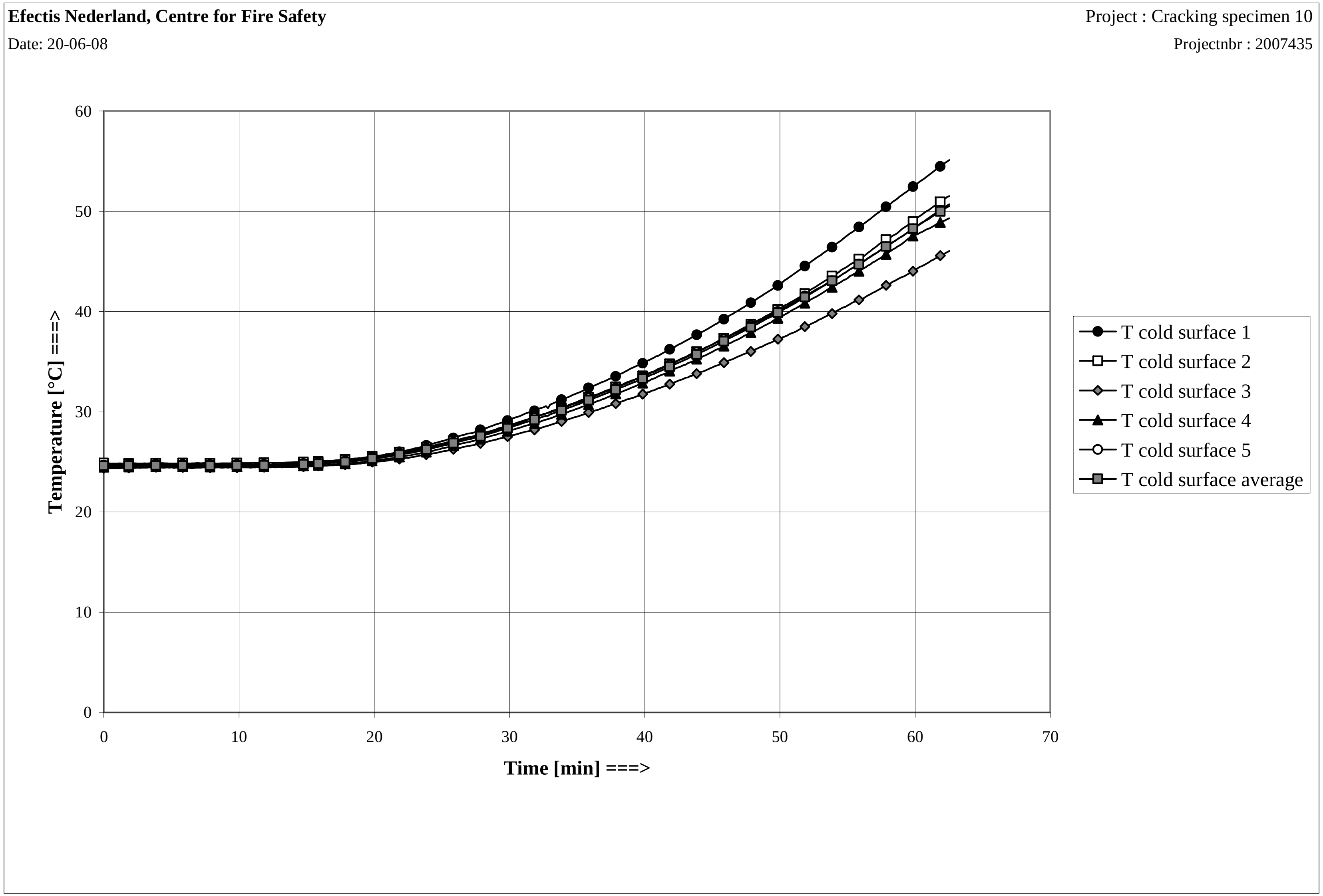

Figure C2 Cold surface temperatures

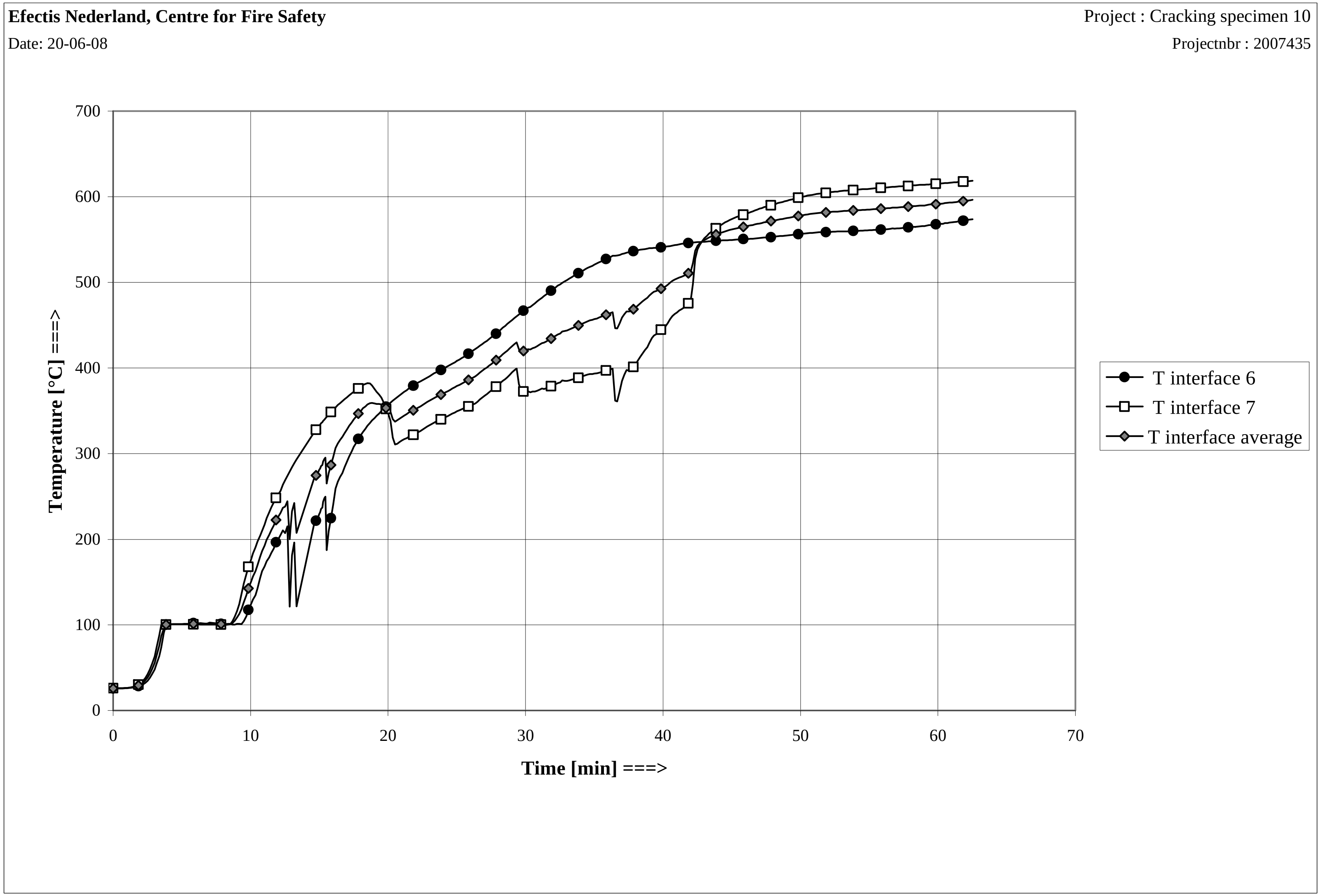

Figure C3 Interface temperatures

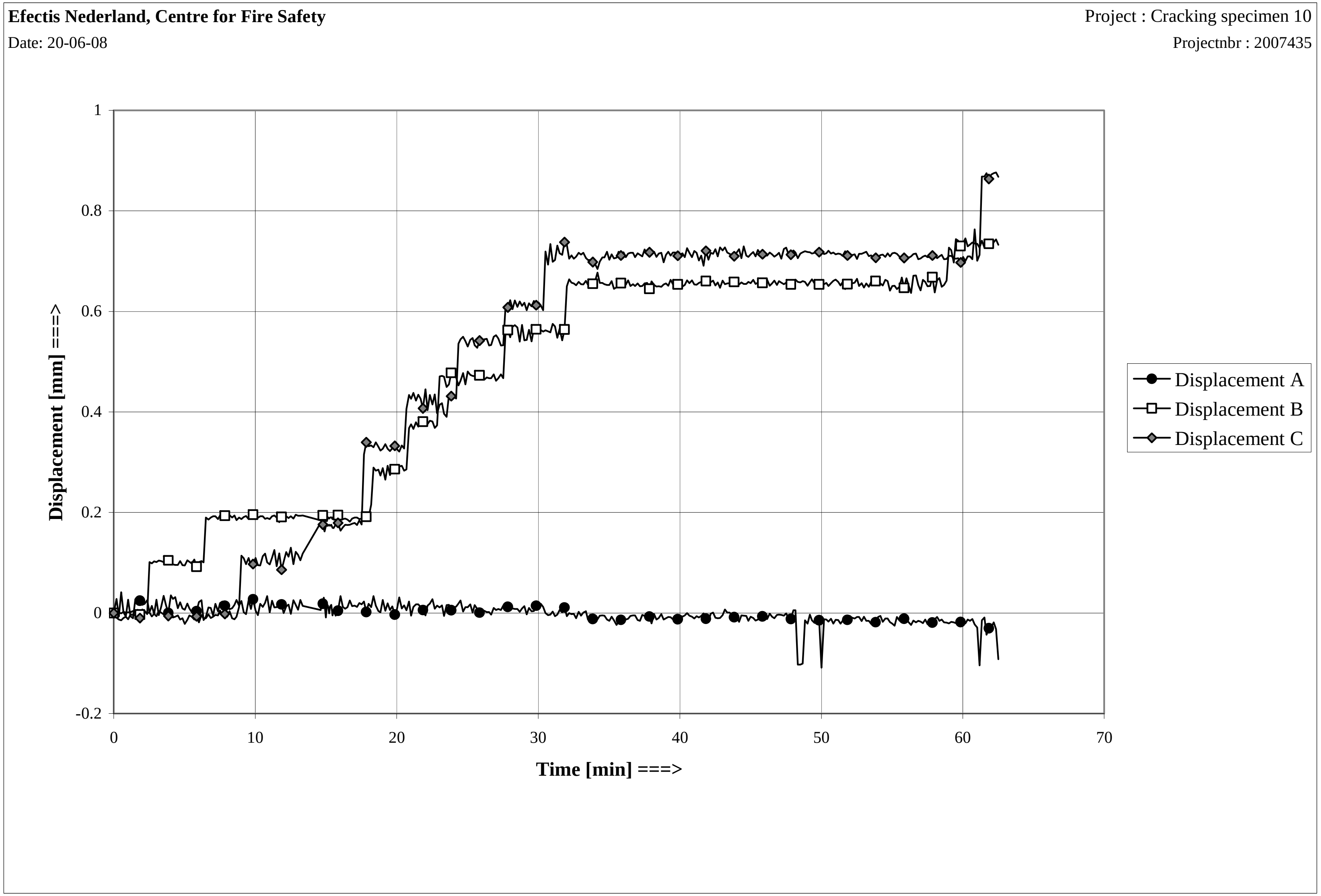

Figure C4 Displacement of the cold surface

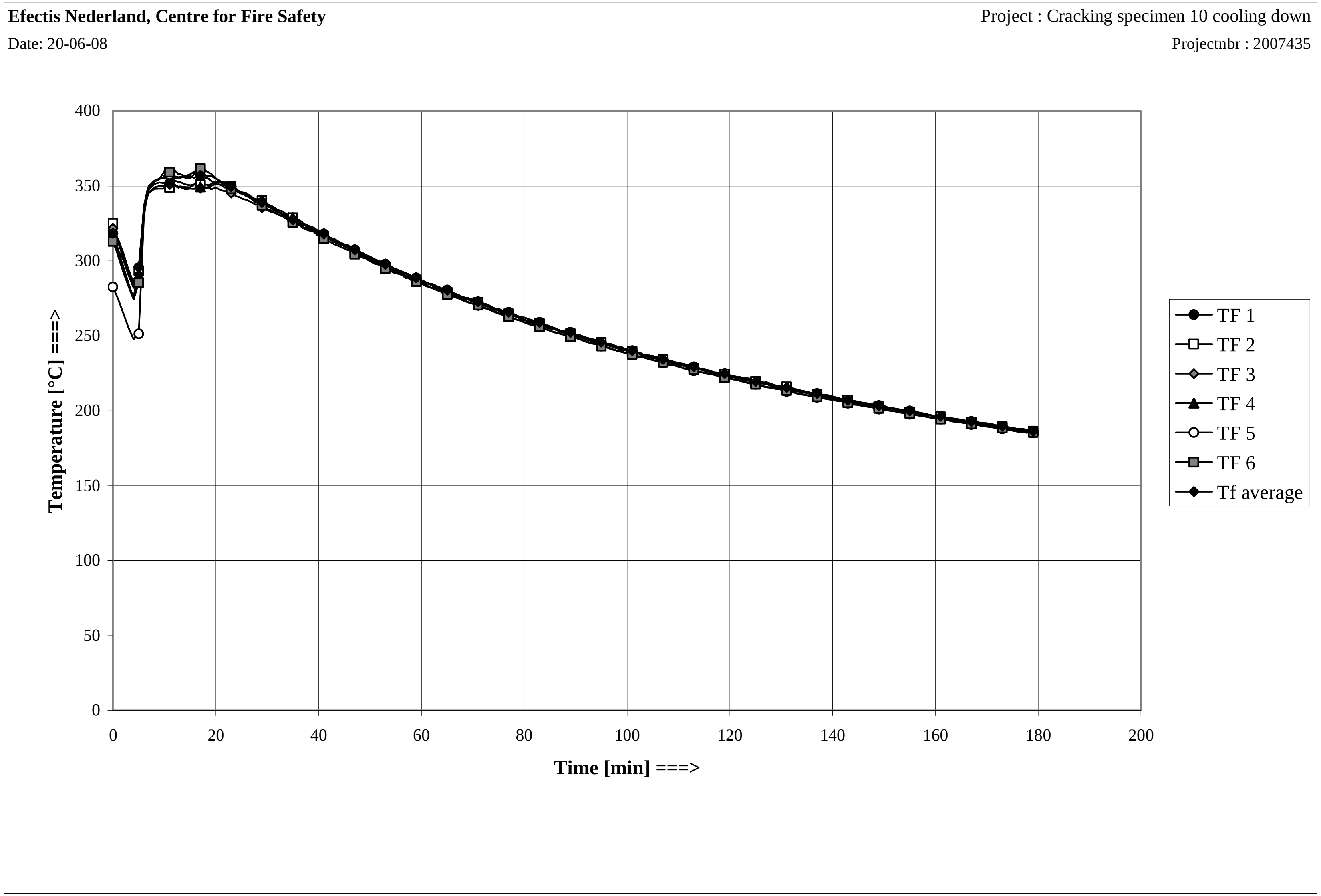

Figure C5 Furnace temperature during cooling down

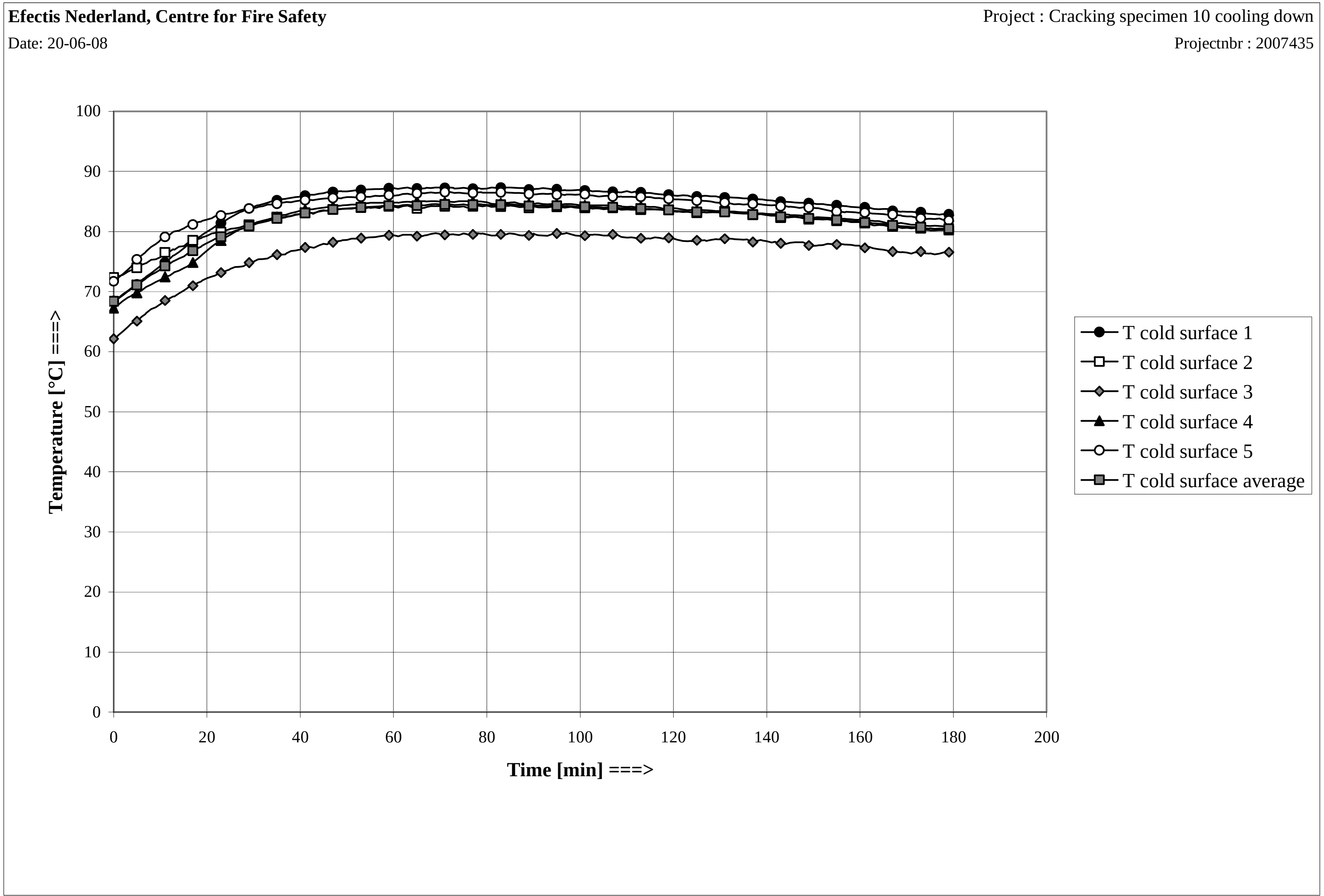

Figure C6 Cold surface temperatures during cooling down

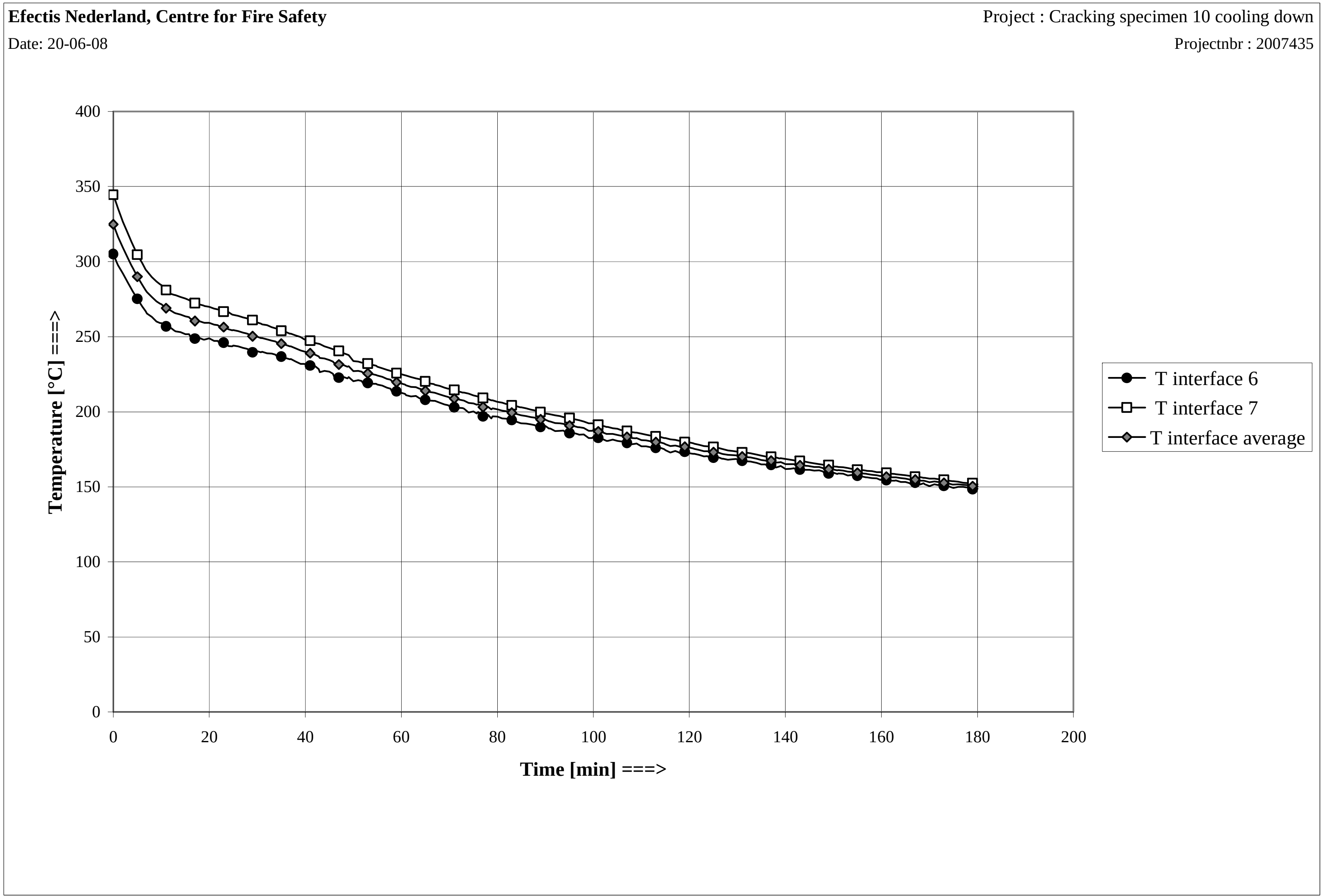

Figure C7 Interface temperatures during cooling down

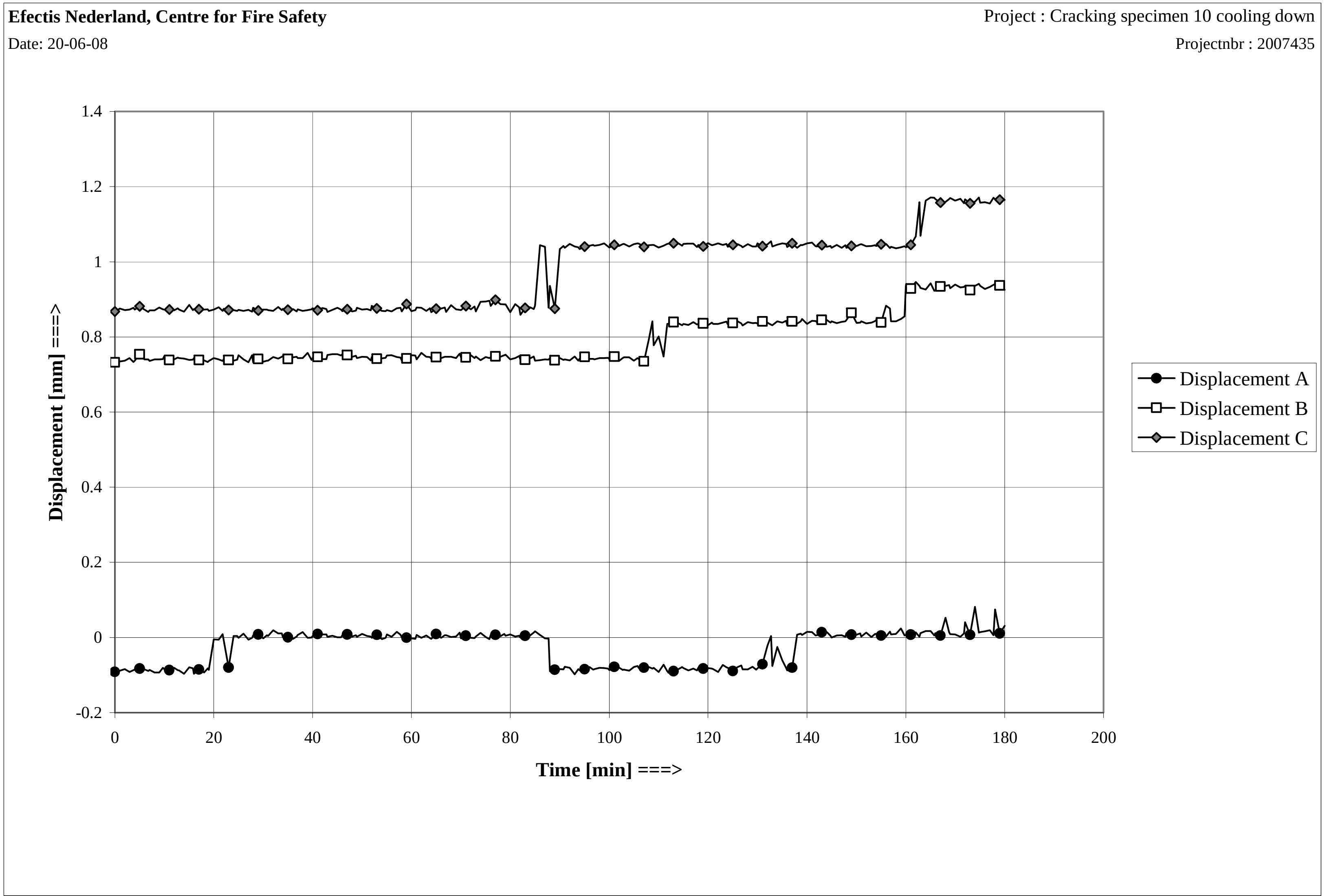

Figure C8 Displacements cold surface during cooling down

Figure C9 Element before the fire test

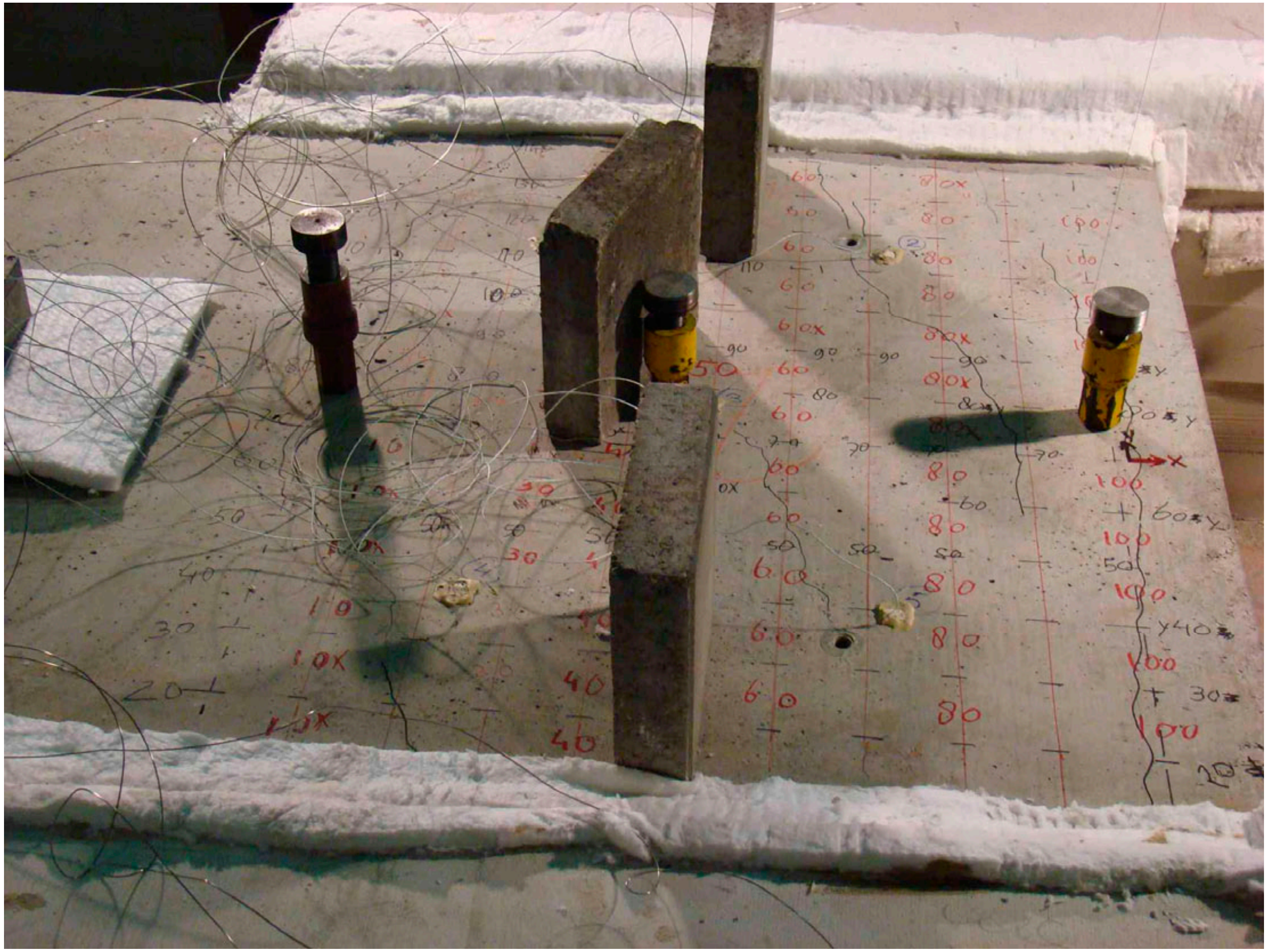

Figure C10 Element 10 after 19 minutes of heating

Figure C11 Element 10 after 20 minutes of heating, a view on the non heated tube. Note that the bottom of the element is lifted from the floor

Figure C12 Element 10 after 29 minutes of heating, view on the side surface

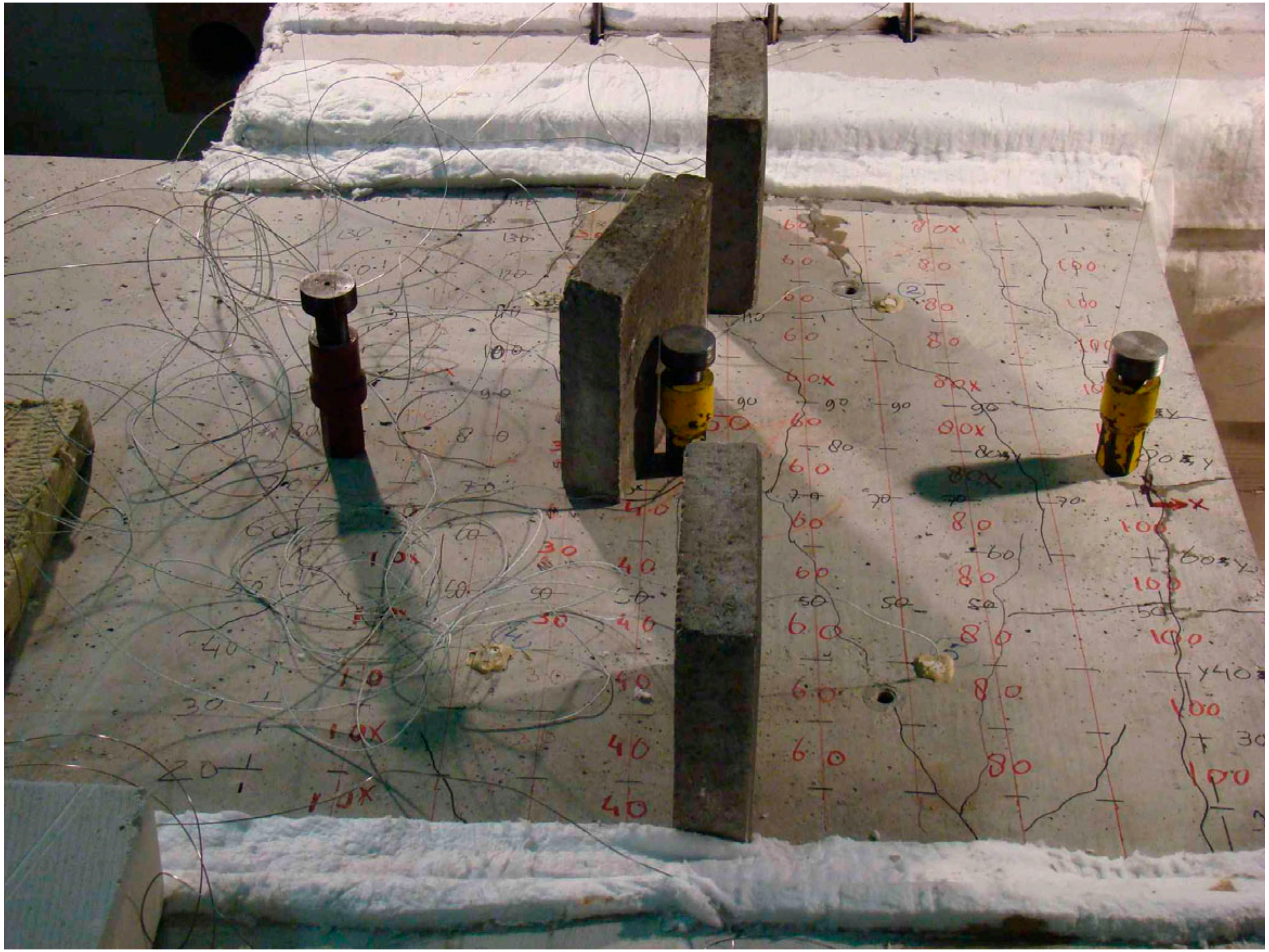

Figure C13 Element 10 after 48 minutes of heating

Figure C14 Element 10 after 48 minutes of heating, a view on the side surface

D Test results element 8

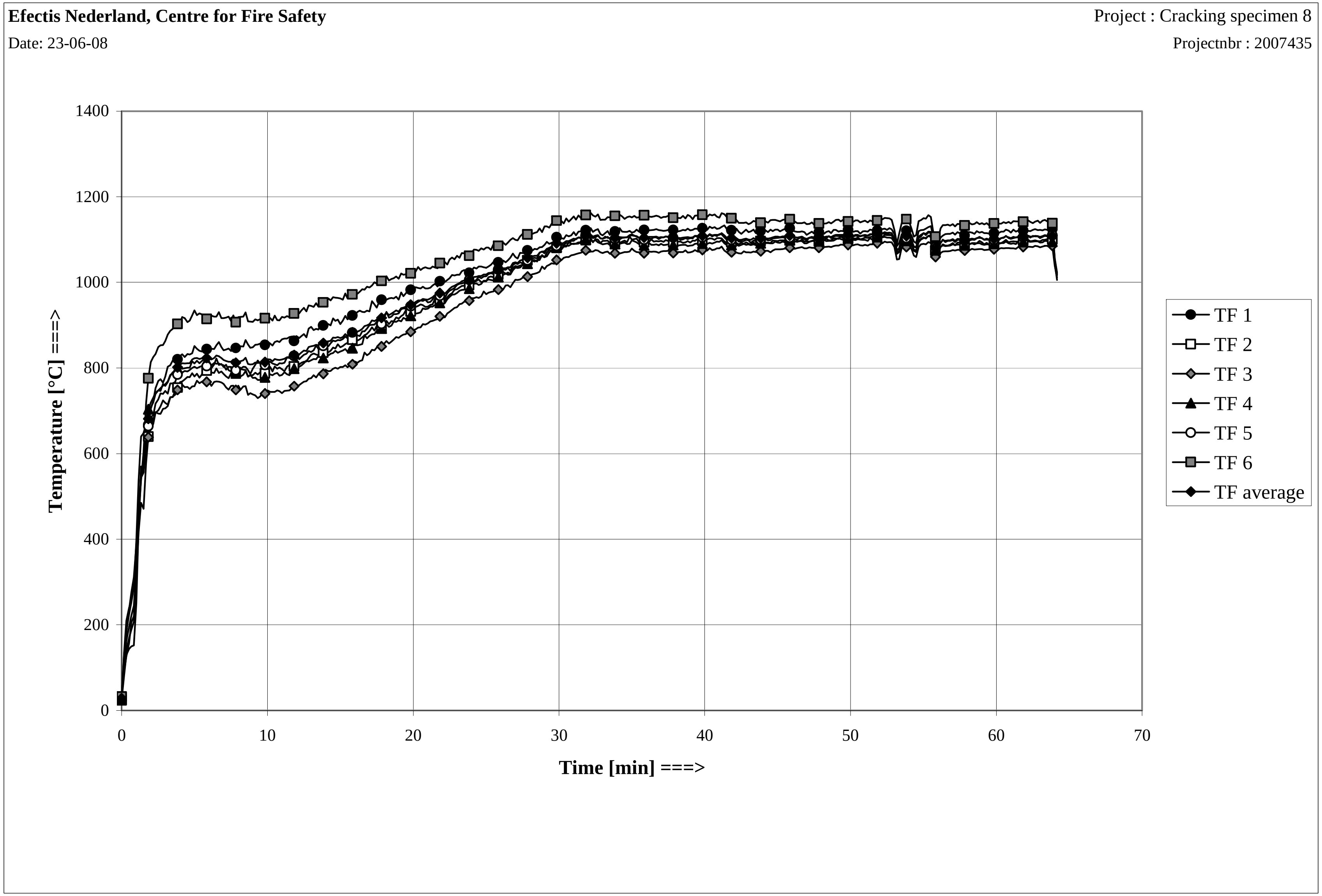

Figure D1 Furnace temperature

Efectis Nederland, Centre for Fire Safety

Date: 23-06-08

Project : Cracking specimen 8

Projectnbr : 2007435

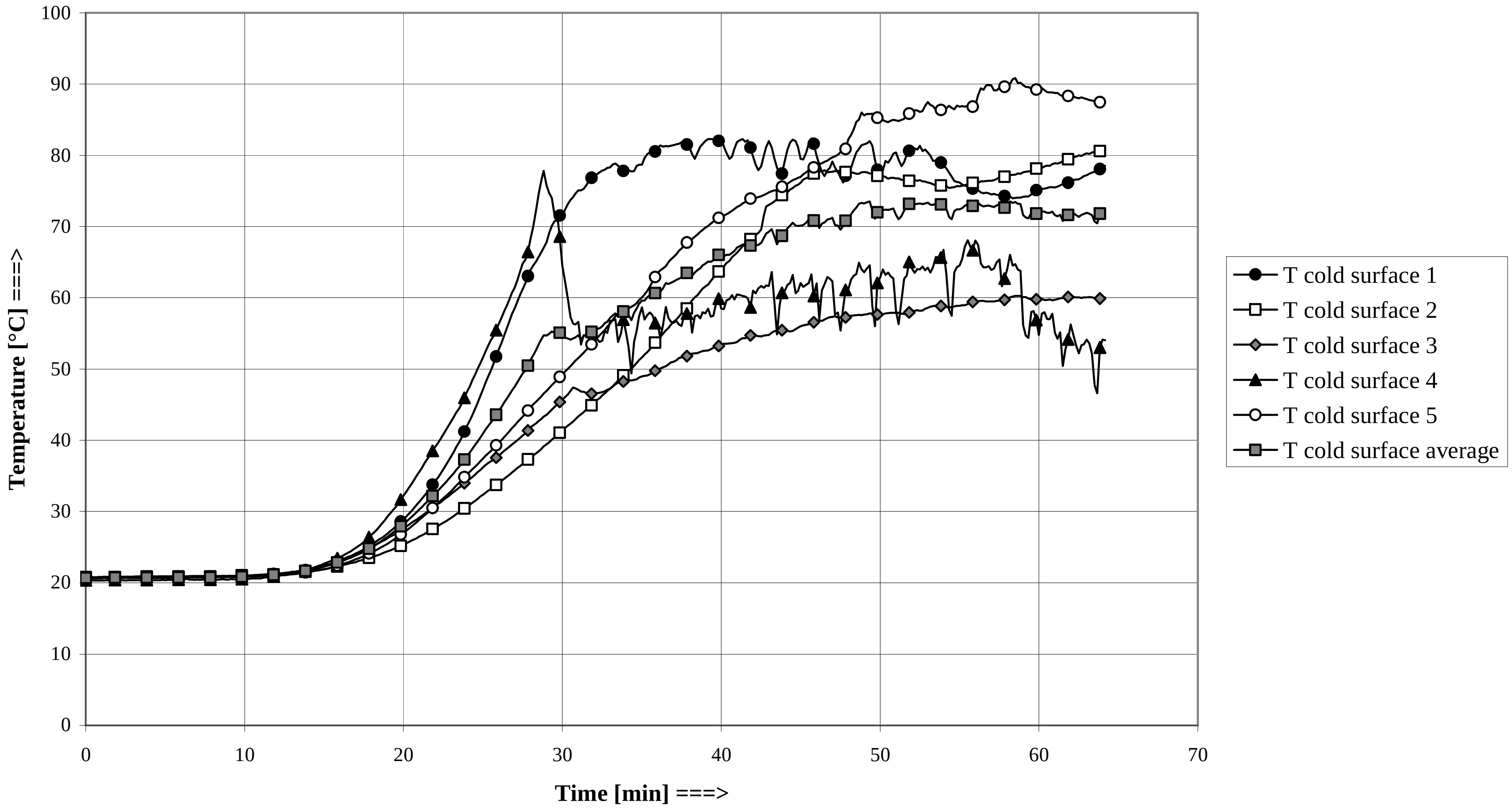

Figure D2 Cold face temperatures

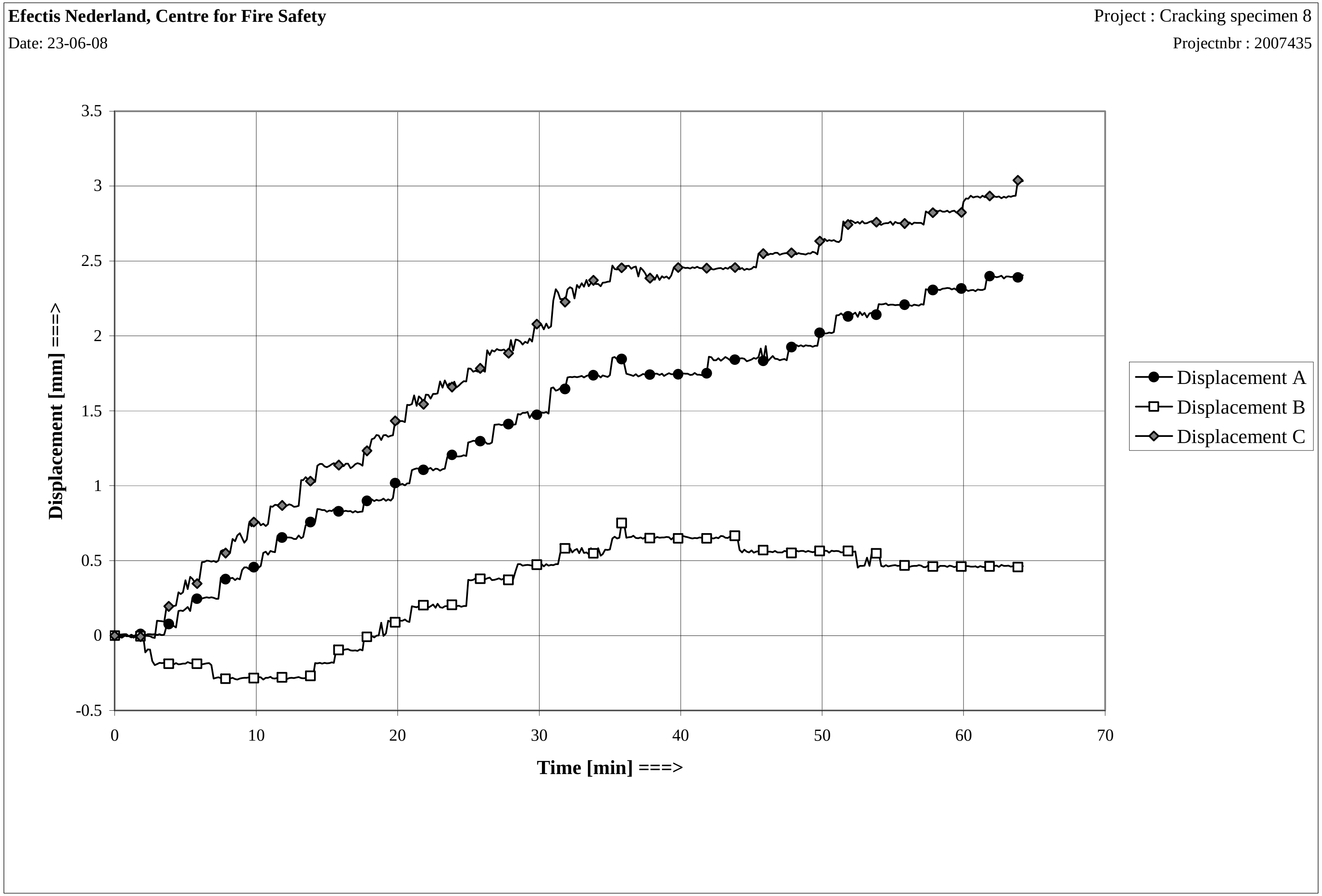

Figure D3 Displacements of the cold surface

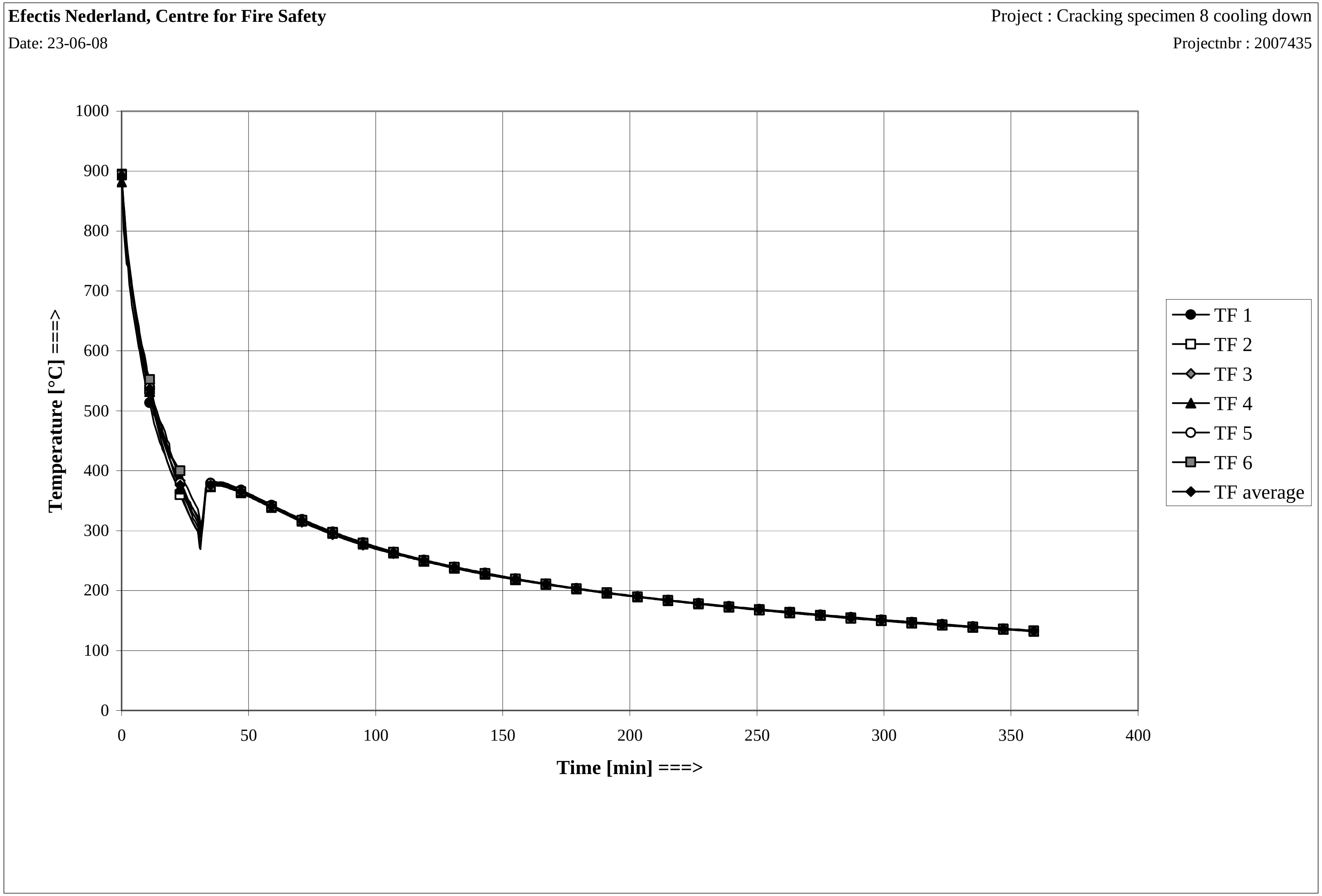

Figure D4 Furnace temperature during cooling down

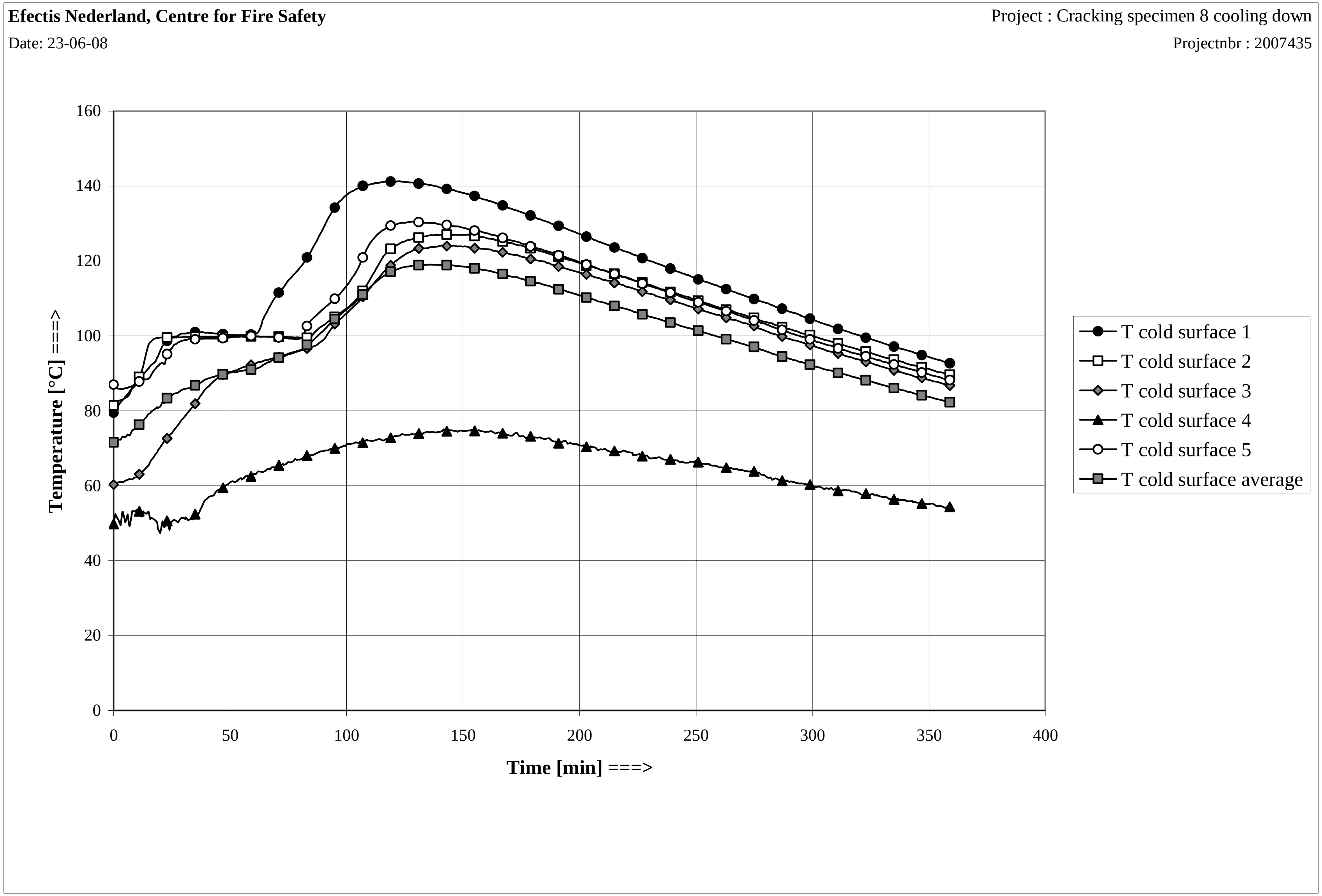

Figure D5 Cold surface temperatures during cooling down

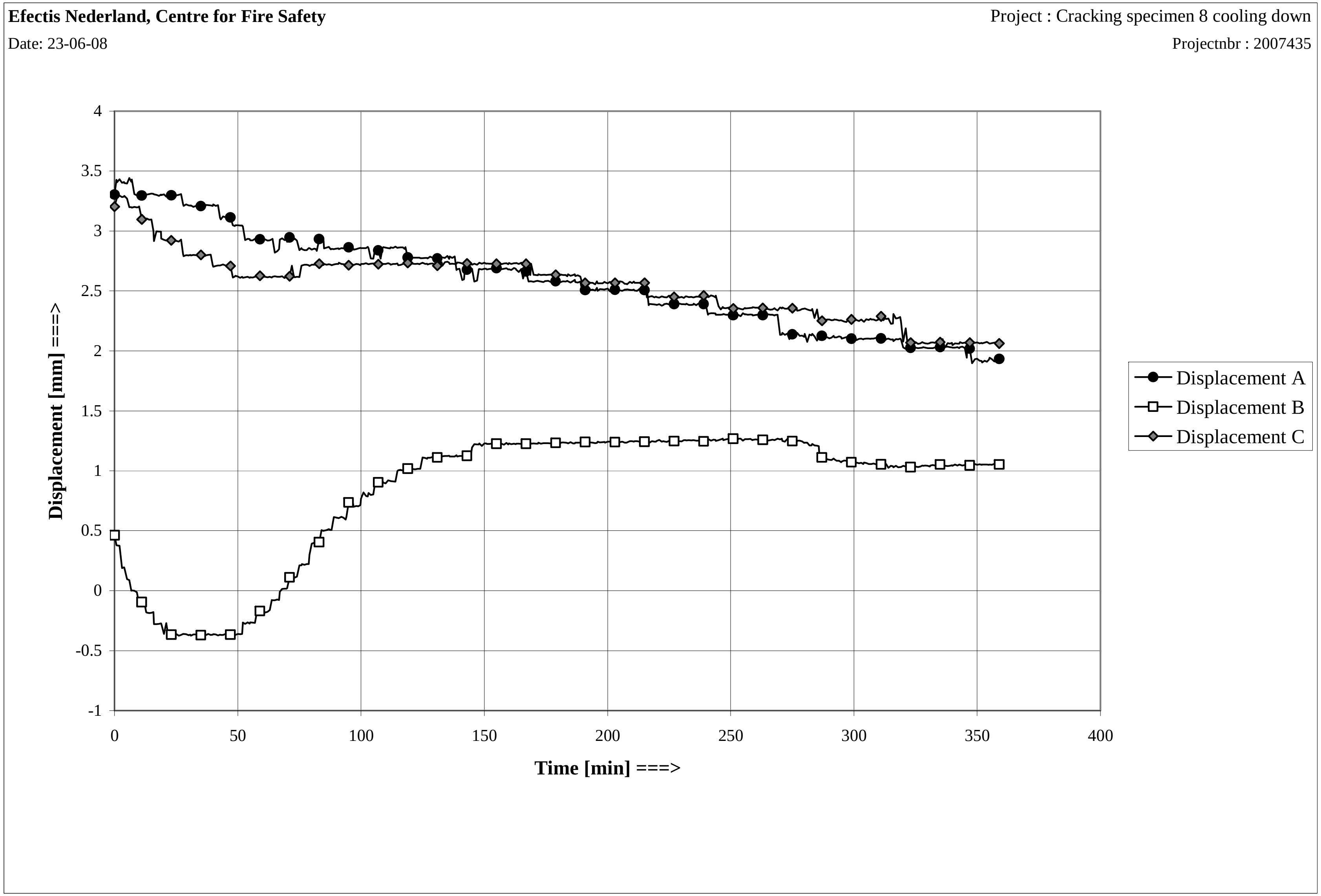

Figure D6 Displacements during cooling down

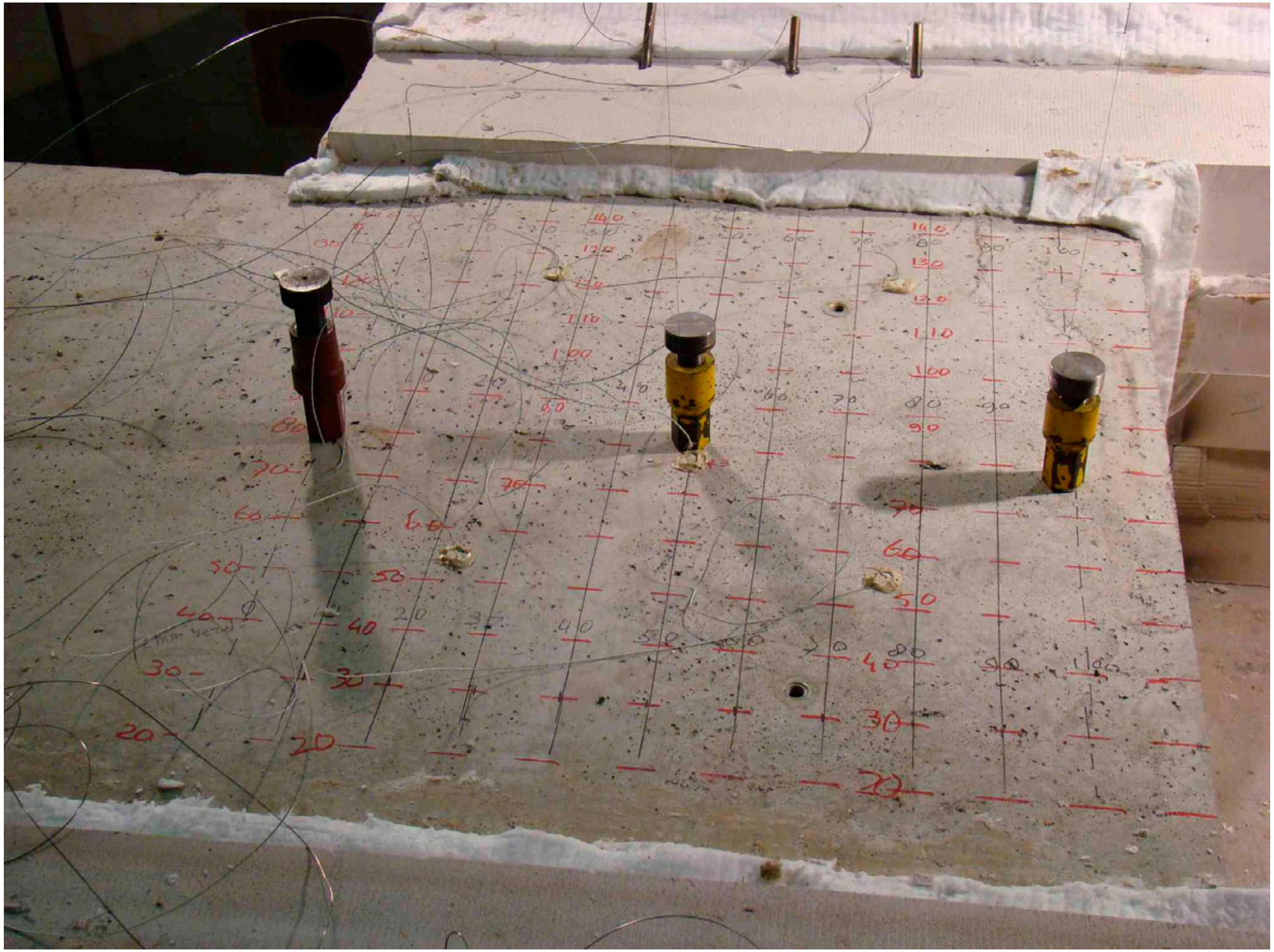

Figure D7 Element 8 before the fire test

Figure D8 Element 8 after 6 minutes of heating

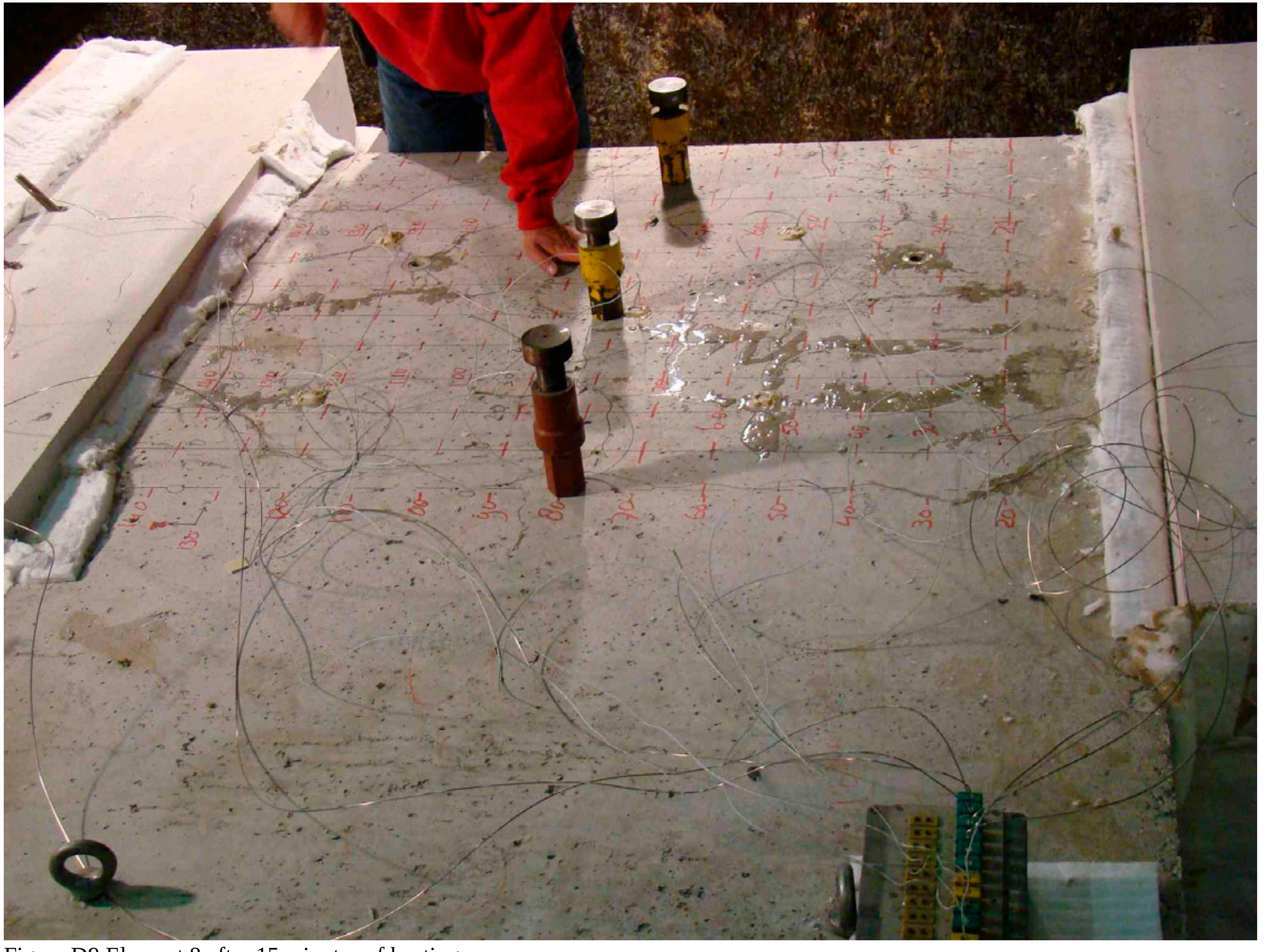

Figure D9 Element 8 after 15 minutes of heating

Figure D10 Element 8 after 29 minutes of heating

Figure D11 Element 8 after 44 minutes of heating. This is side surface of the non heated tube which is lifted approximately 10 mm

Figure D12 Element 8 ± 5 minutes after the fire test

E Test results element 6, loaded

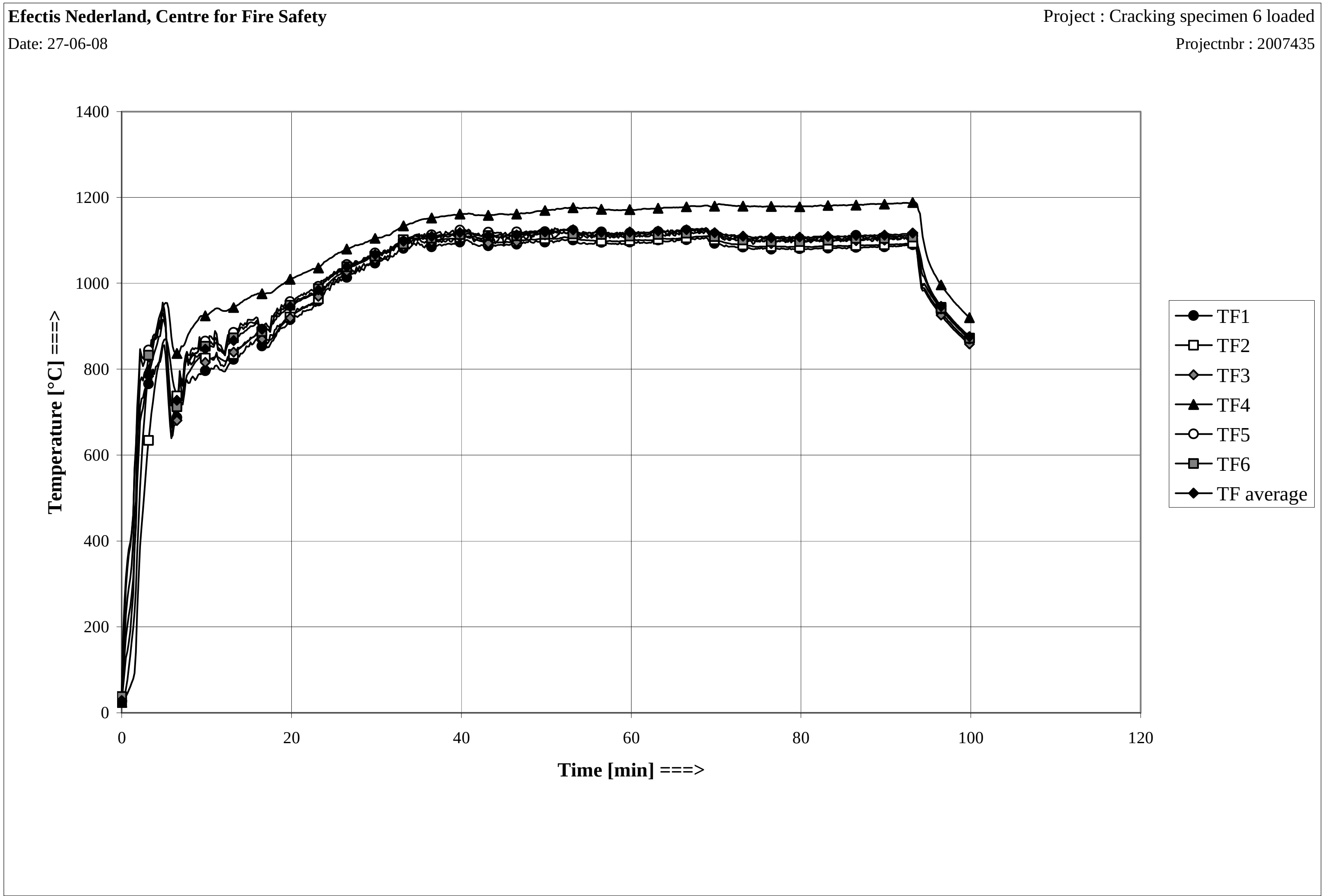

Figure E1 Furnace temperature

Efectis Nederland, Centre for Fire Safety
Date: 27-06-08

Project : Cracking specimen 6 loaded
Projectnbr : 2007435

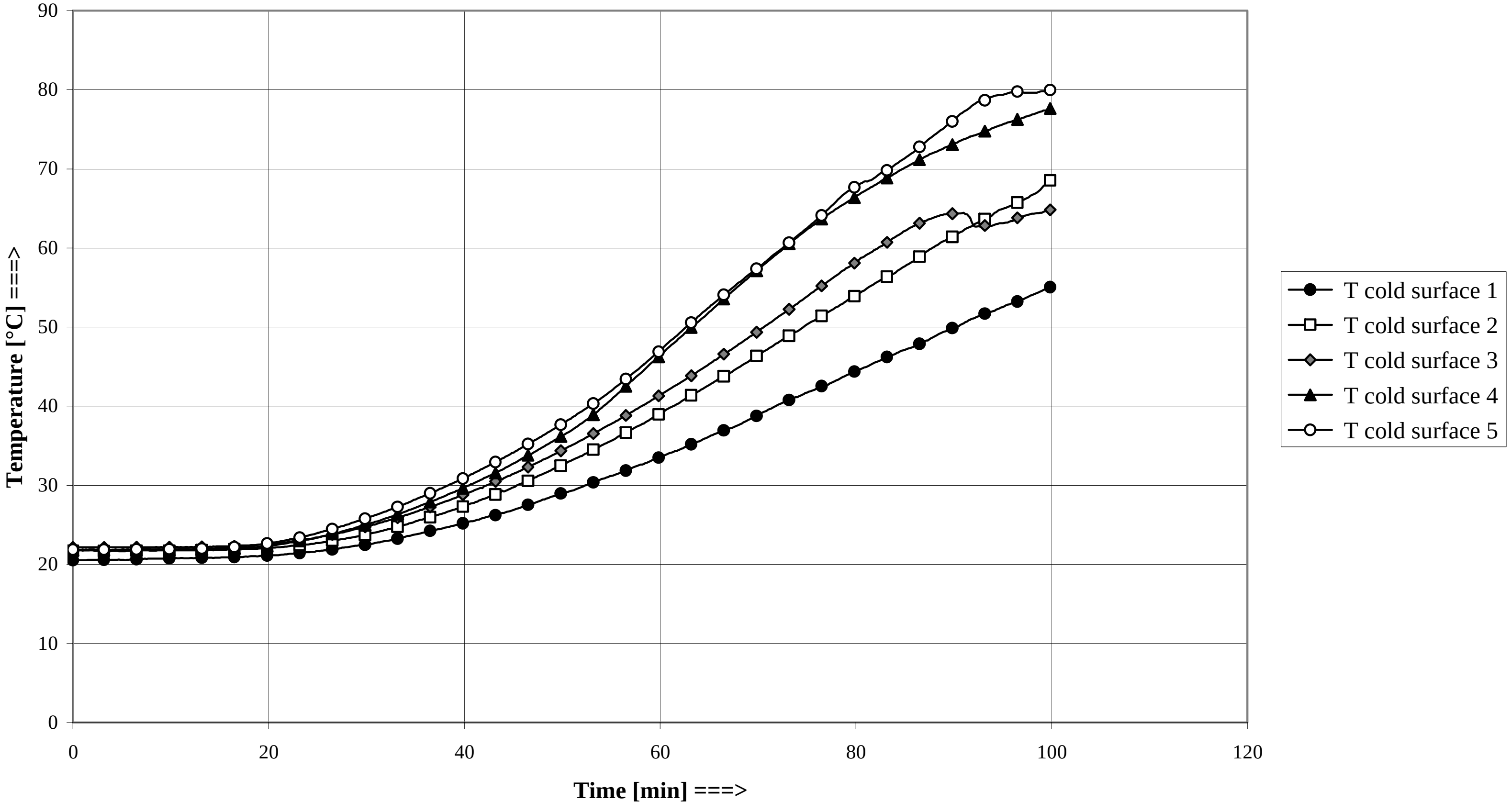

Figure E2 Cold face temperatures

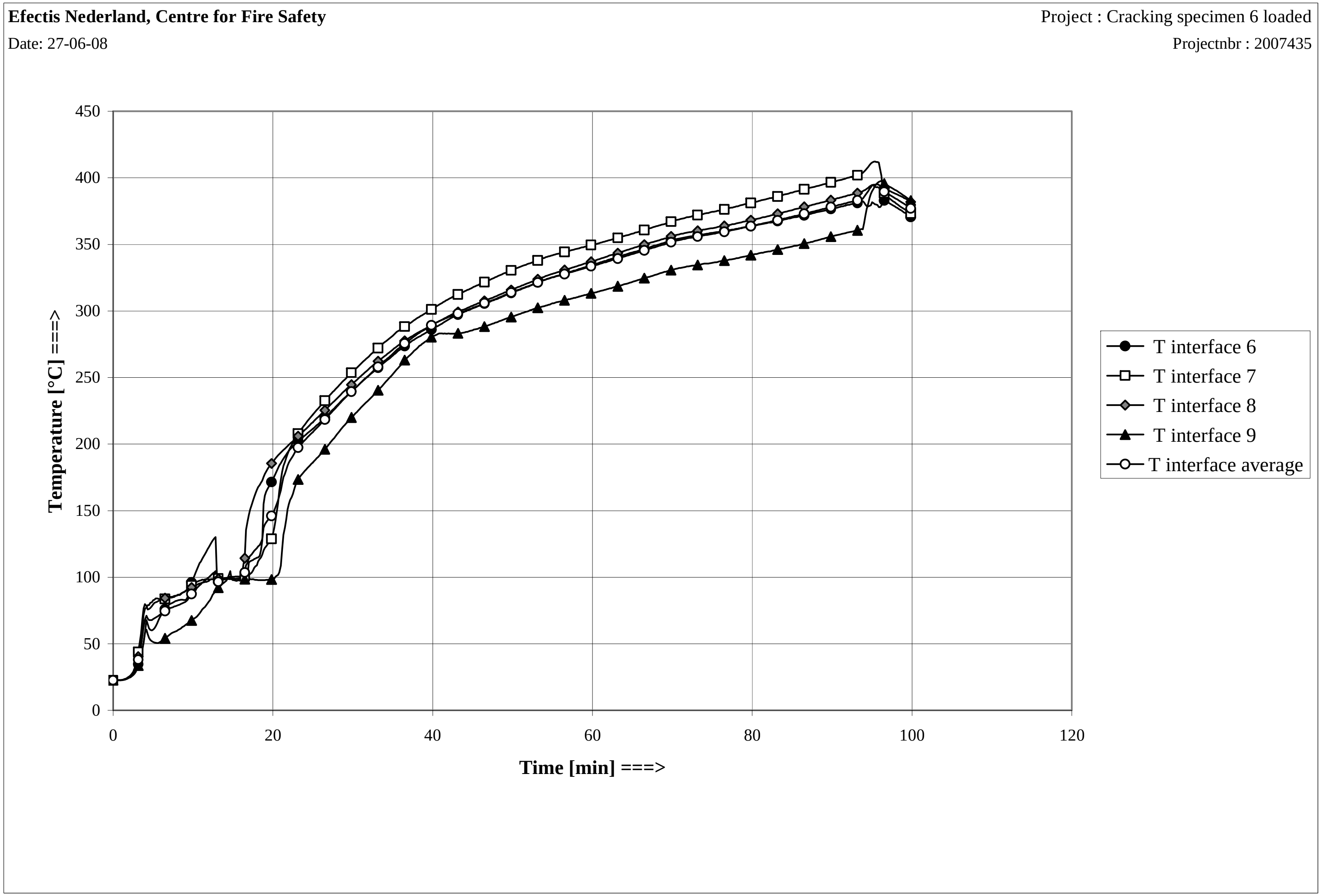

Figure E3 Interface temperatures

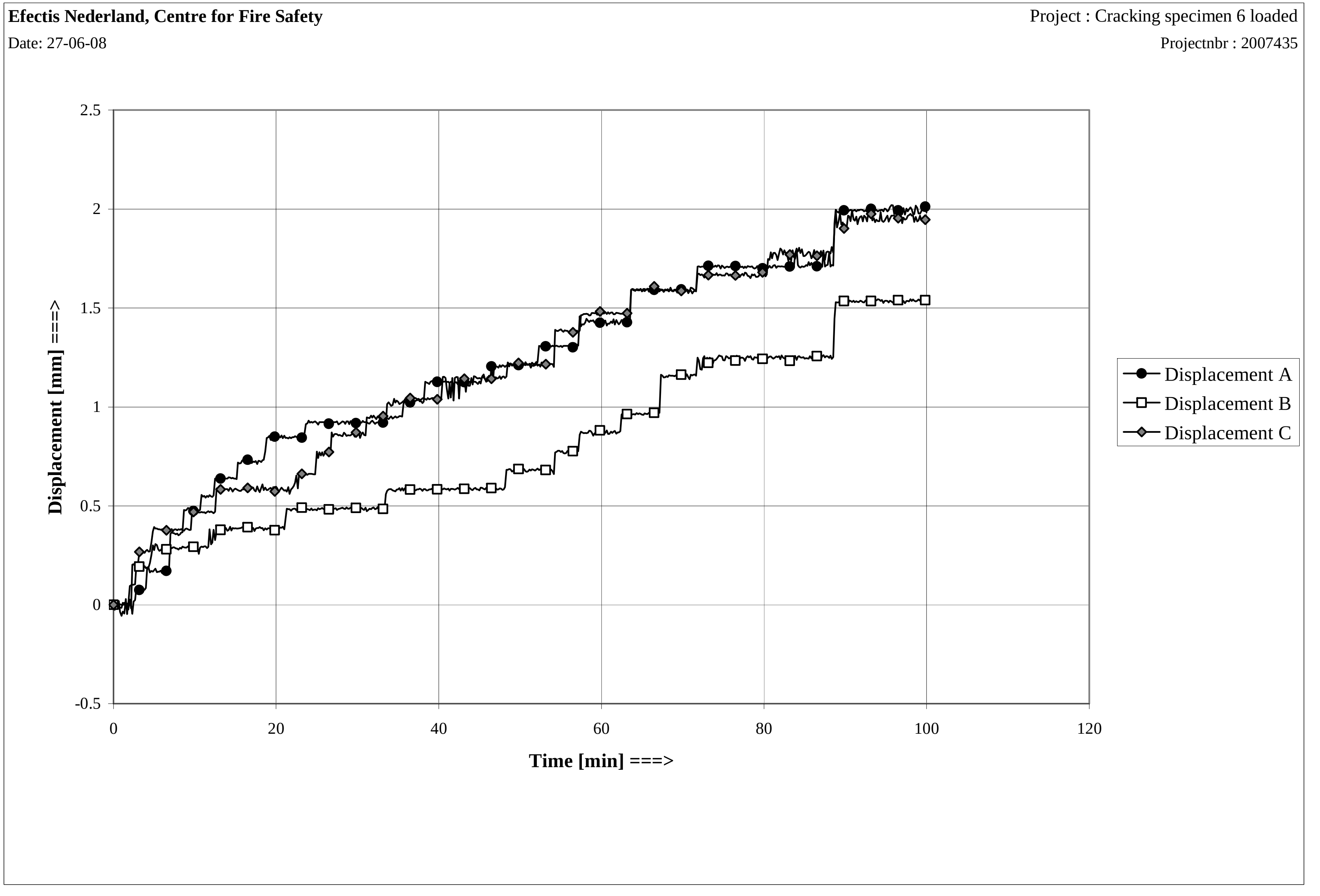

Figure E4 Displacements of the cold surface

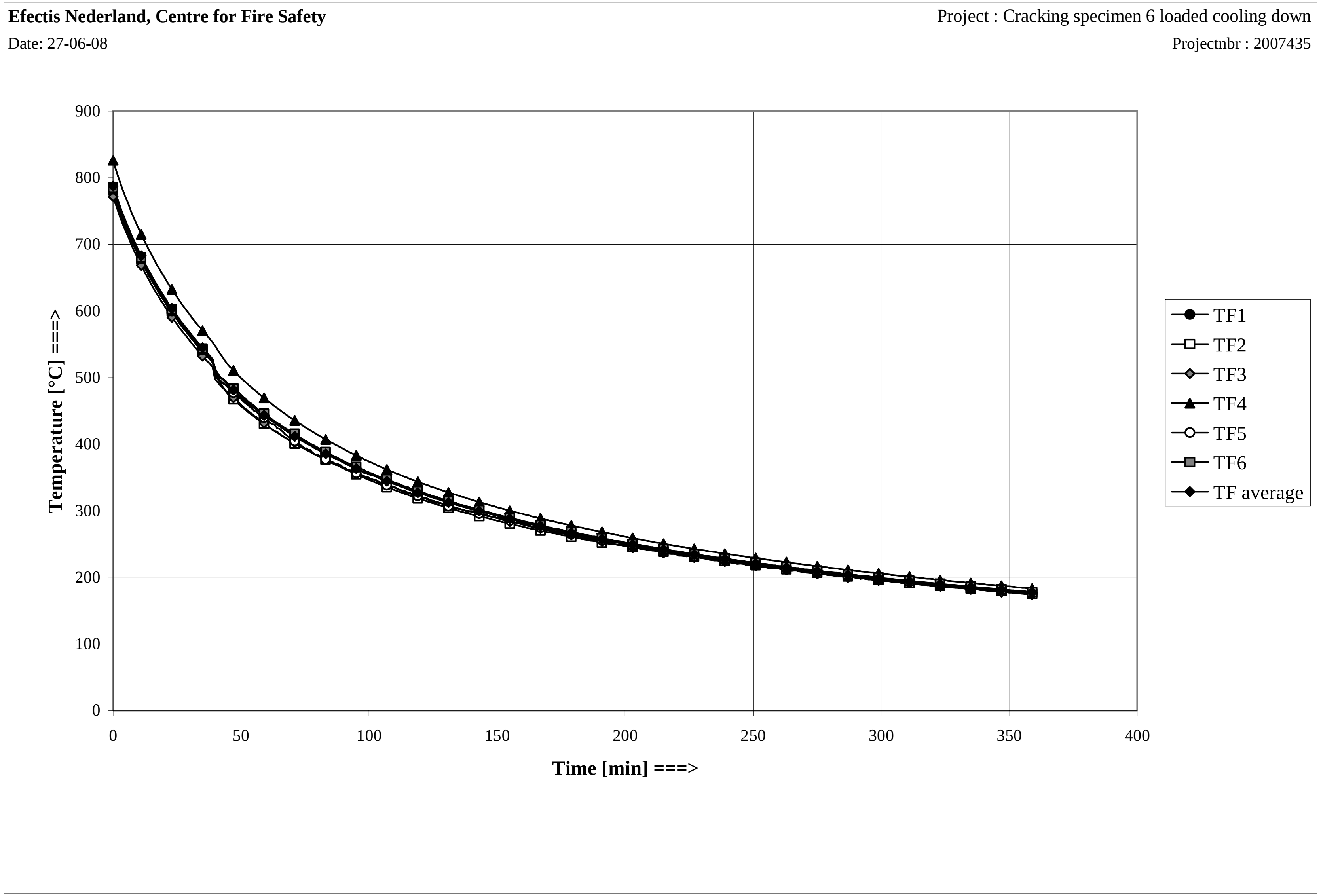

Figure E5 Furnace temperature during cooling down

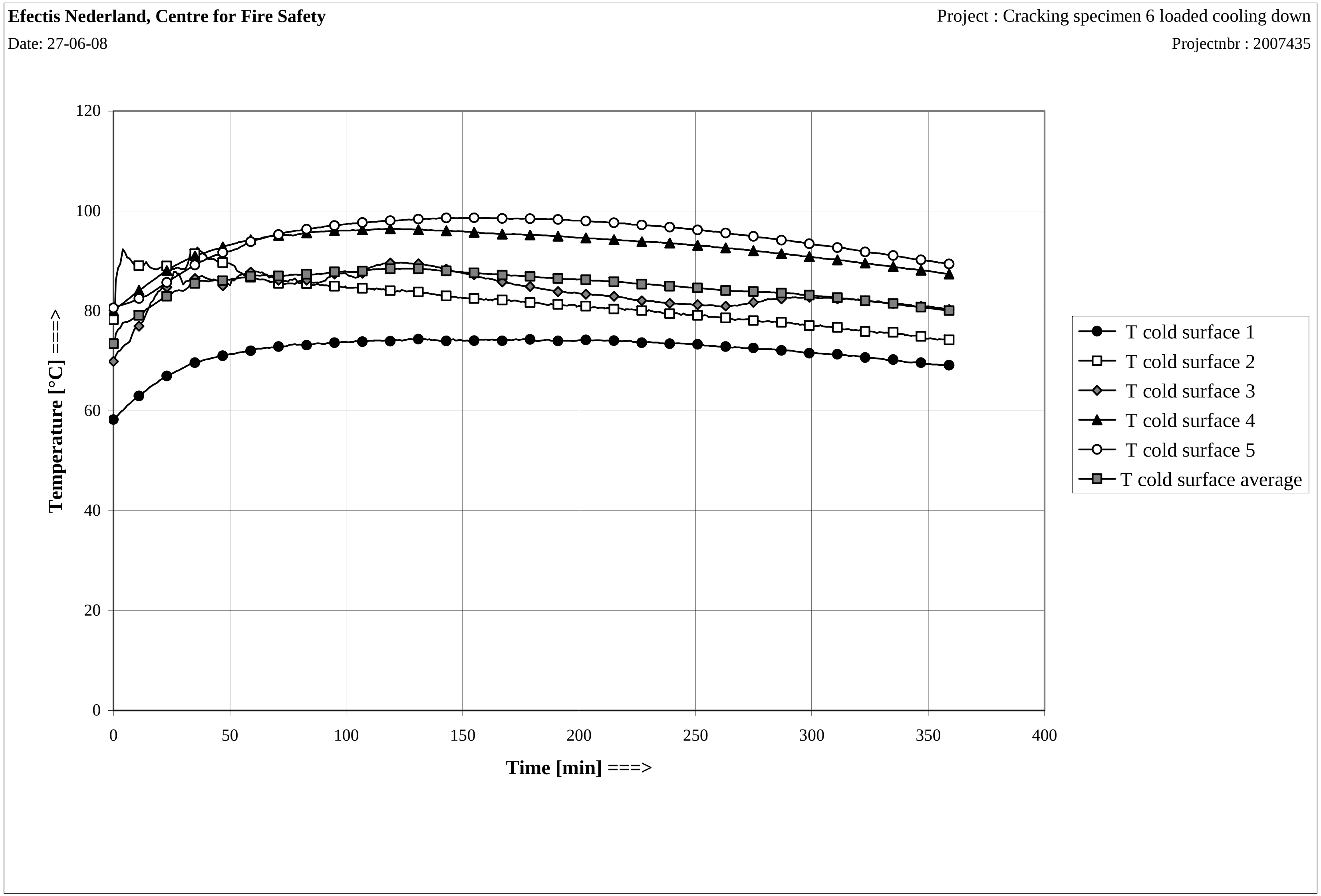

Figure E6 Cold surface temperatures during cooling down

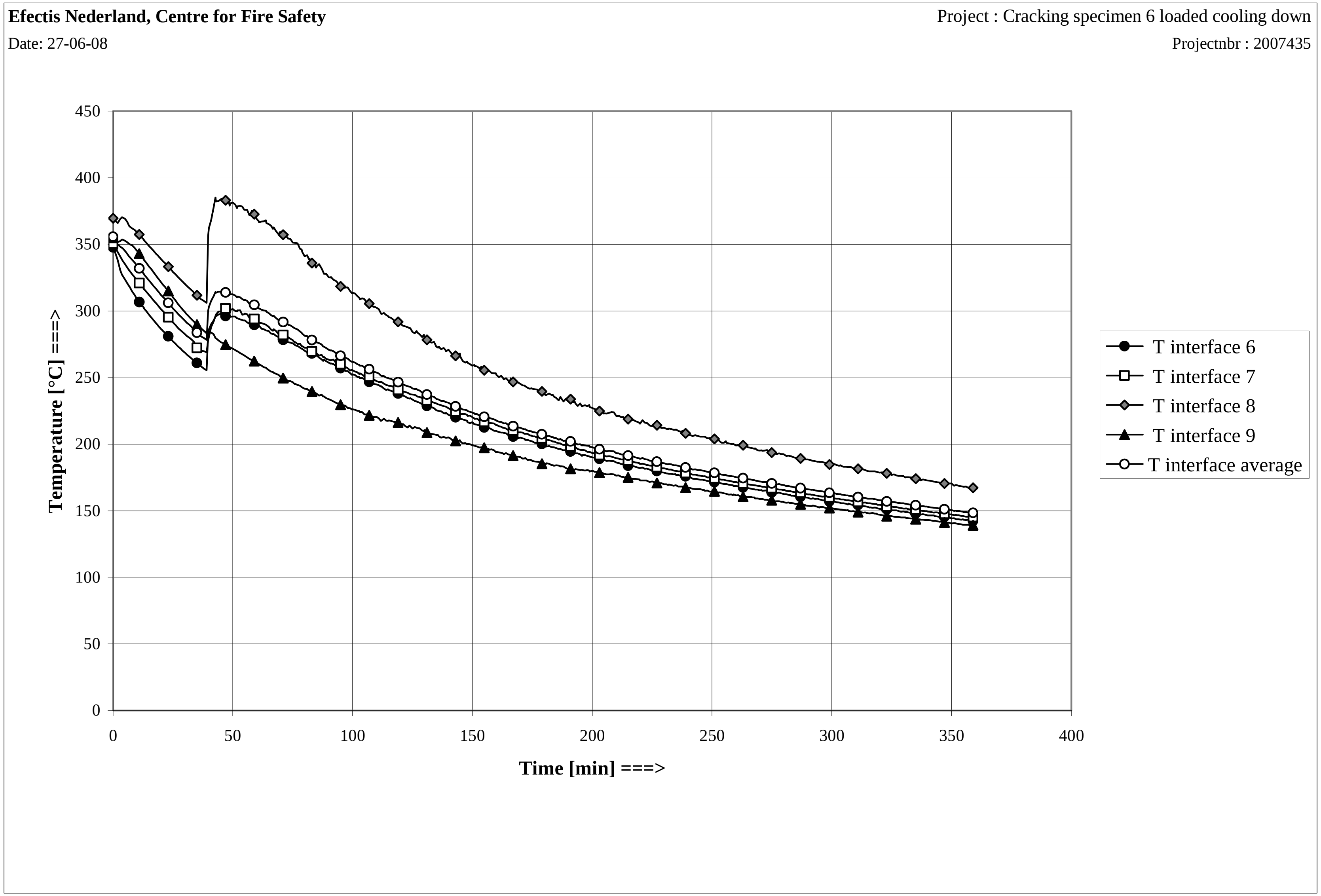

Figure E7 Interface temperatures during cooling down

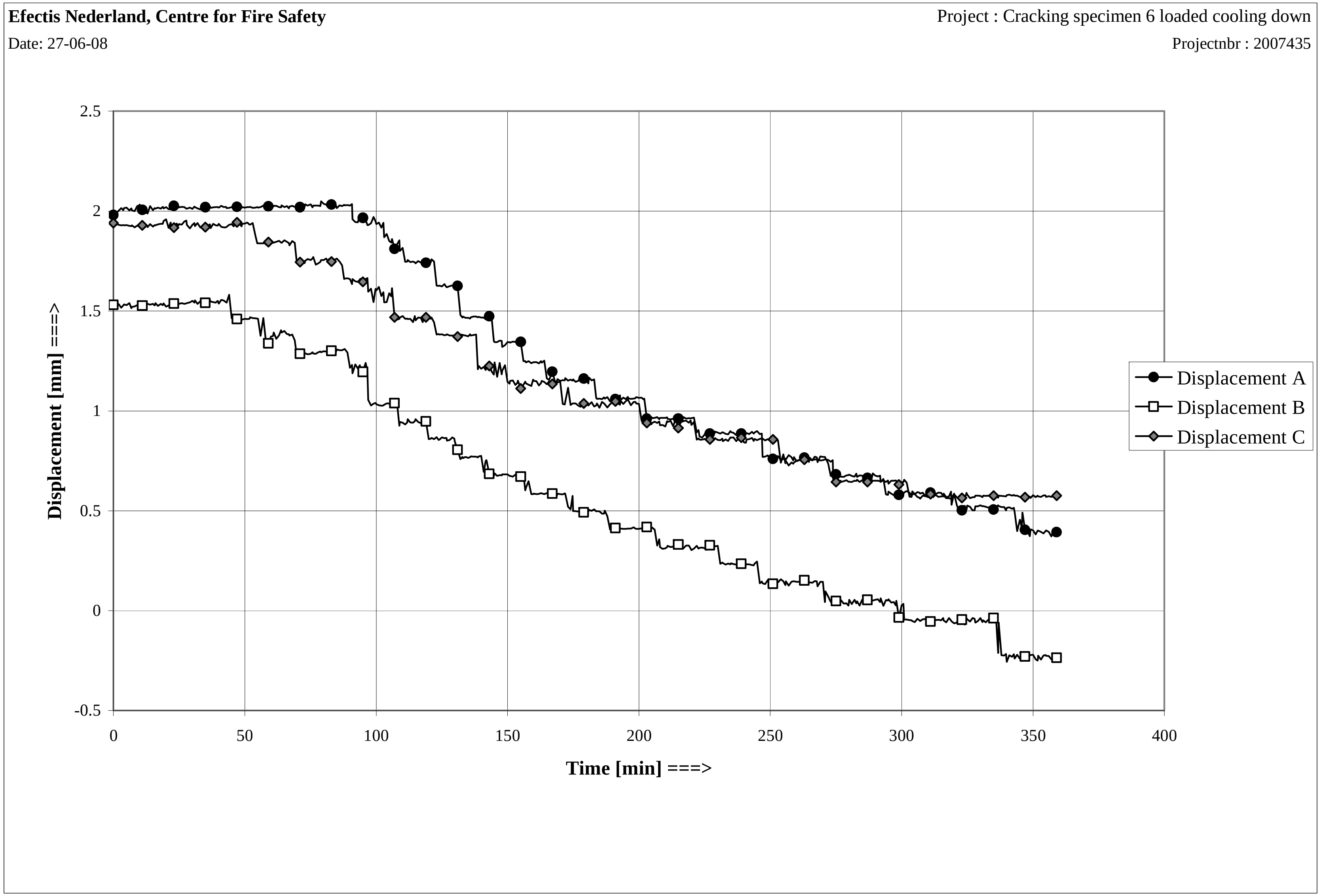

Figure E8 Displacements of the cold surface during cooling down

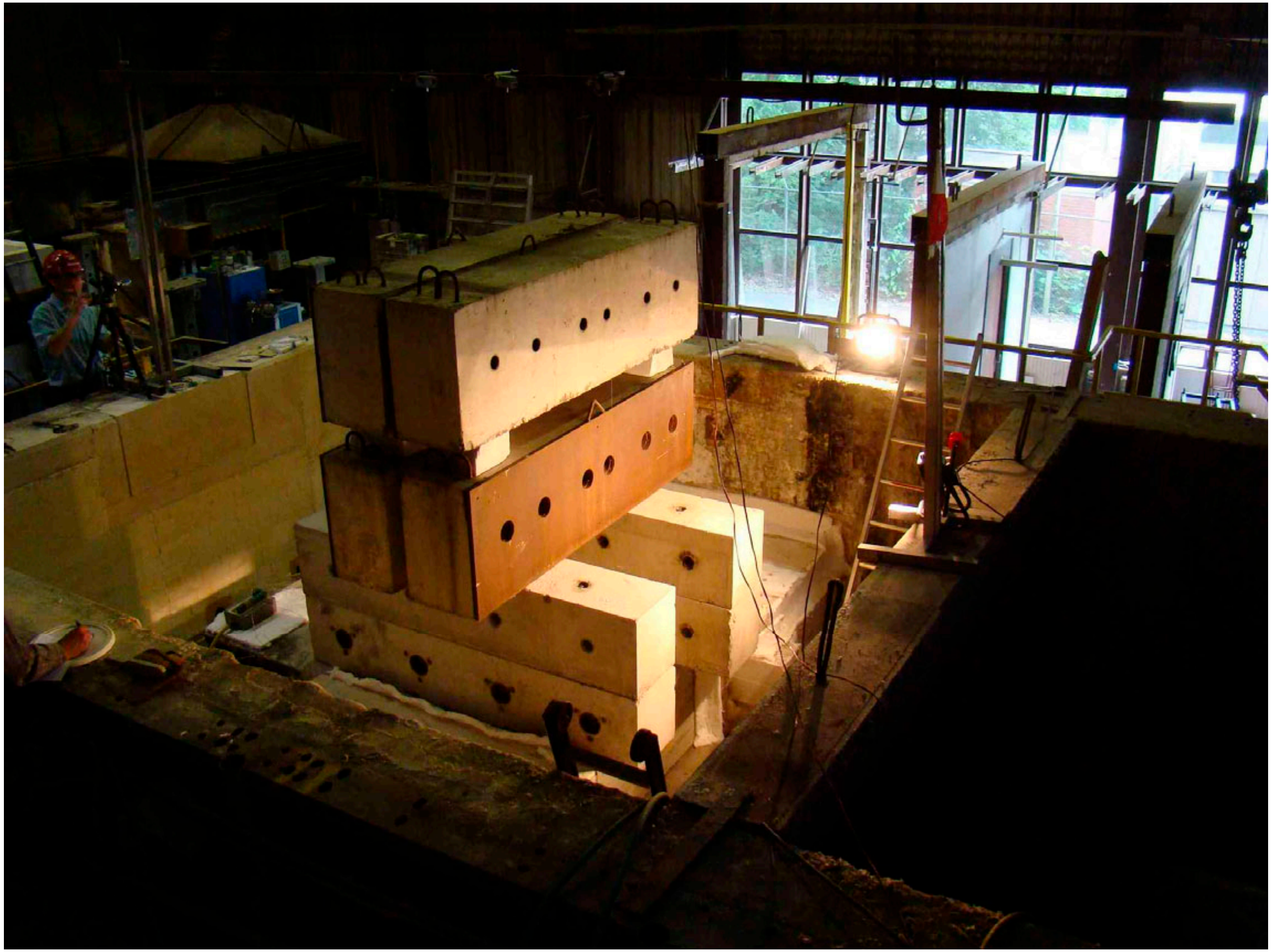

Figure E9 Element 6 before the fire test

Figure E10 Element 6 after 28 minutes of heating

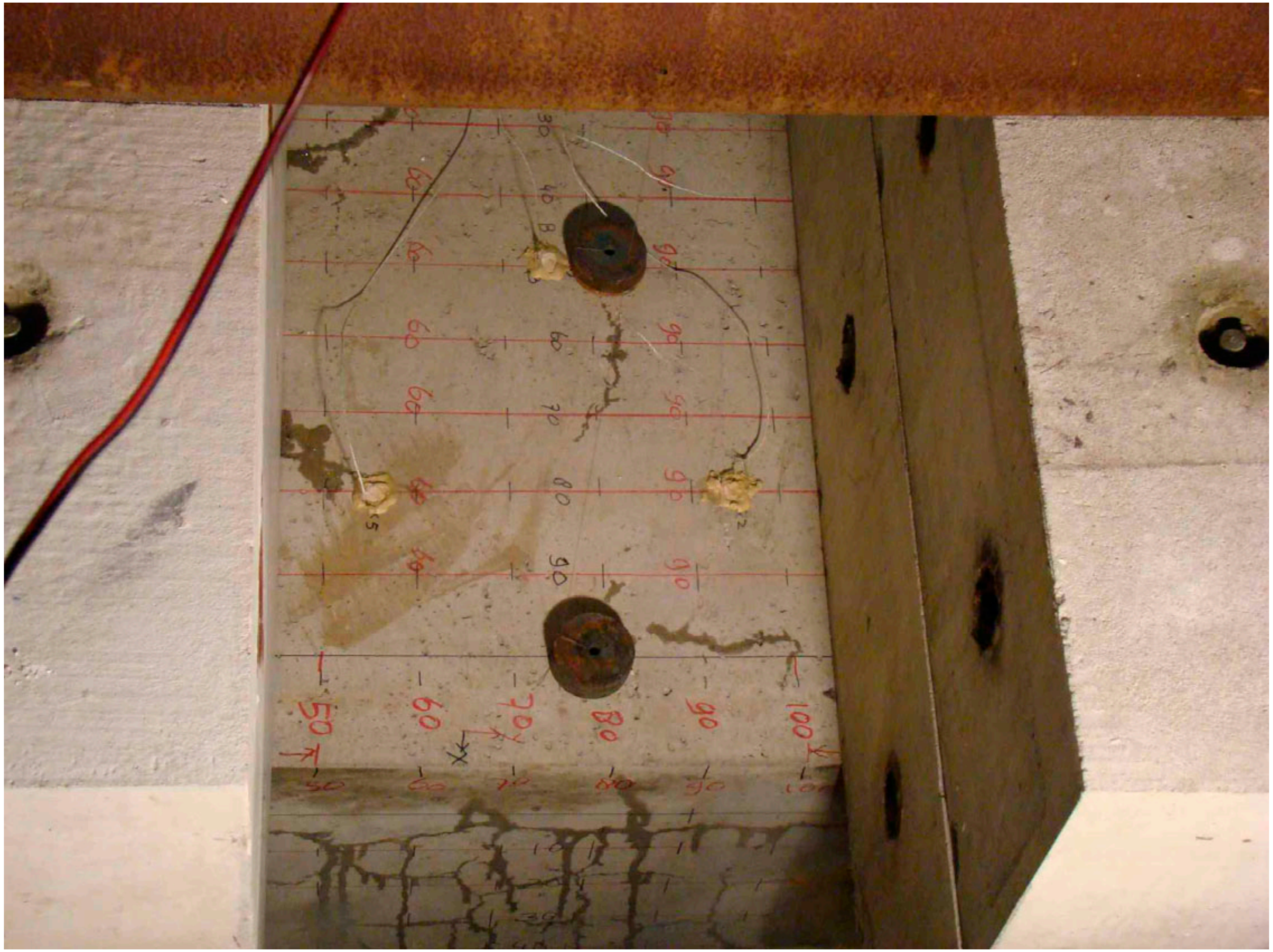

Figure E10 Element 6 after 61 minutes of heating

Figure E11 Element 6 after 78 minutes of heating

F Test results element 2

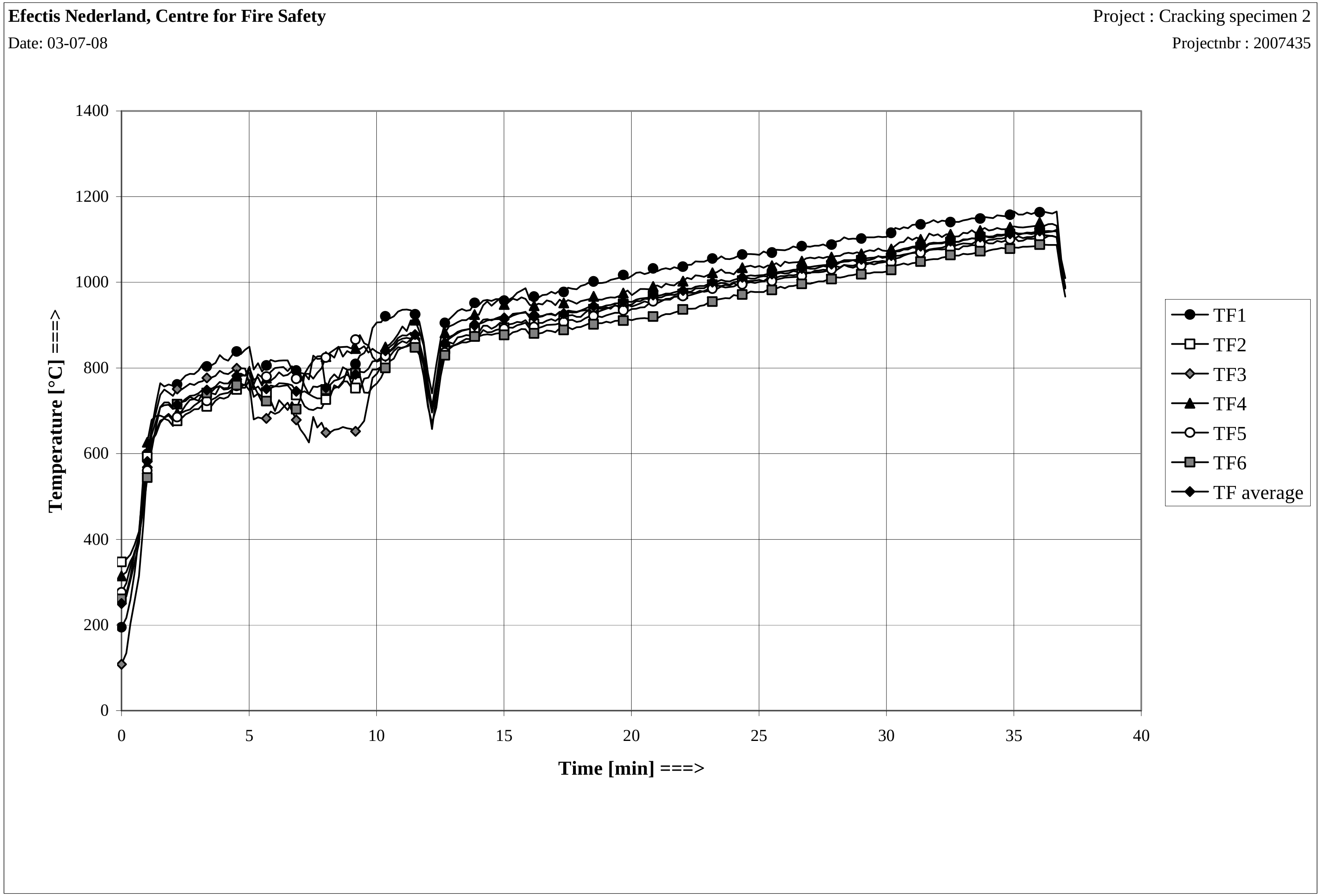

Figure F1 Furnace temperatures

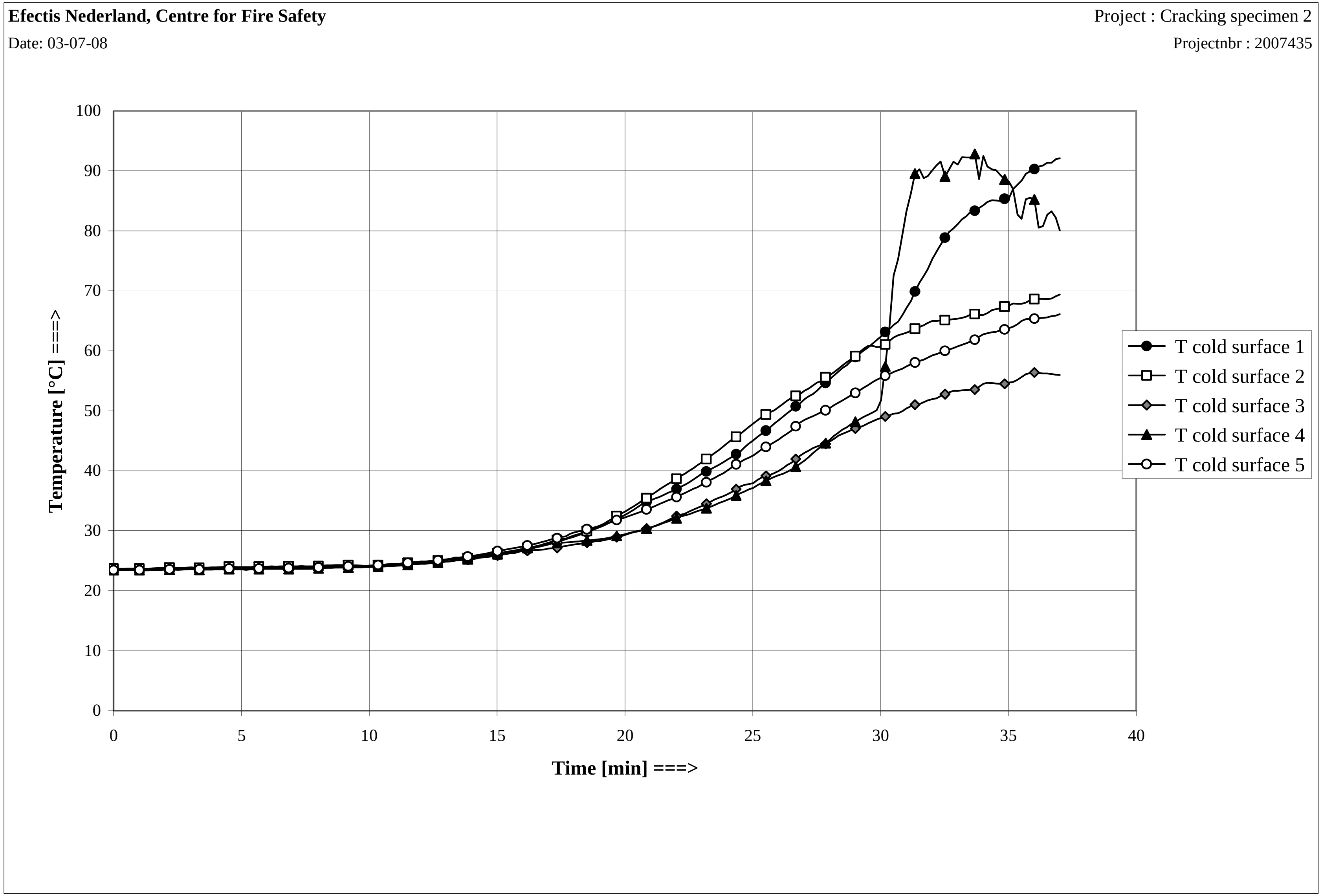

Figure F2 Cold face temperatures

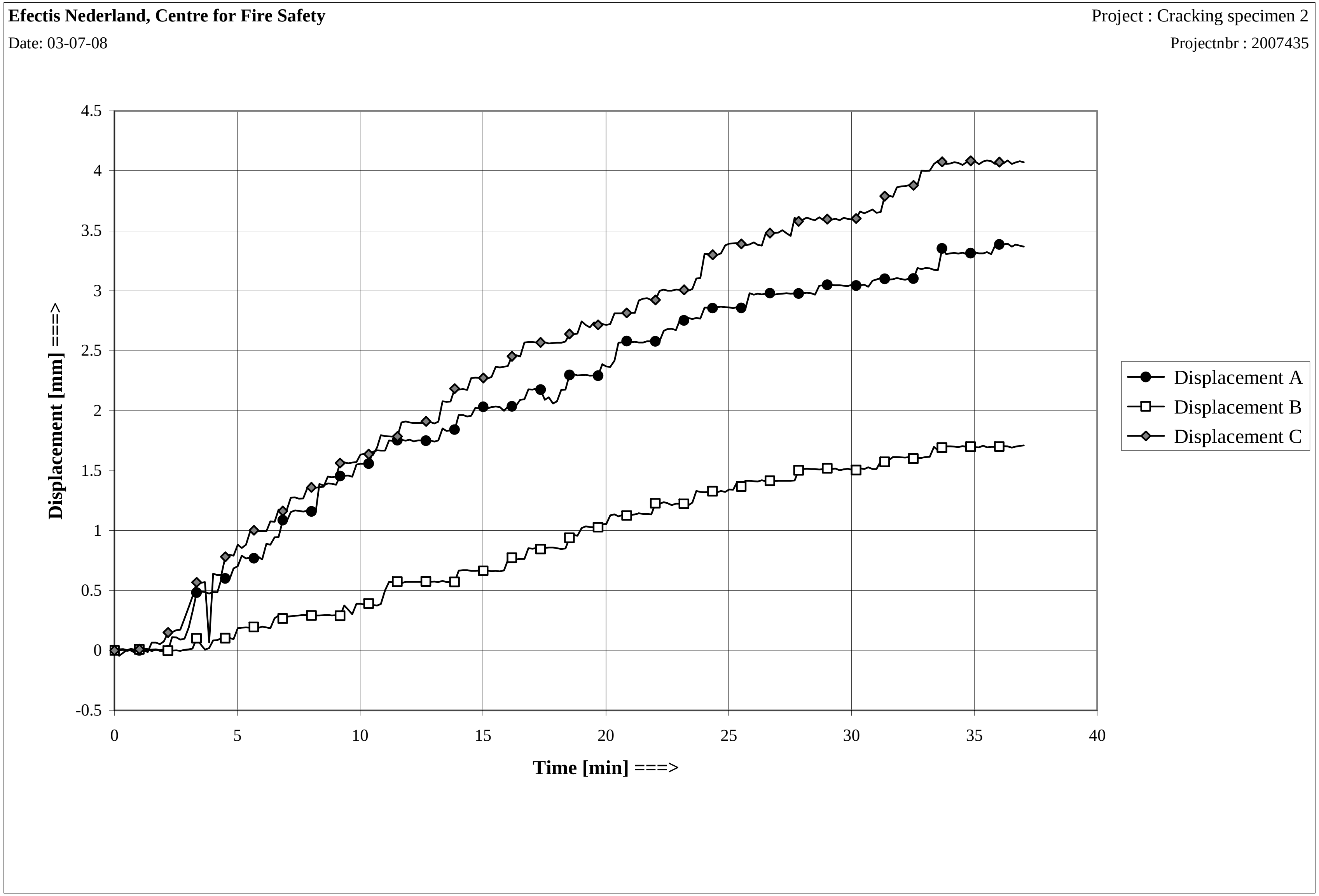

Figure F3 Displacement of the cold surface

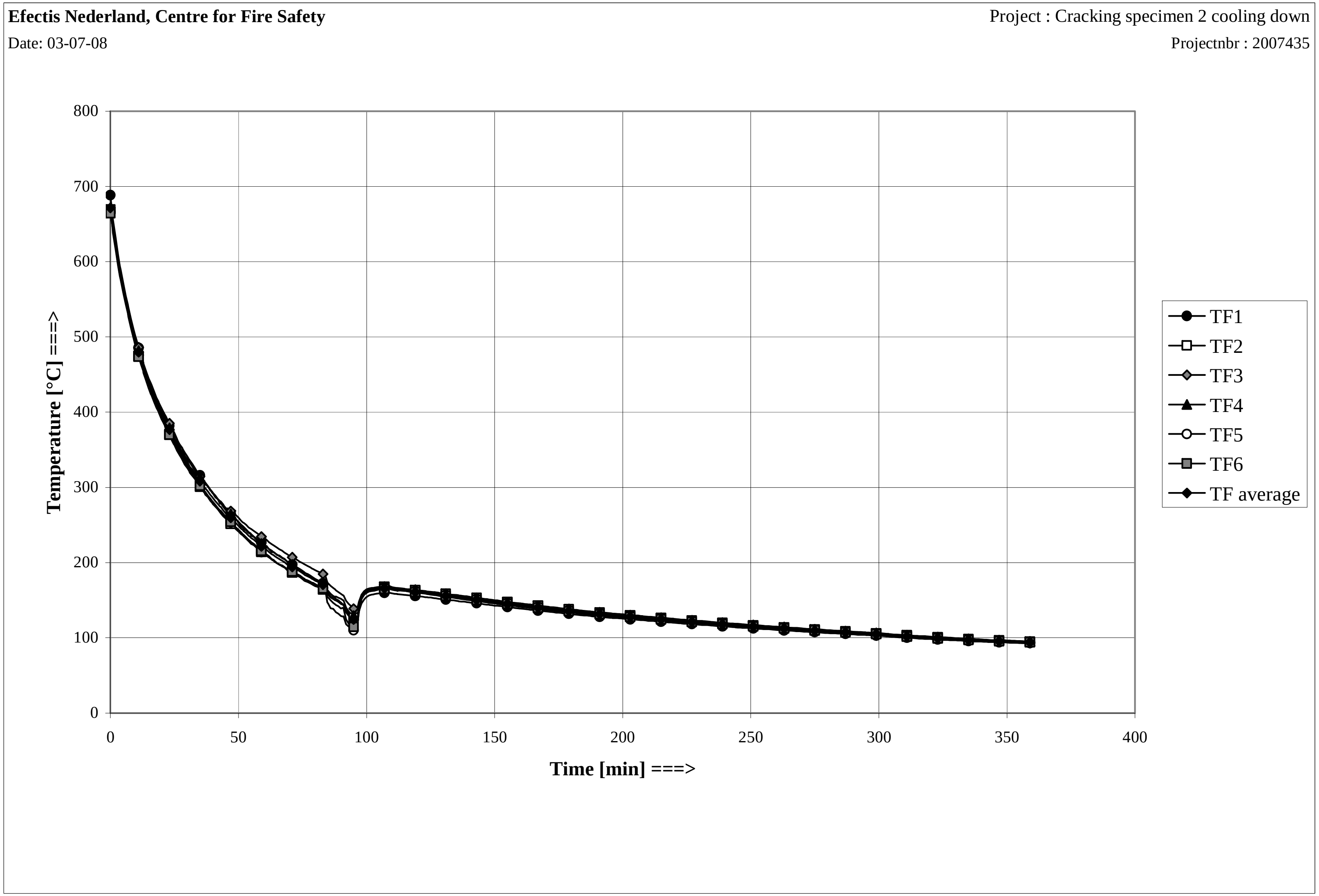

Figure F4 Furnace temperature during cooling down

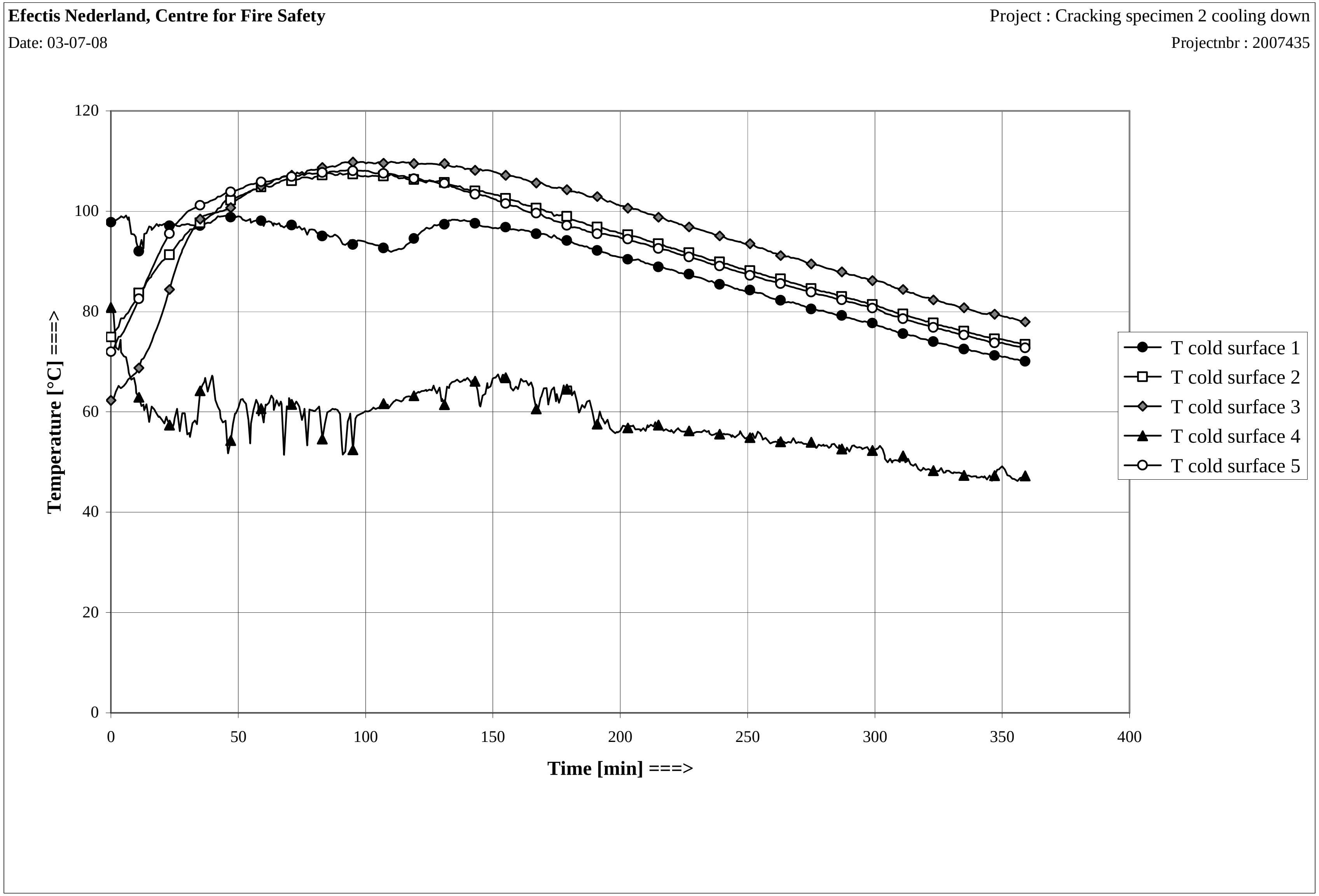

Figure F5 Cold face temperatures during cooling down

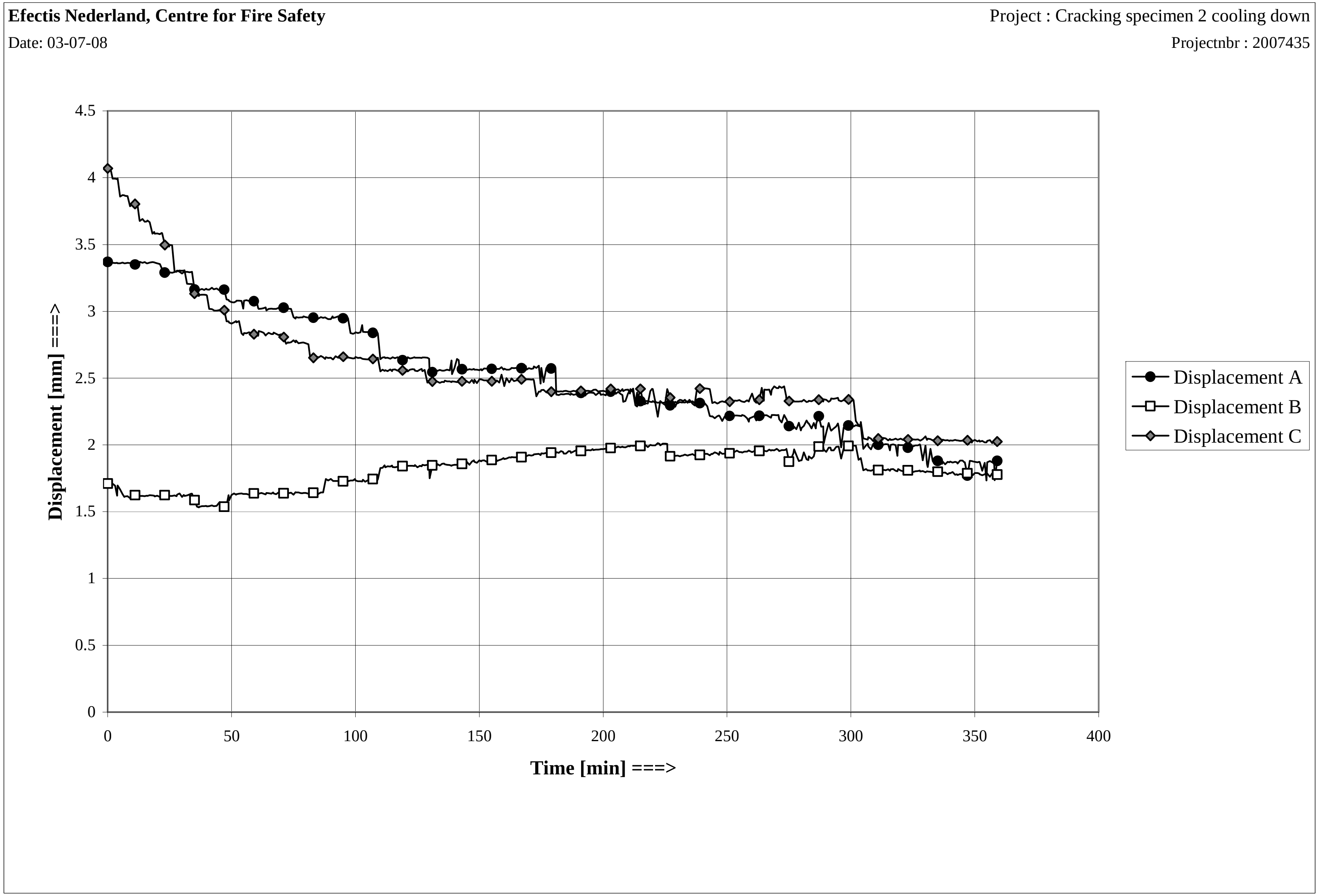

Figure F6 Displacements cold surface during cooling down

Figure F7 Element 2 before the fire test

Figure F8 Element 2 after 9 minutes of heating

Figure F9 Element 2 after 20 minutes of heating

Figure F10 Element 2, 8 minutes after the fire test. The cracking pattern is clearly visible

G Test results element 9

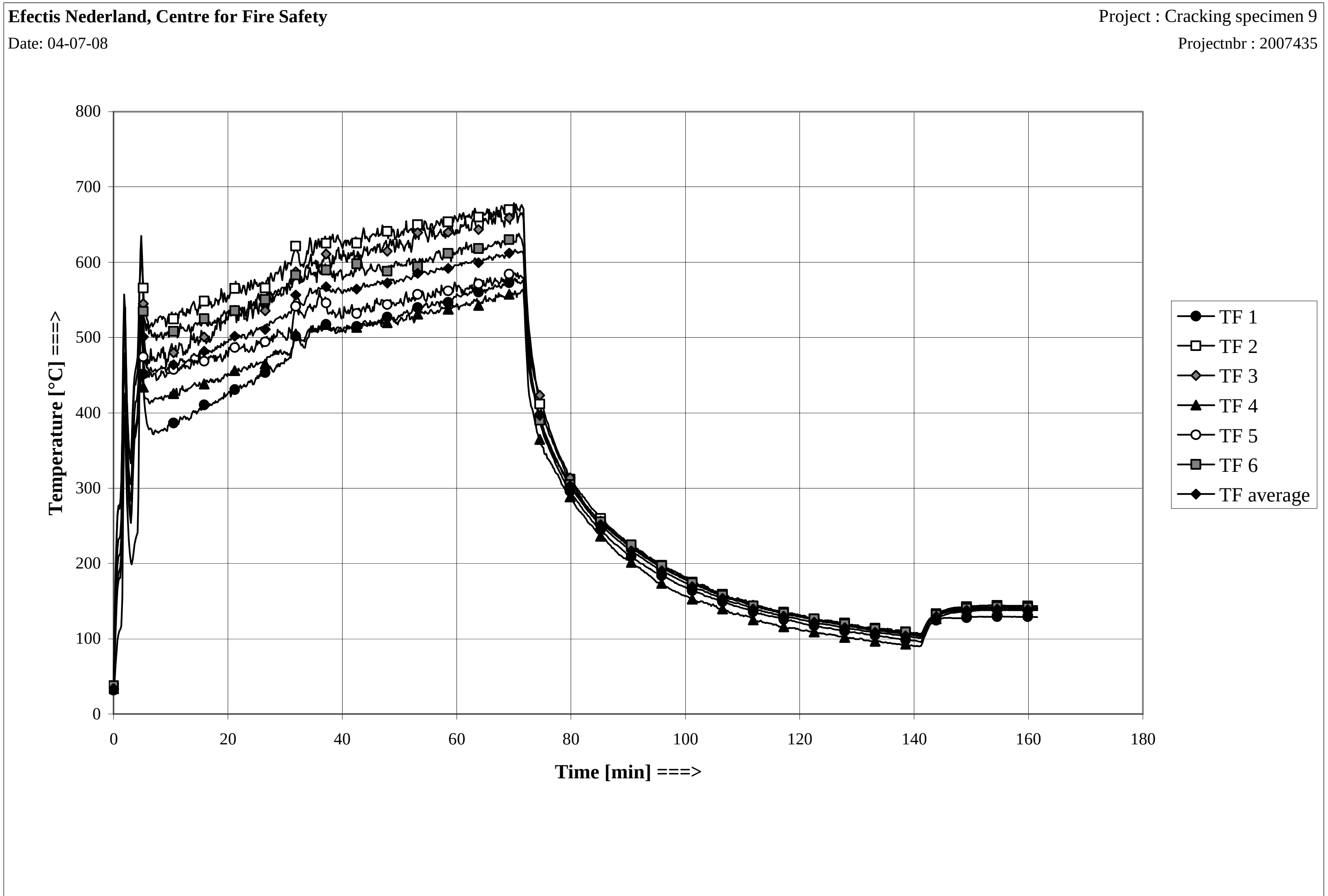

Figure G1 Furnace temperatures

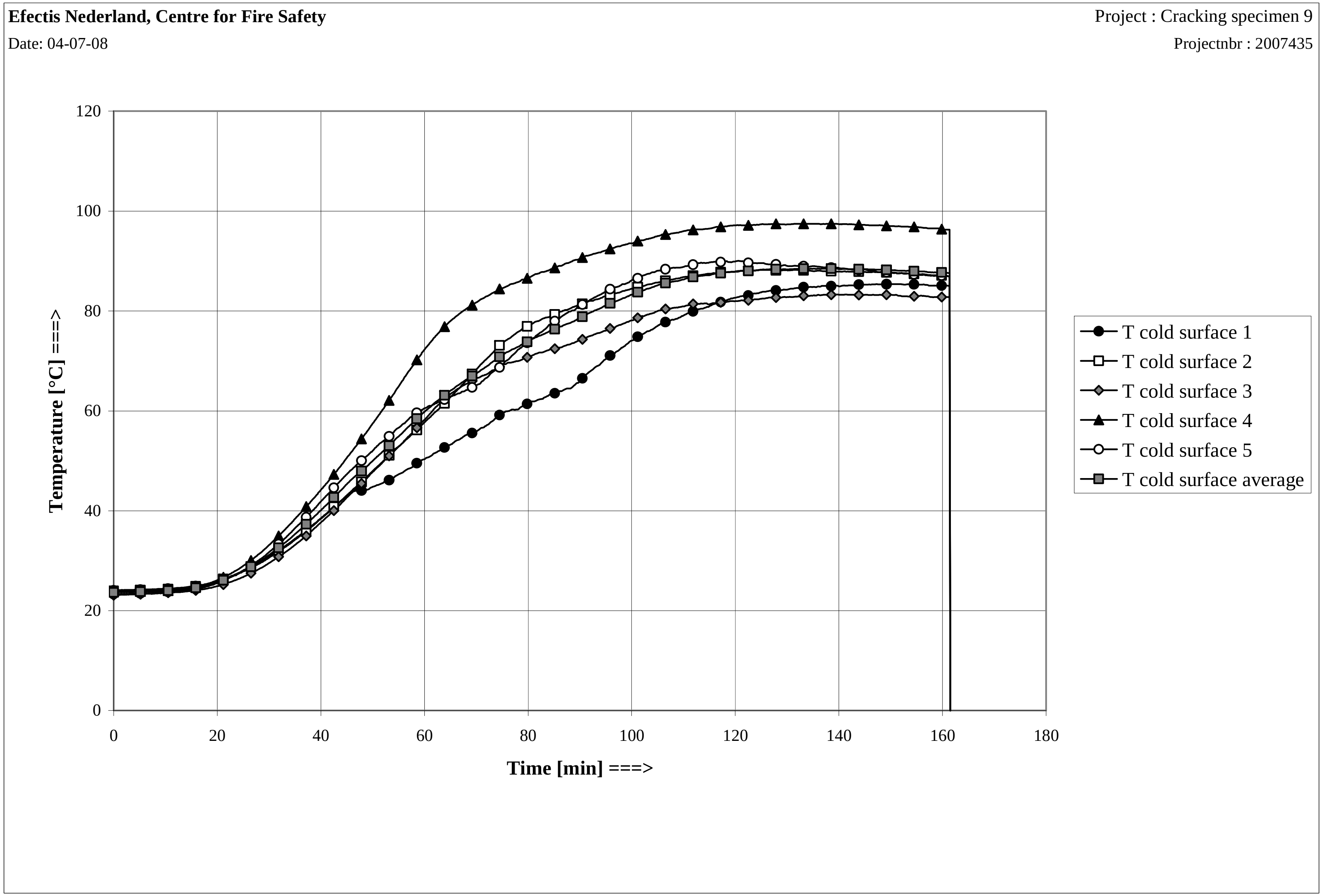

Figure G2 Cold face temperatures

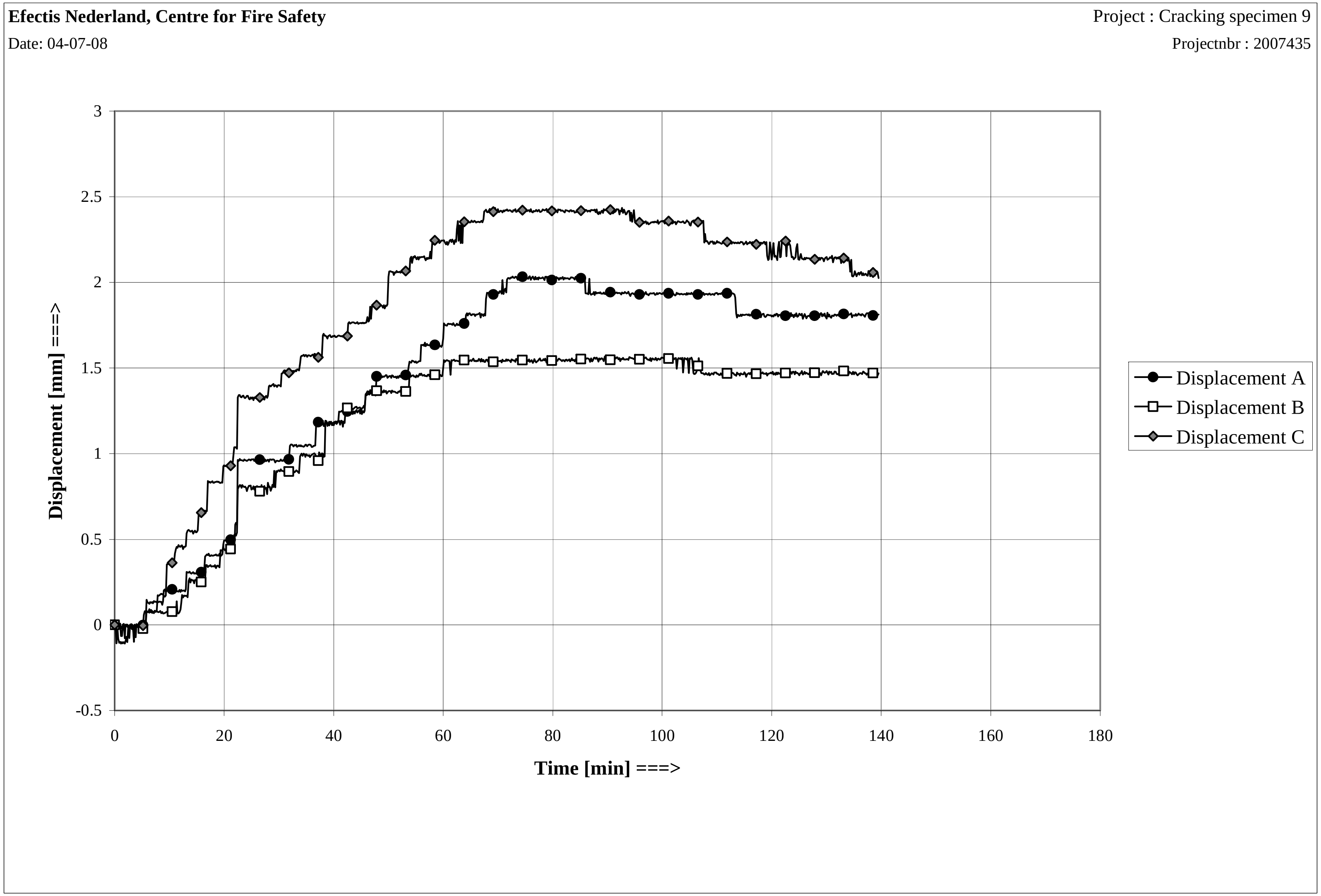

Figure G3 Displacement cold surface

Figure G4 Element 9 before the fire test

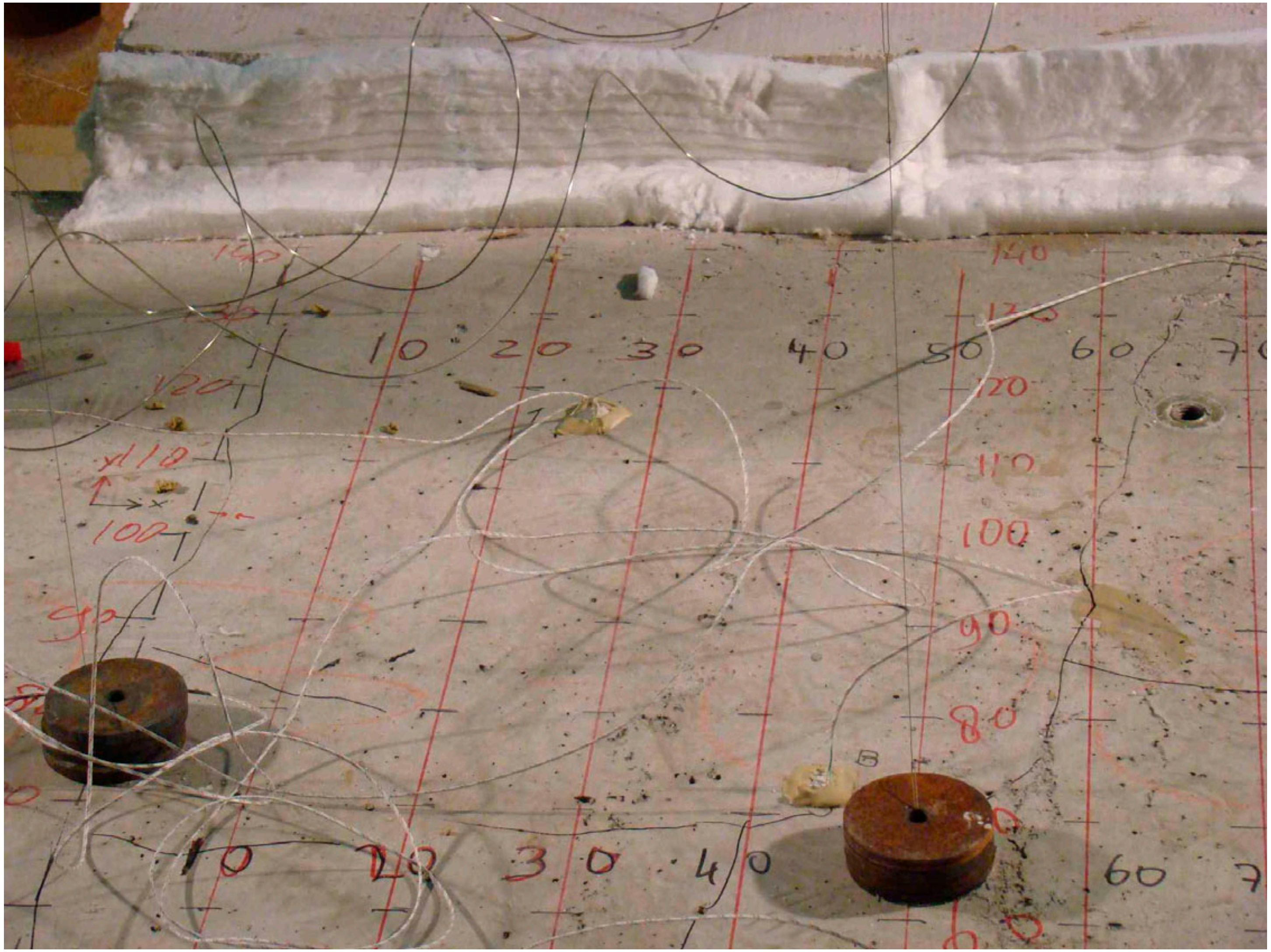

Figure G5 Element 9 after 14 minutes of heating, upper left corner

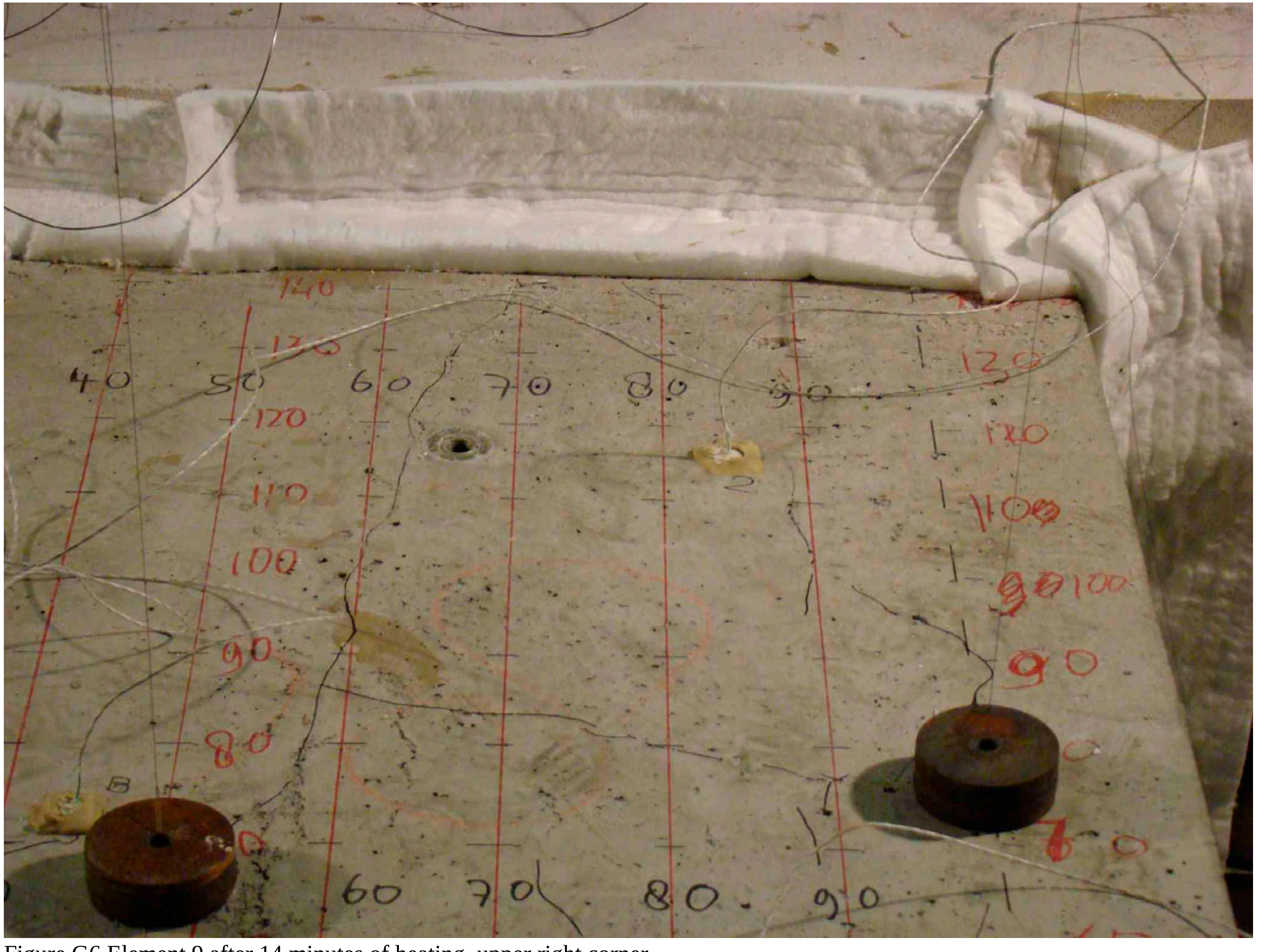

Figure G6 Element 9 after 14 minutes of heating, upper right corner

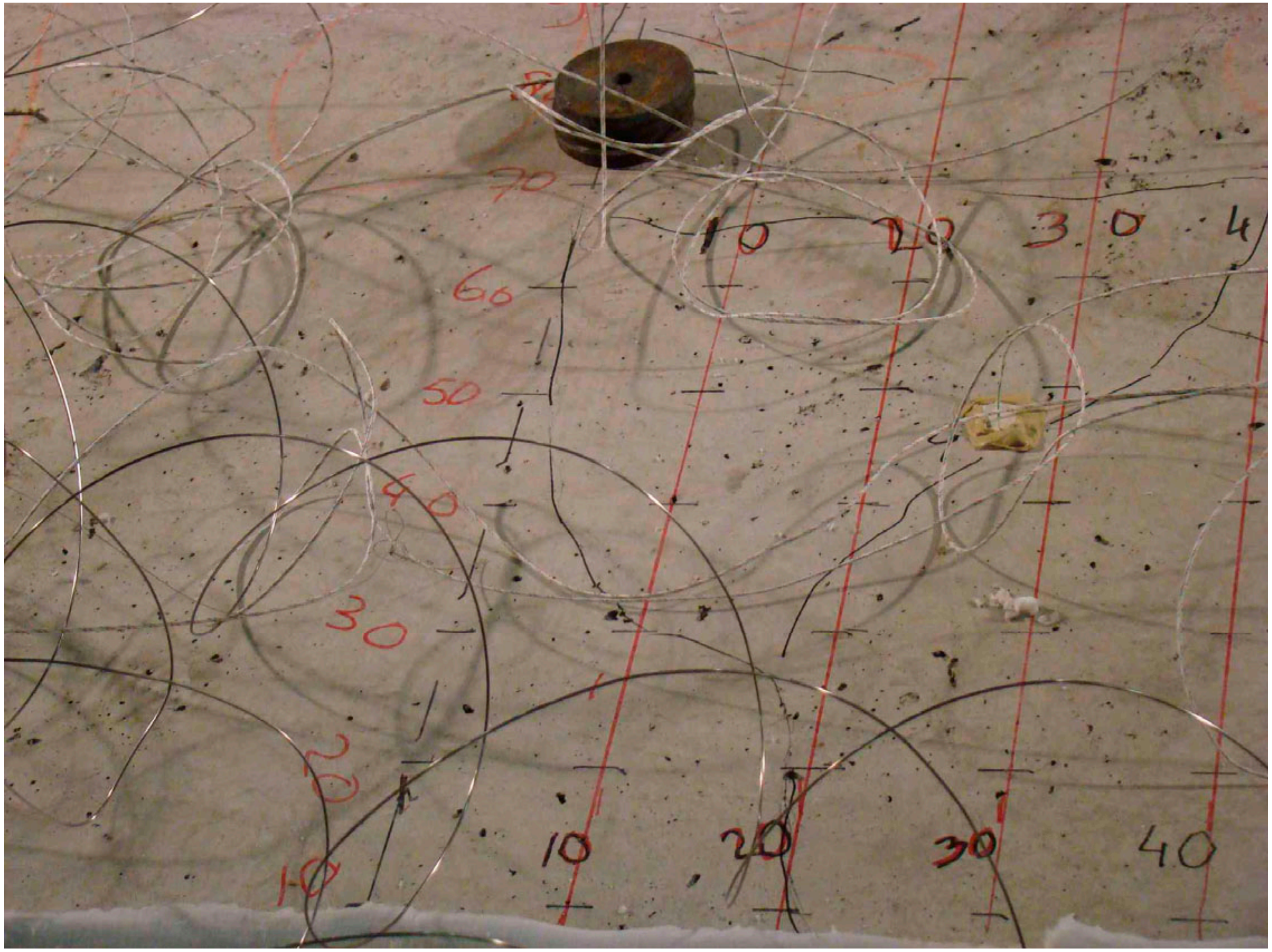

Figure G7 Element 9 after 14 minutes of heating, lower left corner

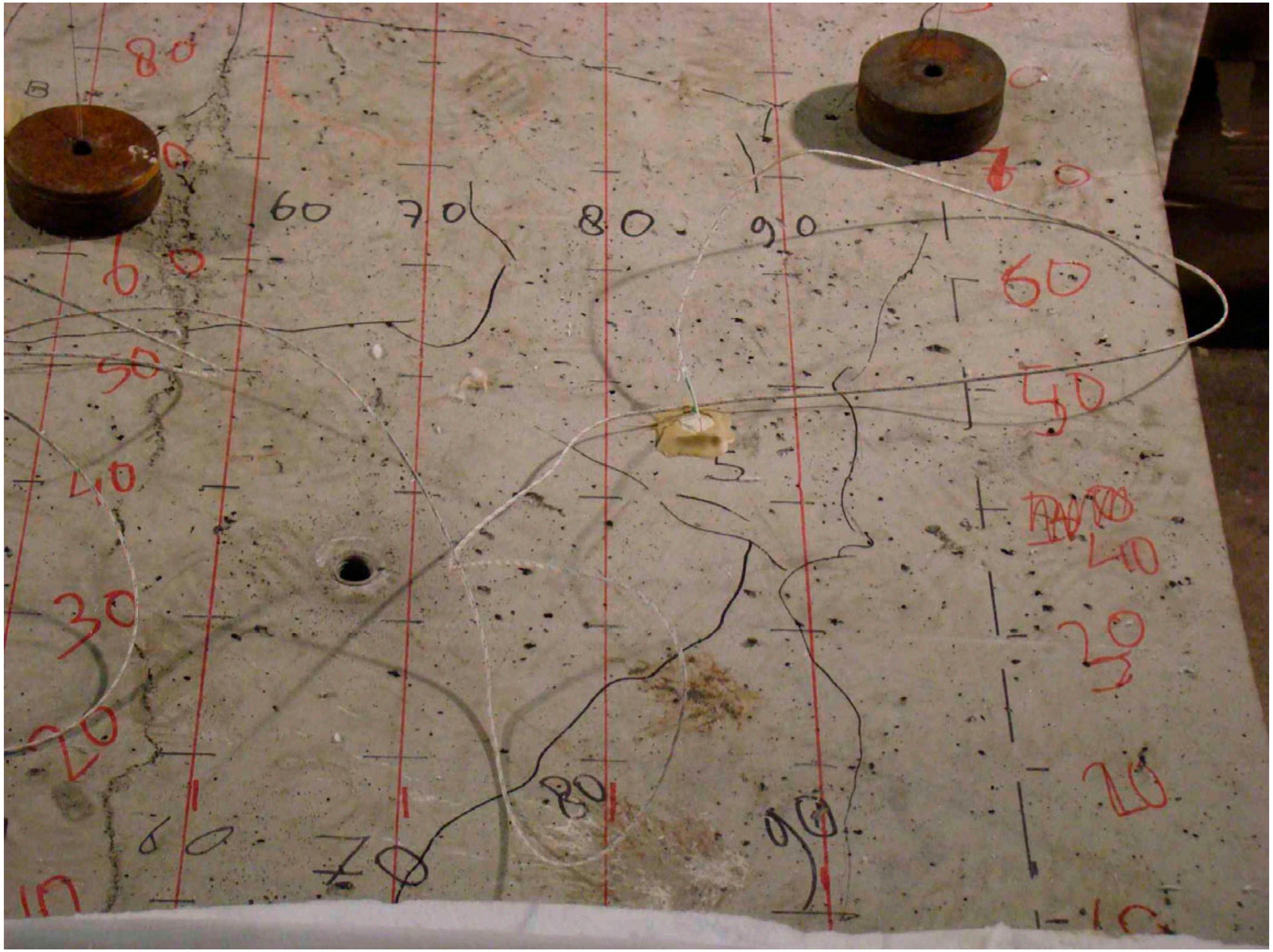

Figure G8 Element 9 after 14 minutes of heating, lower right corner

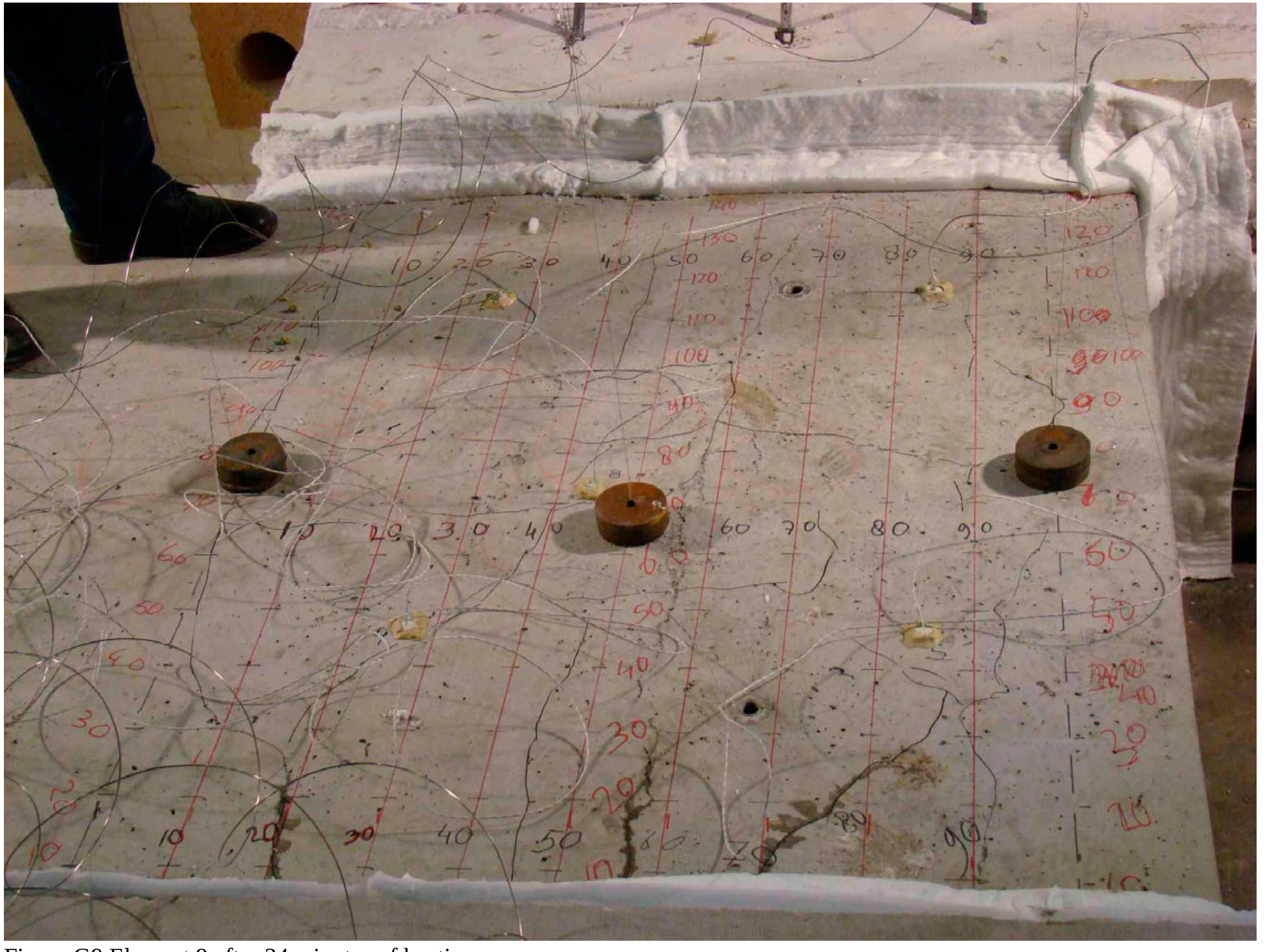

Figure G9 Element 9 after 24 minutes of heating

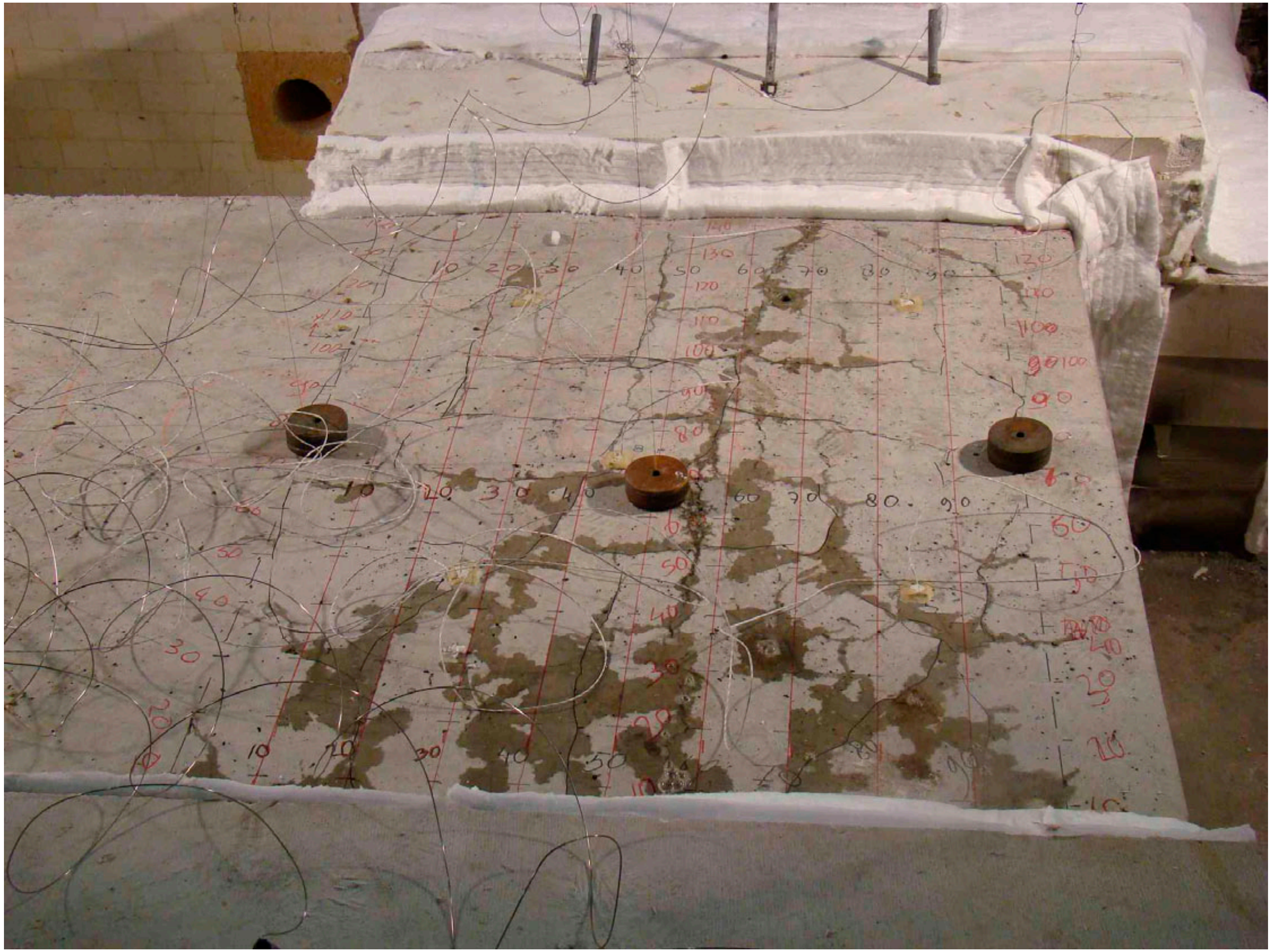

Figure G10 Element 9 after 45 minutes of heating

Figure G11 Element 9 after 48 minutes of heating

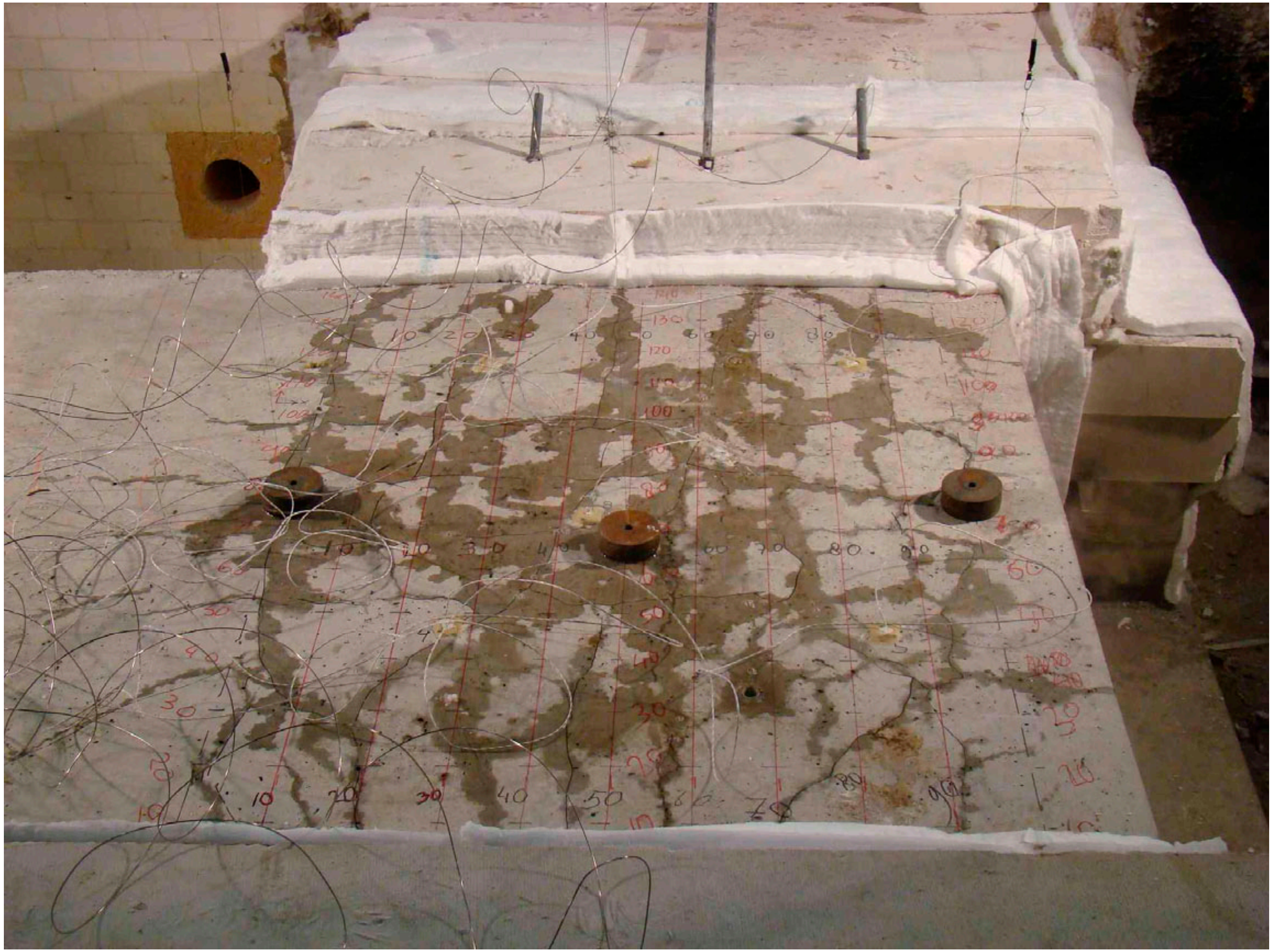

Figure G12 Element 9 directly after the fire test

H Test results element 5

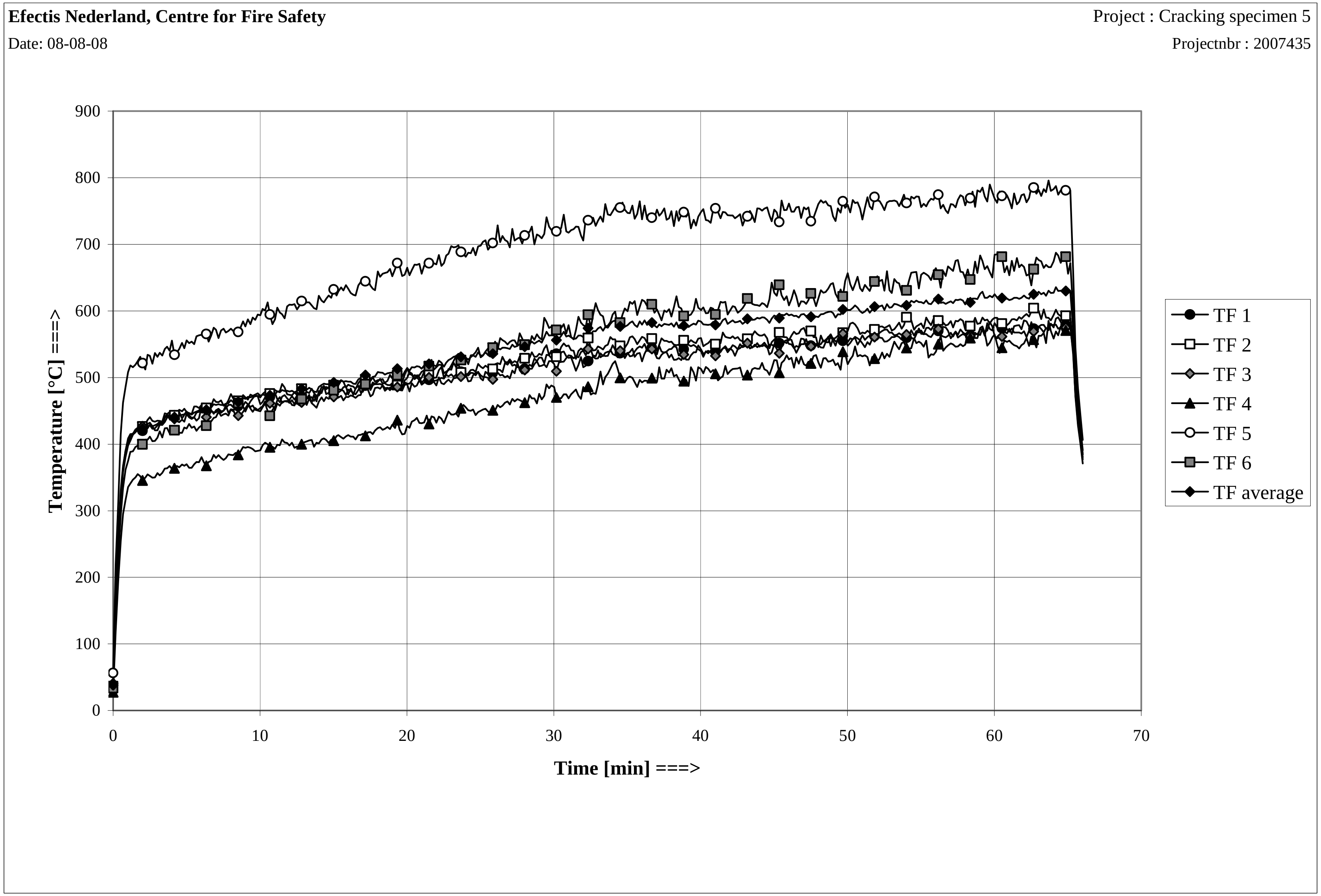

Figure H1 Furnace temperatures

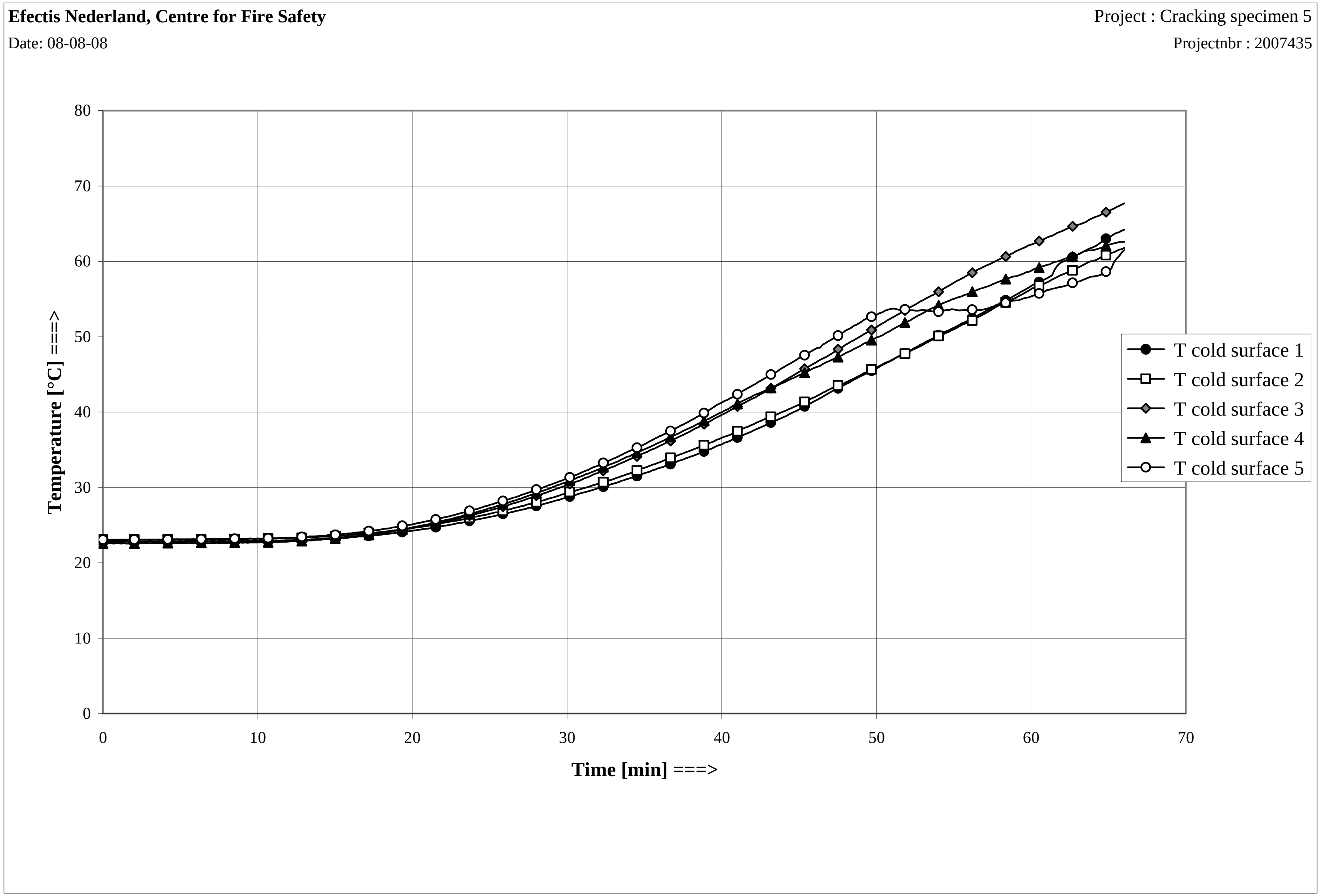

Figure H2 Cold face temperatures

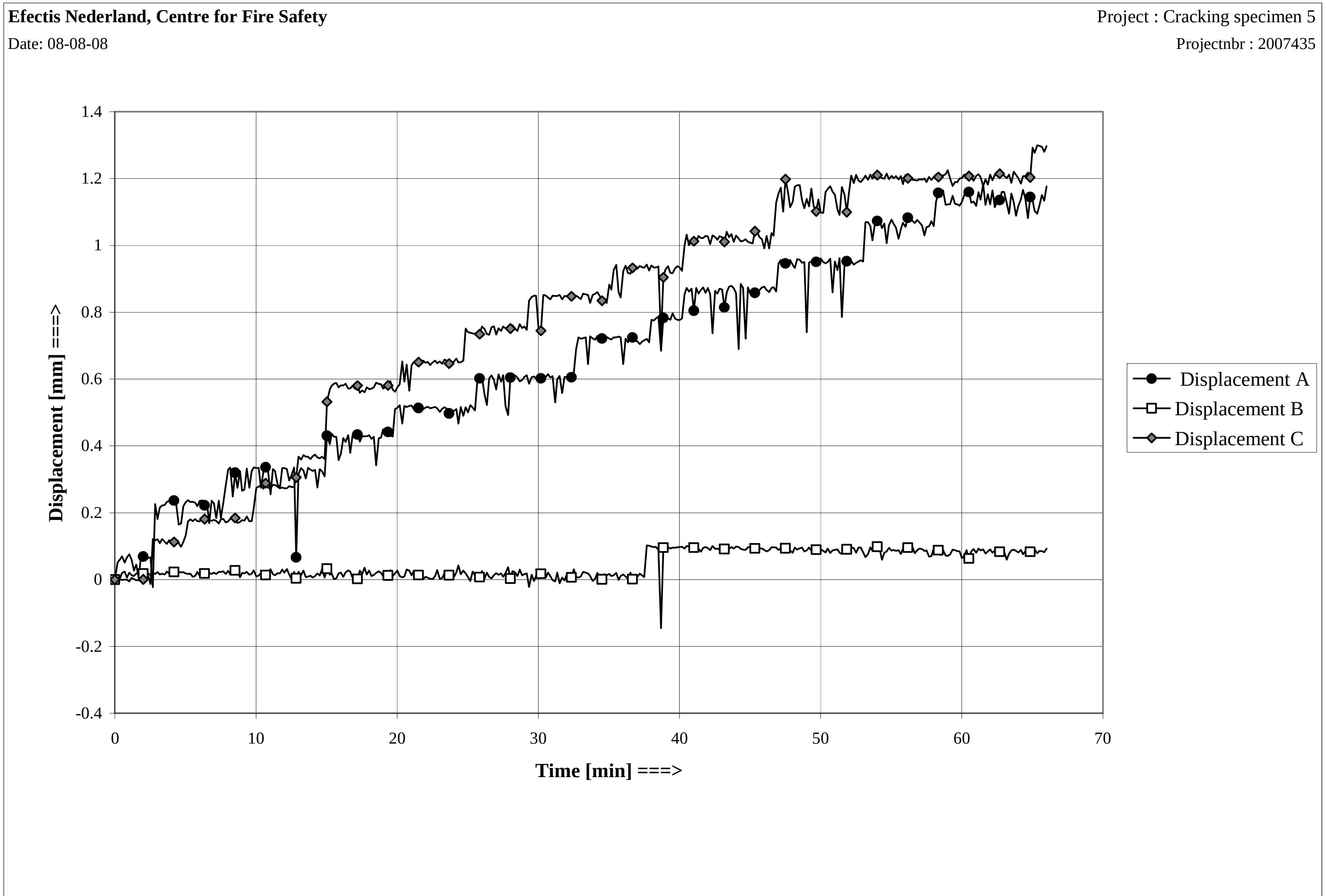

Figure H3 Displacement cold surface

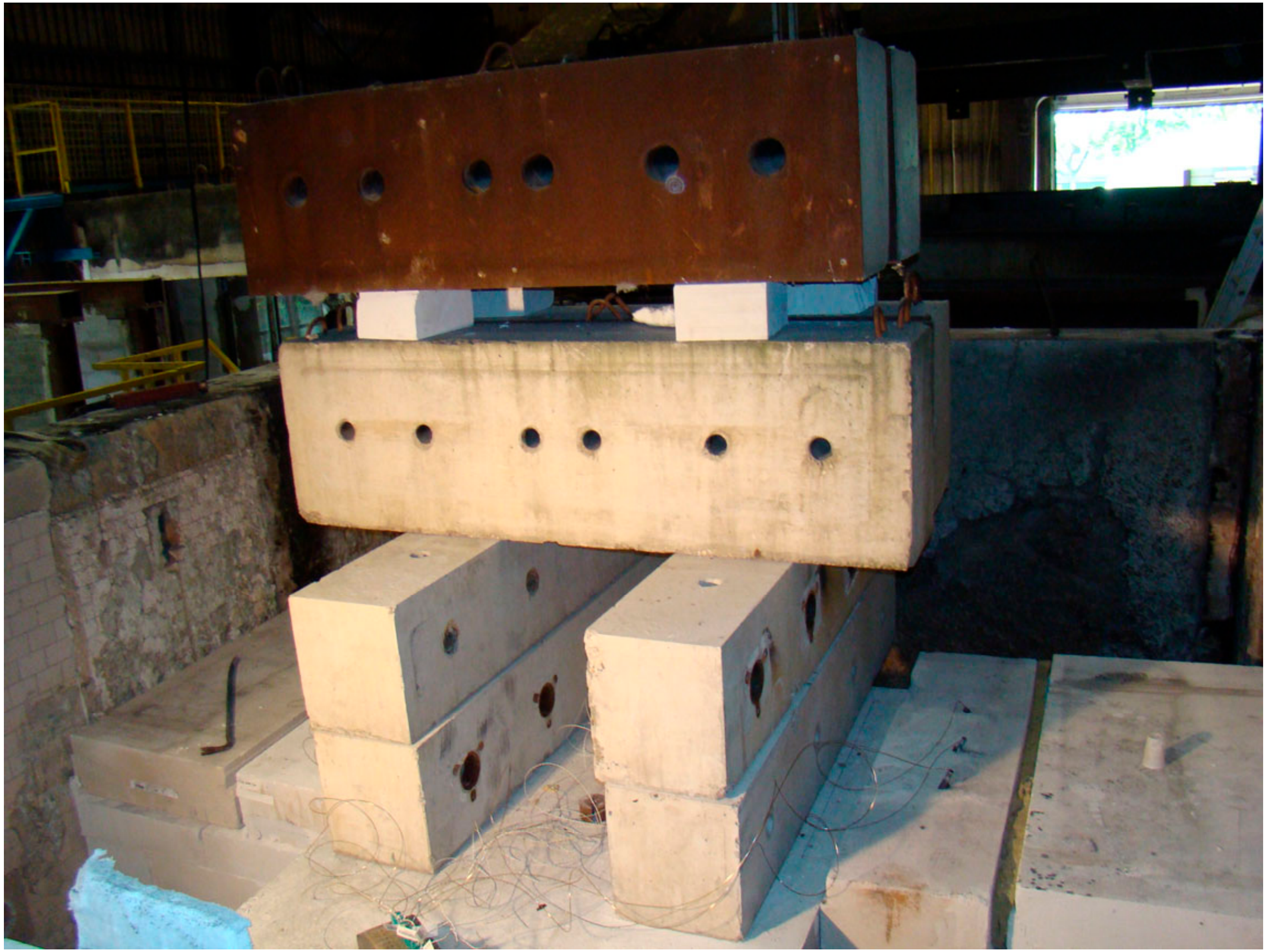
Figure H4 Element 5 before the fire test

Figure H5 Element 5 after approximately 40 minutes of heating. Detail photograph of the region X = 75-100, Y = 90-105

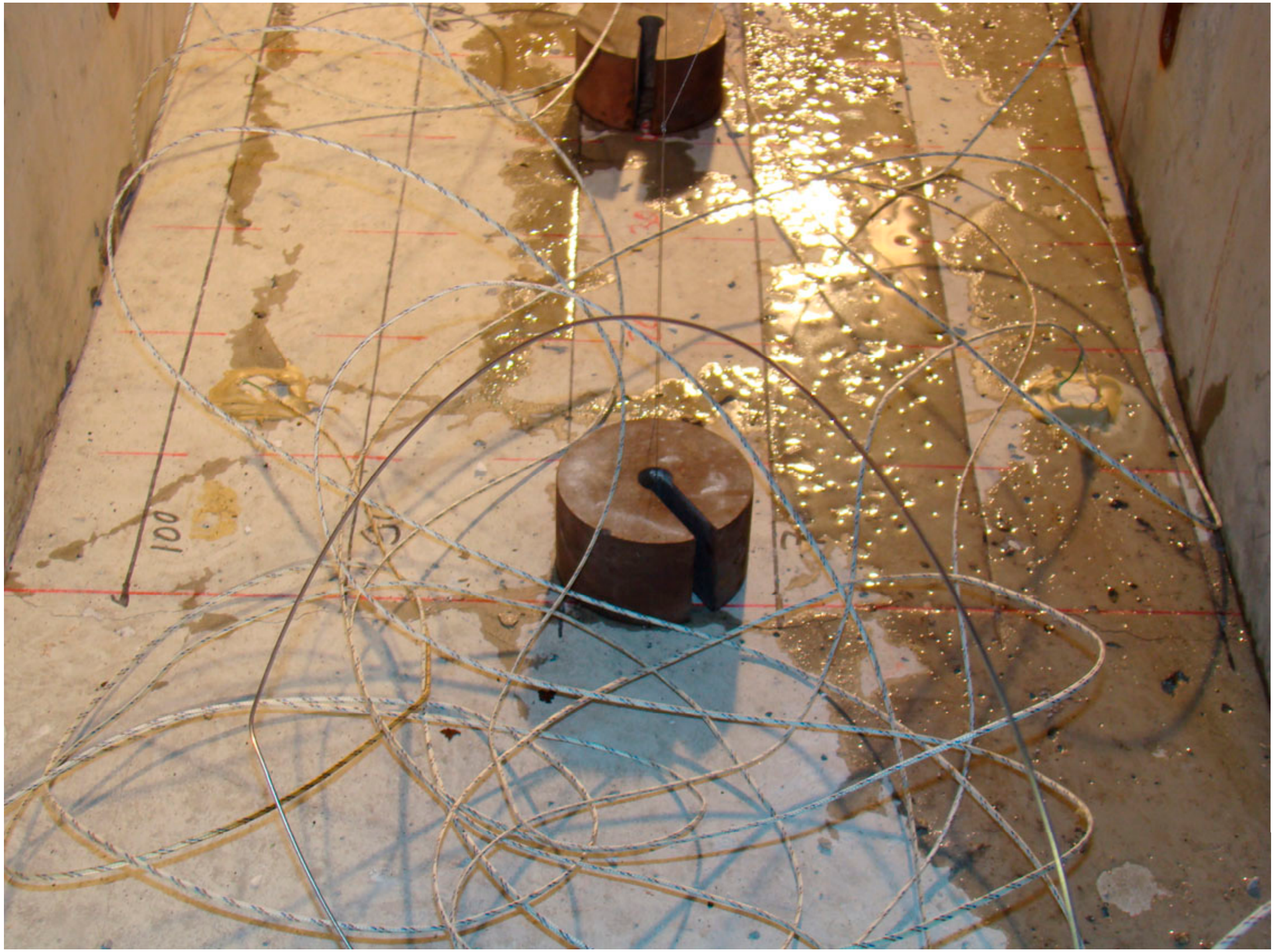

Figure H6 Element 5 after approximately 47 minutes of heating.

I Test results element 7

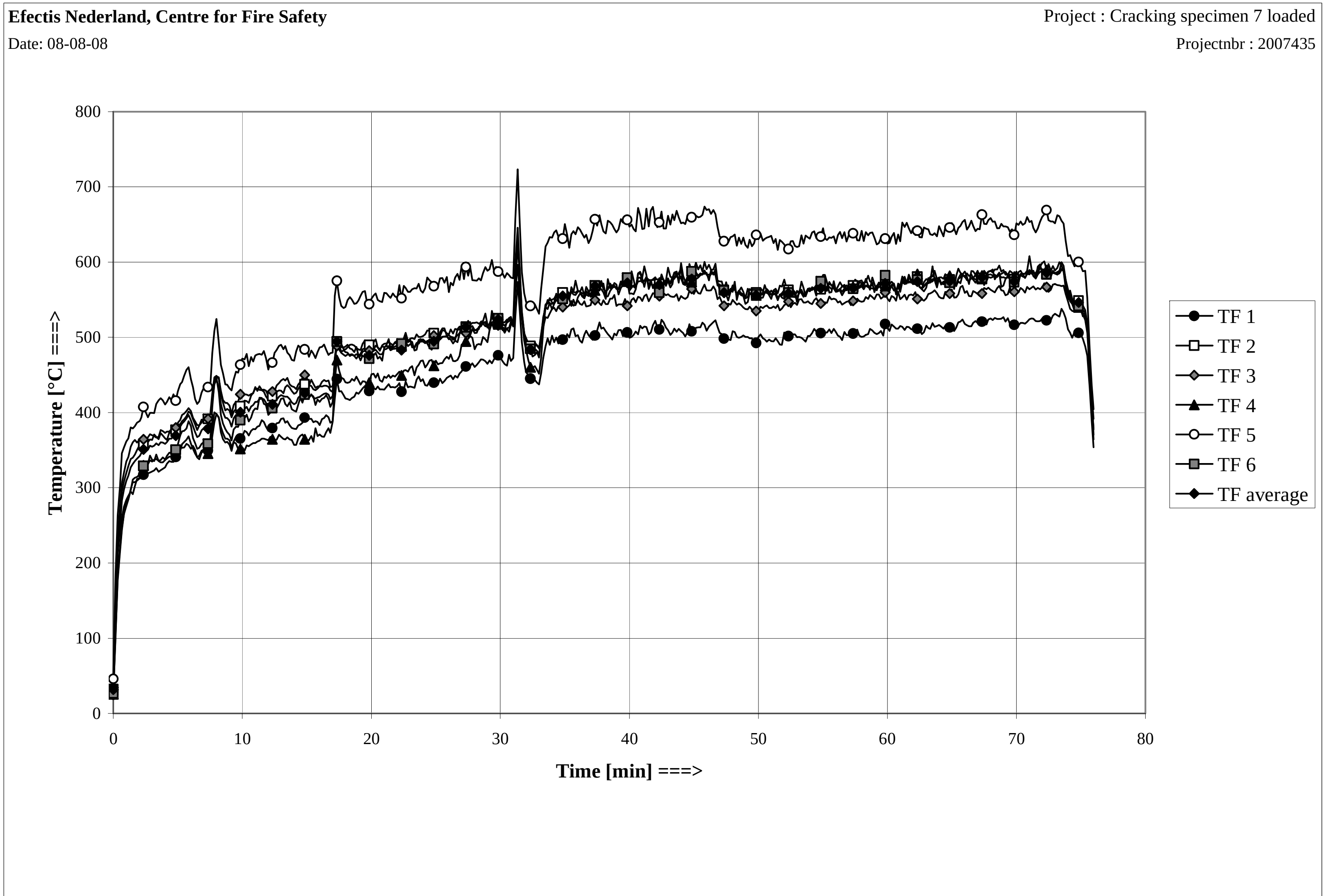

Figure I1 Furnace temperatures

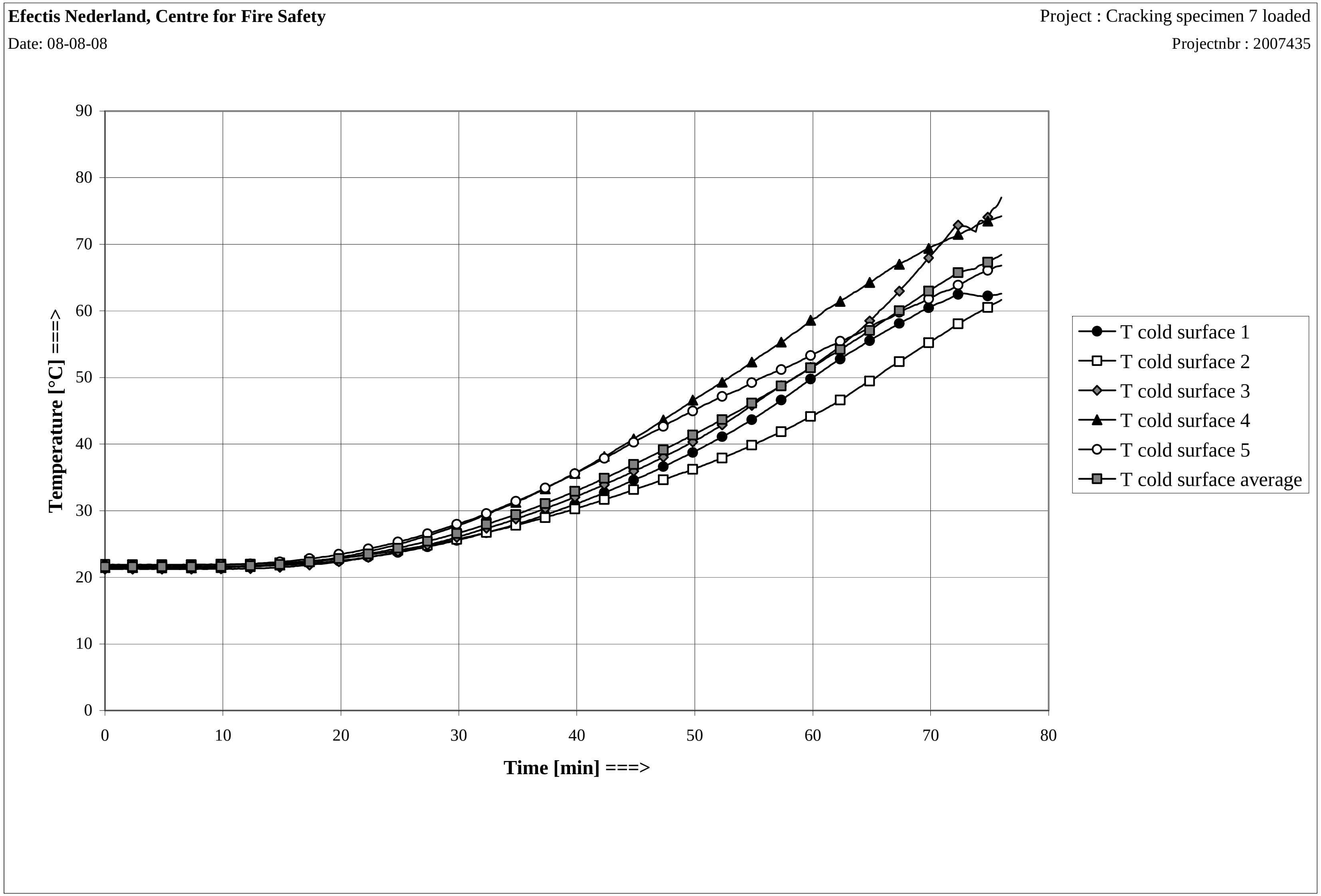

Figure I2 Cold surface temperatures

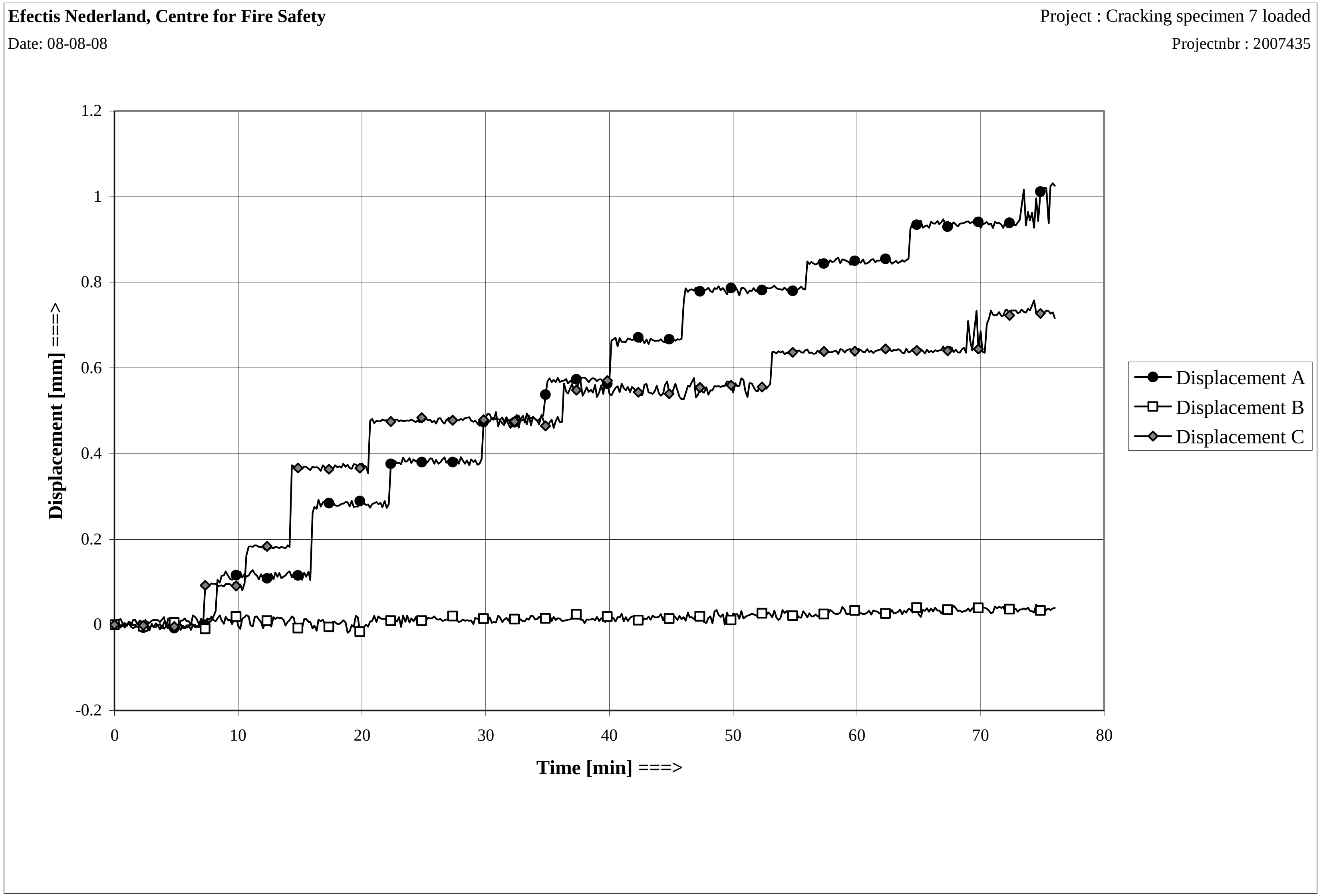

Figure I3 Displacement cold surface

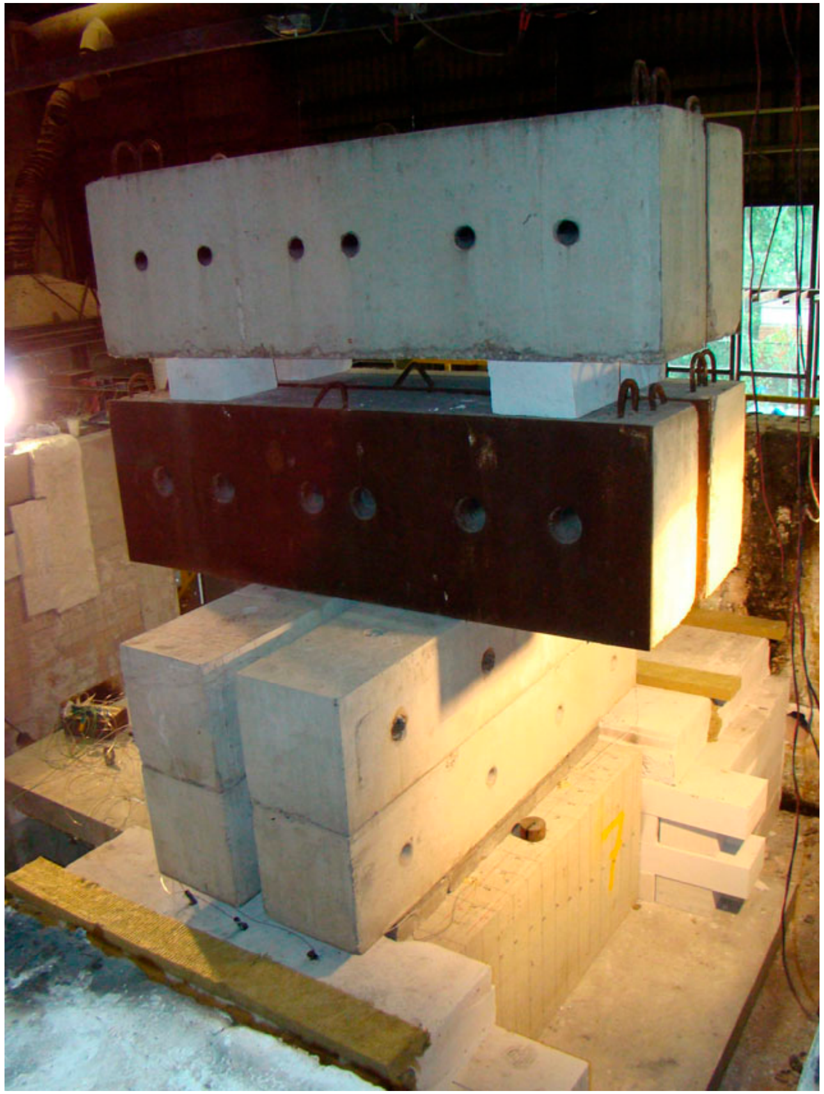

Figure I4 Element 7 before the fire test

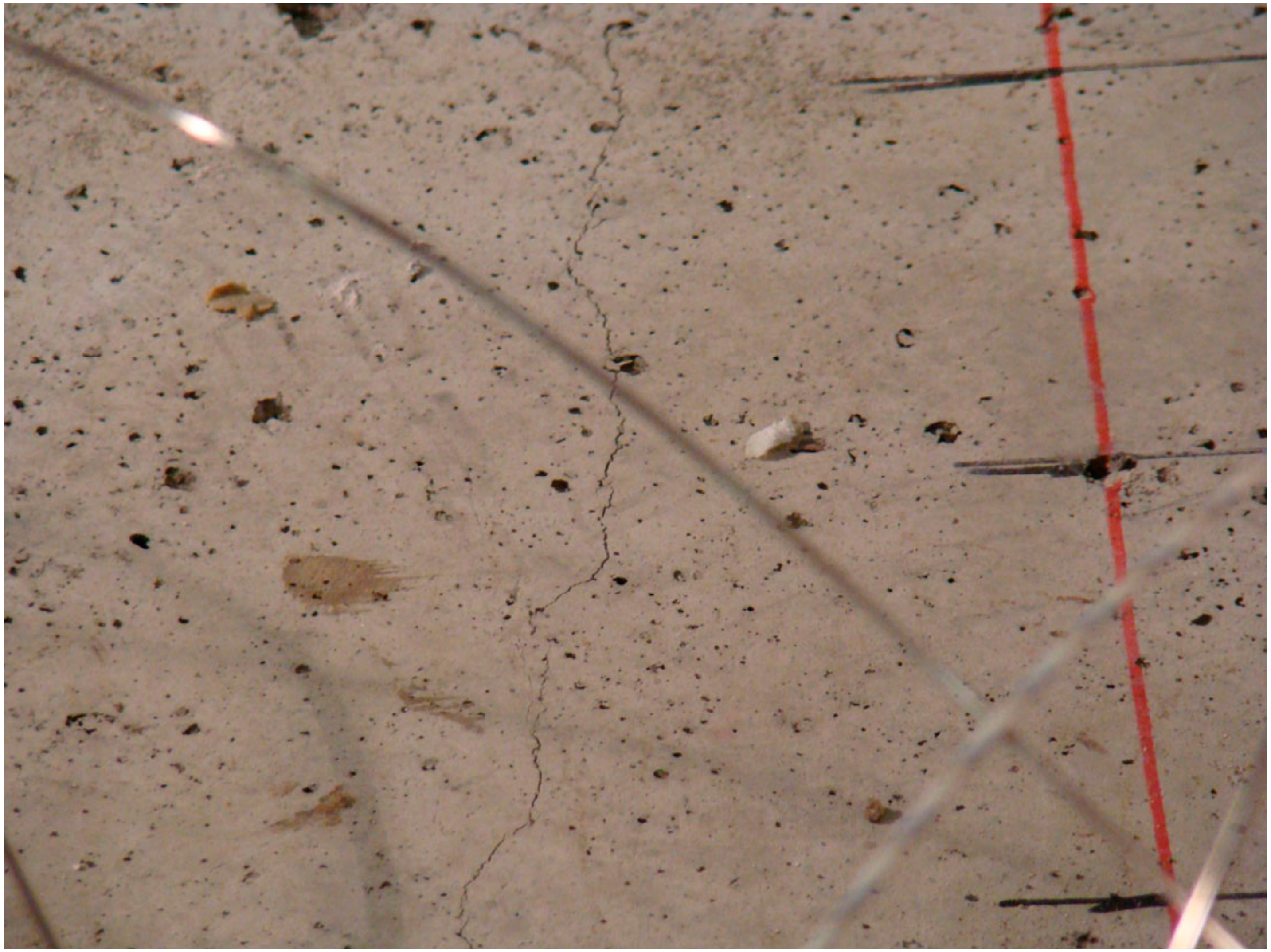

Figure I5 Element 7 after 14 minutes of heating, detail of the crack above the middle wall

Figure I6 Element 7 after 35 minutes of heating, a view on the side surface

Figure I7 Element 7 after 50 minutes of heating, a view on the middle wall

Figure I8 Element 7 after 75 minutes of heating