Our Ref: C128533
28th August 2003

Mr James Lawson
Carboline UK
Telford House
Hamilton Close
Basingstoke
Hampshire
RG21 6YT

Dear Mr Lawson

Please find enclosed Assessment of Performance Report referenced C128533, entitled

"The Fire Resistance Performance of Steel I-Shaped Sections Protected with a Cementitious Based Coating Known as Pyrocrete 40"

If you require any further information or clarification, please do not hesitate to contact the undersigned.

Yours sincerely

P.W. Crewe
For and on behalf of
WARRINGTON FIRE RESEARCH CENTRE

WFRC Report No. 128533: The Fire Resistance Performance of Steel I-Shaped Sections Protected with a Cementitious Based Coating Known as Pyrocrete 40

Report for

Carboline UK
Telford House
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1 Introduction

This report presents an assessment of the ability of a cementitious coating known as Pyrocrete 40 to fire protect structural steel sections when exposed to heating conditions meant to simulate fires burning hydrocarbon fuels.

The data which forms the basis of this assessment was obtained from tests in accordance BS 476: Part 21: 1987 on loaded steel beams, an unloaded tall column and short sections which were subjected to the heating conditions as similar to those specified in Appendix D of this standard.

This assessment relates to I-shaped steel sections protected with Pyrocrete 40 for periods of fire resistance of up to 240 minutes and for critical steel temperatures derived from tests on fully loaded sections and accepted principles.

The data referred to in Sections 9 and 10 has been considered for the purpose of this assessment which has been prepared in accordance with the general principles of the Fire Test Group Resolution No. 82: 2001.

2 Assumptions

It is assumed that the protection material will be applied to the steel sections in a similar manner to that used for the tested sections referred to in this report.

It is assumed that the loading applied to the sections will be calculated on the same basis as the sections subjected to the loaded tests, i.e. the load will not exceed the maximum permissible design load for the steel grade in accordance with BS449: Part 2: 1969.

3 Basic Test Data

The supporting fire test evidence is provided by the test reports which are referenced in Section 9 of this report.

WFRC Test report - WARRES No. 126669
Report on a fire resistance test in accordance with BS 476: Part 21: 1987, Clause 5, utilising the heating conditions specified in Appendix D of BS 476: Part 20: 1987 (hydrocarbon heating).

The test was performed on a specimen of an I-shaped steel beam of serial size 406mm by 178mm by 60kg/m protected with 13mm of Pyrocrete 40. Included in the test were a number of short sections for assessment purposes, the appropriate details of which are summarised in the body of this report.

WARRES No. 126671
Report on a fire resistance test in accordance with BS 476: Part 21: 1987, Clause 5, utilising the heating conditions specified in Appendix D of BS 476: Part 20: 1987 (hydrocarbon heating).

The test was performed on a specimen of an I-shaped steel beam of serial size 406mm by 178mm by 60kg/m protected with 60mm of Pyrocrete 40. Included in the test were a number of short sections for assessment purposes, the appropriate details of which are summarised in the body of this report.

WARRES No. 126671B
Report on a fire resistance test which utilised the heating conditions specified in Appendix D of BS 476: Part 20: 1987 (hydrocarbon heating). The test was carried out on two steel sections protected with various thicknesses of Pyrocrete 40.

Underwriters Laboratories Inc
File R7209 Project 89NK4838 and 89NK12002
Reports on a fire tests to UL 1709 (hydrocarbon test conditions) on four unloaded columns (size W10x49) protected with Pyrocrete 240 (also known as Pyrocrete 40). The columns were about 2.51m high.

4 Assessment Procedure

For fire protection coatings such as Pyrocrete 40 the required thickness of protection for a given steel section and fire resistance period can be assessed by differential equation analysis.

The differential equation used for the analysis is based on one dimensional heat flow and assumes the predominant heat flow is conduction through the protection material with the outer face assumed to be at the hydrocarbon fire temperature. A basic equation for this type of approach is referred to in the European test and assessment method ENV 13381-4: 2002.

The protection material is described using its thermal conductivity, specific heat and density and the moisture content is also taken into account.

The basic equation is:

$$\Delta\theta_a = \left[\frac{\lambda_p / d_p}{C_a \rho_a} \times \frac{A_p}{V} \times \frac{1}{1+\phi/3} \times (\theta_t - \theta_{a,t}).\Delta t\right] - \left(e^{\phi/10} - 1\right)\Delta\theta_t$$

where $$\phi = \frac{C_p \rho_p}{C_a \rho_a} \times d_p \times \frac{A_p}{V}$$

And

$\Delta\theta_\alpha$	=	incremental increase in steel temperature (°C)
λ_p	=	thermal conductivity of protection material (W/m.°C) at time t
d_p	=	thickness of protection material (m)
C_a	=	specific heat of steel (J/kg °C) taken as 600J/kg °C (ENV 1993-1-2:2001)
C_p	=	specific heat of protection material (J/kg°C) taken as 1000 J/kg ° C (ENV 13381-4)
ρ_a	=	density of steel (7850 kg/m^3)
ρ_p	=	density of protection material (kg/m^3) taken as 624 kg/m^3 (as tested).
A/V	=	section factor (m^{-1})
θ_t	=	furnace temperature at time t (° C)
$\theta_{a,t}$	=	steel temperature at time t (° C)
Δ_t	=	time interval (secs)
$\Delta\theta_t$	=	increase in the furnace temperature during time interval Δ_t (° C)

The time interval to be used in the analysis should be ≤ 30 seconds.

The loaded beam sections and the tall columns provide evidence of performance for 'stickability' under standard hydrocarbon fire test conditions and temperature data derived from appropriate short sections was used in the predictive analysis.

The details of each specimen, i.e. the section factor (the ratio of the heated perimeter to cross-sectional area - A/V), the protection thickness and the duration of heating required for the sections to reach a specified steel temperature were used as input data for the analysis.

The analysis adopted a constant thermal conductivity approach similar to that referred to in ENV 13381-4: 2002.

5 Analysis of Data

Test Data/Critical Steel Temperatures

The tests referenced WARRES Nos. 126669, 126669B and 126671 included loaded beams which were used to determine the critical steel temperature to be used in the analysis for beams (three-sided protection) presented in this report.

The above referenced tests included short column and beam sections which were used to derive the thermal properties of the coating together with additional information from a test carried out in the United States.

The tests also demonstrated the ability of the coating to remain attached to the sections at elevated temperatures and for prolonged periods. The loaded beams were loaded to produce the maximum permissible stress for the steel grade.

The mean thicknesses of coating applied to the relevant loaded sections were as follows:

Loaded I-Shaped Beam WARRES No. 126669	:	13mm
Loaded I-Shaped Beam WARRES No. 126671	:	60mm

The loaded beams at minimum and maximum protection thickness maintained loadbearing capacity for periods of 53 minutes (13mm) and 496 minutes (60mm) respectively.

The beam with the highest protection thickness was tested for an extended period of 496 minutes after which time the beam buckled close to one end. It is likely that heat had bypassed the furnace seal at this point and caused localised high temperatures. As no thermocouples are fixed to the extremities of the beam the high temperatures would not have been detected.

The critical steel temperature for beams was therefore derived from the loaded beam with the minimum thickness.

The temperature at which this section was no longer capable of satisfying the performance criteria for loadbearing capacity defined by the test standard was as follows:

Beam (3 sided protection with a concrete slab)	:	>620°C.

For fully loaded sections, currently accepted procedures limit the steel temperatures at which assessments may be performed to 550°C for columns and 620°C for beams or lower temperatures which have been shown to be appropriate.
In the absence of a loaded column test, the assessment of the protection to columns is considered to be appropriate for the following reasons:

- Test experience shows that fully loaded I-section columns with passive fire protection usually maintain loadbearing capacity at a temperature of least 550°C.
- The current draft of the European test and assessment method prENV 13381-4 requires loaded tests on beams to demonstrate the 'stickability' of the coating for both beams and columns i.e. does not require a loaded column test.
- Columns are not as susceptible to 'stickability' related problems when compared with beams due to their mode of failure i.e. columns are not subject to significant bending.
- Four tall unloaded columns (2.55m) coated with different thicknesses of the same product to that considered in this report were included in a test carried out at the Underwriters Laboratories of the United States. This test demonstrated no loss of material for an extended period.

Therefore for the purpose of this report the following critical steel temperatures have been adopted:

Beams (3 sided protection with a concrete slab)	:	620°C.
Columns and Beams (4 sided protection)	:	550°C.

The test data from Underwriters Laboratories Inc. (USA) was generated under similar heating conditions (UL1709) to that specified in BS 476: Part 20: 1987, Appendix D and therefore is considered suitable as supplementary data.

Temperature Data

The appropriate data to be used in the analysis is taken from the test reports referred to in Section 9 of this report and a summary is given in Table A as follows:

Table A

Test No. WARRES	Type Ref	Section Size mmxmmxkg/m	Section Factor m^{-1}	Mean Thick' Mm	Time to Reach minutes		Loadbea-ring Capacity mins
					550°C	620°C	
126669	LB1	406x178x60	175	13	37	44	53
	SBN	305x102x25	287	22	75	89	-
	SBM	305x102x25	284	42	148	165	-
	SBR	356x171x67	150	38	166	188	-
126671	LB2	406x178x60	175	60	458	496*	496
	SBO	610x305x238	73	30	100	121	-
126671B	SCC	203x203x52	188	54	224	259	-
	SCF	254x254x132	99	29	103	112	-
File R7209 89NK4838 and 89NK12002	UL1	W10x49	162	19	60	70	
	UL2	W10x49	162	34	122	136	
	UL3	W10x49	162	48	206	236	
	UL4	W10x49	162	56	265	270**	

LB loaded beam UL tall unloaded column SB(x) short beam SC(x) Short column
(x) reference
* test terminated before temperature reached.
** test terminated before temperature reached therefore time is conservative estimate.

Principles of Assessment/Comments on Output Values
In line with the assessment procedures the data from the loaded sections were not used as input data but was used in part to determine the acceptability of the predicted analysis.

For each of the tested unloaded sections the thermal conductivity required to produce the same time to the specified temperature was determined for 550°C and 620°C using the inverse function of the basic equation.

Table B shows the calculated thermal conductivity value for each section.

Table B

Section	Thermal Conductivity W/m.°C for Steel Temperature	
	620°C	550°C
SBM	0.08271	0.08710
SBN	0.07459	0.07459
SBR	0.11171	0.10612
SBO	0.19443	0.17696
SCC	0.10704	0.10320
SCF	0.24440	0.24812
UL 1	0.12730	0.12512
UL 2	0.12797	0.11942
UL 3	0.11185	0.10728
UL 4	0.11888	0.10129

It can be seen from Table B that two sections SBO and SCF showed thermal conductivity values much greater than the general trend.

Observations given in the appropriate test report shows that the protection material to the ends of short beam SBO was lost during the test and therefore it is likely that heat could have been transmitted via the ends of the beam. This could account for the apparent 'higher' thermal conductivity.

A number of the thermocouples attached to the short column SCF were not functioning at the beginning of the test and the few that appeared to be working exhibited erratic behaviour.

It is therefore considered reasonable to omit these sections from the analysis on the basis that the temperature data may not be considered reliable.

The assessment method referred to in ENV 13381-4: 2002 uses the calculated thermal conductivity values to derive an 'effective' thermal conductivity for a range of steel temperatures (350°C to 750°C) by linear regression. However it was found that this method when considering the two critical temperatures did not produce a good agreement between the values i.e. the co-efficient of determination (r^2) was low. Therefore a more realistic 'effective' thermal conductivity was derived.

It was found that the arithmetic mean for each set of thermal conductivity values (excluding SBO and SCF) produced a more predictive analysis. These were calculated to be 0.10302 and 0.10776 for temperatures of 550°C and 620°C respectively.

The following Tables C and D shows a comparison of the actual and predicted times to reach the specified steel temperatures using these thermal conductivity values together with the calculated percentage differences for each section.

Table C

Ref	Actual Time to 550°C minutes	Predicted Time to 550°C minutes	Difference minutes	% Difference
SBM	148	126	-20	-14.6
SBN	75	55	-20	-26.7
SBR	166	171	5	3.0
SCC	225	226	1	0.4
UL 1	60	72	12	20.0
UL 2	122	141	19	15.6
UL 3	206	215	9	4.4
UL 4	265	261	-4	-1.5
			Sum	**0.4**

The positive sum value indicates that the prediction overall is marginally optimistic.

Table D

Ref	Actual Time to 620°C minutes	Predicted Time to 620°C minutes	Difference minutes	% Difference
SBM	165	143	-22.0	-13.3
SBN	89	62.5	-26.5	-29.8
SBR	188	195	7.0	3.7
SCC	259	257	-2.0	-0.8
UL 1	70	52.5	-17.5	-25.0
UL 2	136	160.5	24.5	18.0
UL 3	236	245	9	3.8
UL 4	270	297	27	10.0
			Sum	**-33.3**

The negative sum value generally indicates that the prediction overall is conservative.

The above tables however need to be considered in relation to the performance of the loaded sections.

Adopting the calculated thermal conductivity values the predictions for the loaded beams are given in Table E.

Table E

Ref	Thickness mm	Actual Time to 550°C minutes	Predicted Time to 550°C minutes	Difference minutes	% Difference
LB 1	13	37	45	8	21.6
LB 2	60	458	271	-187	-40.8
Ref	**Thickness mm**	**Actual Time to 620°C minutes**	**Predicted Time to 620°C minutes**	**Difference minutes**	**% Difference**
LB 1	13	44	51	7	15.9
LB 2	60	496	271	-225	-45.4

It is clear that the analysis is predicting a better performance for the beam with the maximum thickness compared with the tested section but a worst performance for the beam with the minimum thickness.

This may be attributable to the thermal characteristics of the protection material and the specified constant furnace temperature after about 30 minutes of testing.

Appendix D of BS 476: Part 20: 1987 shows furnace temperature relationship for a simulated hydrocarbon fuelled fire. This shows a rapid rise initially (e.g. within 10 minutes up to 1032°C and 30 minutes up to 1098°C) and a constant temperature of 1100°C after 60 minutes.

Consequently, after about 30 minutes of testing the sections will be exposed to largely constant heat temperatures and therefore largely constant heat input.

Consequently, once the furnace temperature became largely constant the amount of heat being transferred to the steel via the coating would tend to become fairly constant. This effect would be similar to 'thermal equilibrium' were the heat being transferred to the coating is effectively absorbed by the coating and only transferred to the steel when the insulating properties of the coating are eroded.

This effect is demonstrated by the prolonged period of performance achieved by the loaded beam with 60 mm of material i.e. 496 minutes but not by that with the minimum thickness.

As the maximum period considered in this report is 240 minutes it is reasonable to adjust the thermal conductivity values to obtain predictions closer to the performance of the loaded beam with the minimum thickness.

This adjustment will also ensure that the positive sum recorded in Table C becomes negative indicating a more conservative analysis.

Increasing the thermal conductivity values to 0.11312 and 0.1100 for temperatures of 550°C and 620°C respectively produced a reasonable overall prediction as shown in Table F.

Table F

Ref	Thickness mm	Actual Time to 550°C minutes	Predicted Time to 550°C minutes	Difference minutes	% Difference
LB 1	13	37	41	4	10.8
Ref	**Thickness mm**	**Actual Time to 620°C minutes**	**Predicted Time to 620°C minutes**	**Difference minutes**	**% Difference**
LB 1	13	44	42	-2	-4.6

Using the modified thermal conductivity values the predicted values for the tested sections are a reasonable comparison to the actual values and the overall assessment based on the percentage difference between the actual and predicted times for each temperature is considered conservative as shown by Table G.

Table G

Ref	Actual Time to 550°C minutes	Predicted Time to 550°C minutes	Difference minutes	% Difference
SBM	148	115	-33	-22.3
SBN	75	51	-24	-32.0
SBR	166	156	-10	-6.0
SCC	225	206	-19	-8.4
UL 1	60	66	6	10.0
UL 2	122	129	7	5.74
UL 3	206	196	-10	-4.9
UL 4	265	238	-27	-10.2
			Sum	**-68.1**
Ref	**Actual Time to 620°C minutes**	**Predicted Time to 620°C minutes**	**Difference minutes**	**% Difference**
SBM	165	140	-25	-15.2
SBN	89	61	-28	-31.5
SBR	188	191	3	1.6
SCC	259	252	-7	-2.7
UL 1	70	80.5	10.5	-15
UL 2	136	157.5	21.5	15.8
UL 3	236	240	4	1.7
UL 4	270	292	22	8.2
			Sum	**-7.1**

The results of the analysis for columns with four sided protection adopting a design temperature of 550°C for up to 240 minutes is given in Table 1 to this report. This table is also considered acceptable for four sided beams.

The results of the analysis for beams with three sided protection and a concrete slab adopting at design temperature of 620°C for up to 240 minutes is given in Table 2 to this report.

The tables contain an extrapolation in minimum thickness of 5mm (to 8mm) and 6mm (to 66mm) in maximum thickness.

6 Limits of Applicability

The method of protection should be as described in the appropriate test report.

Three sided protection for beams refers to beams supporting a concrete slab.

7 Conclusions

An assessment of the ability of a cementitious coating known as Pyrocrete 40 to protect structural steel sections in accordance with BS 476: Part 21: 1987, utilising the hydrocarbon heating conditions has been undertaken.

The specified hydrocarbon heating conditions as given in Appendix D of BS 476: Part 21: 1987.

The data which forms the basis of this assessment was obtained from tests in accordance BS 476: Part 21: 1987 on loaded steel sections and short sections which were subjected to the specified heating conditions.

Additional the test data from Underwriters Laboratories Inc. (USA) generated under similar heating conditions (UL1709) to that specified in BS 476: Part 20: 1987, Appendix D was used as supplementary input data.

This assessment relates to I-shaped steel sections for periods of fire resistance of up to 240 minutes.

The assessment method used for the analysis is based on the differential equation (constant thermal conductivity approach) referred to in the European test and assessment method ENV 13381-4: 2002.

Tables 1 and 2 show the result of the analysis of the data.

8 Validity

This assessment is issued on the basis of test data and information available at the time of issue. If contradictory evidence becomes available to WFRC the assessment will be unconditionally withdrawn and Carboline UK will be notified in writing.

Similarly the assessment is invalidated if the assessed construction is subsequently tested because actual test data is deemed to take precedence over an expressed opinion. The assessment is valid initially for a period of two years, i.e. until 1st September 2008, at which time it is recommended that it be returned for re-appraisal.

This appraisal is only valid provided that no other modifications are made to the construction other than those described in this report.

9 Summary of Primary Supporting Data

WARRES No. 126669

Report on a fire resistance test in accordance with BS 476: Part 21: 1987, Clause 5, utilising the heating conditions specified in Appendix D of BS 476: Part 20: 1987 (hydrocarbon heating).
The test was performed on a specimen of an I-shaped steel beam of serial size 406mm by 178mm by 60kg/m.

The steel beam supported a concrete slab on its upper flange and it was protected on three sides with cementitious coating known as Pyrocrete 40.

The mean thickness of the coating was 13mm and the beam was loaded to produce the maximum allowable bending stress of 165N/mm^2 calculated in accordance with BS 449: Part 2: 1969.

The specimen satisfied the performance criteria for loadbearing capacity defined in BS 476: Part 21: 1987 for the following period:

Loadbearing capacity : 53 minutes

Included in the test were a number of short sections for assessment purposes, the appropriate details of which are summarised in the body of this report.

Test Date	:	4th October 2002
Test Sponsor	:	Carboline UK.

WARRES No. 126671

Report on a fire resistance test in accordance with BS 476: Part 21: 1987, Clause 5, utilising the heating conditions specified in Appendix D of BS 476: Part 20: 1987 (hydrocarbon heating).The test was performed on a specimen of an I-shaped steel beam of serial size 406mm by 178mm by 60kg/m.

The steel beam supported a concrete slab on its upper flange and it was protected on three sides with cementitious coating known as Pyrocrete 40.

The mean thickness of the coating was 60mm and the beam was loaded to produce the maximum allowable bending stress of 165N/mm^2 calculated in accordance with BS 449: Part 2: 1969.

The specimen satisfied the performance criteria for loadbearing capacity defined in BS 476: Part 21: 1987 for the following period:

Loadbearing capacity : 496 minutes

Included in the test were a number of short sections for assessment purposes, the appropriate details of which are summarised in the body of this report.

Test Date	:	26th October 2002
Test Sponsor	:	Carboline UK.

WARRES No. 126671B
Report on a fire resistance test which utilised the heating conditions specified in Appendix D of BS 476: Part 20: 1987 (hydrocarbon heating). The test was carried out on two steel sections protected with various thicknesses of Pyrocrete 40. Test sponsored by Carboline UK.

Underwriters Laboratories Inc
File R7209 Project 89NK4838 and 89NK12002
Report on a fire tests to UL 1709 (hydrocarbon fire test conditions) on a total of four unloaded columns (size W10x49) protected with Pyrocrete 240 (similar to Pyrocrete 40). The columns were approximately 2.51m high.

The test has shown that the coating suffered no adverse affects for the 262 minutes maximum duration of any test.

Test Dates	:	During June 1989
Test Sponsor	:	Carboline Co. USA.

10 Summary of Secondary Supporting Data

ENV 13381-4: 2002
Test methods for determining the contribution to the fire resistance of structural members - Part 4: Applied protection to steel members.

ENV 1993-1-2: 2001
Eurocode 3: Design of steel structures. Part 1-2 General rules –Structural fire design.

11 Declaration by Carboline UK

We the undersigned confirm that we have read and complied with the obligations placed on us by the UK Fire Test Study Group Resolution No. 82: 2001.

We confirm that the component or element of structure, which is the subject of this assessment, has not to our knowledge been subject to a fire test to the Standard against which the assessment is being made.

We agree to withdraw this assessment from circulation should the component or element of structure be the subject of a fire test to the Standard against which this assessment is being made.

We are not aware of any information that could adversely affect the conclusions of this assessment.

If we subsequently become aware of any such information we agree to cease using the assessment and ask Warrington Fire Research Centre to withdraw the assessment.

Signed : ....

For and on behalf of : ....

Table 1 – Four-Sided Protection to I-Section Columns and Beams

Section Factor up to m^{-1}	Thickness of Pyrocrete 40 for Period of Fire Resistance mm					
	30 minutes	60 minutes	90 minutes	120 minutes	180 minutes	240 minutes
60	8	8	11	15	22	28
80	8	10	14	19	27	36
100	8	12	17	23	33	42
120	8	14	20	26	37	48
140	8	15	23	29	41	52
160	9	17	25	32	45	56
180	9	18	27	34	47	60
200	10	20	29	36	50	62
220	11	22	31	38	52	65
240	12	23	32	40	55	66
260	13	24	34	42	56	
280	13	25	35	43	58	
300	14	26	36	44	59	
320	14	27	37	46	60	

Table 2 – Three-Sided Protection to I-Section Beams

Section Factor up to m^{-1}	Thickness of Pyrocrete 40 for Period of Fire Resistance mm					
	30 minutes	60 minutes	90 minutes	120 minutes	180 minutes	240 minutes
60	8	8	9	12	18	24
80	8	8	12	16	23	30
100	8	10	14	19	28	35
120	8	12	17	22	32	40
140	8	13	19	25	37	44
160	8	15	21	27	38	48
180	8	15	22	29	41	51
200	9	17	25	31	43	54
220	10	19	26	33	46	57
240	11	20	28	35	47	59
260	11	21	29	36	49	61
280	12	22	30	38	51	62
300	13	23	31	39	52	64
320	13	24	32	40	53	65

Beams : Three sided protection with a concrete slab over.