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3D Interpolation method for intumescent coatings

The 3D Interpolation method is an assessment method for the characterisation of intumescent coatings for the protection of structural steelwork against fire. This article describes how the factual data from fire tests is used and how measured performance times are projected in a 3-dimensional space. Each of the test specimens is represented by a dot (x,y,z) in the 3-dimensional space. Three dots form a plane and the mathematical equation of the plane facilitates calculation of the performance time t (z-value) for any combination of section factor Hp/A (x-value) and dry film thickness DFT (y-value) within the boundaries of the plane. The combination of a large number of intersecting planes forms a landscape of 'rolling hills', identifying the performance time of any intumescent coating with great precision 3-dimensionally.

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Introduction

In the recent years many discussions have been taking place of how best to characterise the contribution of intumescent coatings to the fire resistance of structural steelwork. It has taken many years to develop different assessment methods, e.g. various graphical methods, differential equation methods and linear regression methods. The general feeling is that all of the existing assessment methods provide a way of predicting the performance times, but that none of the methods can do this without any error. Therefore criteria for acceptability of the assessment results have been put into place in many standards and guidelines. There is a great need for a characterisation method that provides an exact prediction of the performance times and that is based on facts rather than estimations. This article describes the so called 3D Interpolation Method that is based on measured performance times obtained from fire tests and projecting them into a 3 dimensional space. Each of the test specimens and its performance time to a certain temperature of interest is represented by a dot (x,y,z) in the 3 dimensional space. Three dots construct a plane and the mathematical equation of the plane facilitates prediction of the performance time z for any combination of x and y within the plane boundaries, i.e. the triangle of which the three dots form the corners.

Four dimensional problem

The reason that it has taken many years to study the behaviour of intumescent coatings without achieving a factual, mathematical satisfactory characterisation method is due to the complexity of the subject, which is actually a 4-dimensional problem.

The four dimensions are section factor (Hp/A), dry film thickness (DFT), performance time (t) and design steel temperature (T). In order to grasp the behaviour this 4-dimensional mathematical problem can be reduced to 3 dimensions in which:

- x-axis represents the Hp/A
- y-axis represents the DFT
- z-axis represents the performance time.

There is no room for the w-axis in a 3-dimensional space. The w-axis would represent the Temperature. This fourth dimension can be taken into account by visualizing a 3-dimensional space over and over again, for each design steel temperature separately. Hence, it is possible to construct a 3-D space for a steel temperature of 350°C, a separate one for 400°C and so on, up to 750°C, or for any temperature in between, higher or lower, if one would wish to do so.

Performance time as function of a combination of Hp/A and DFT

A test specimen can be identified by a combination of Hp/A and DFT. For example a steel section with an Hp/A value of 230 m^{-1} and a DFT of 1.23mm would be represented as (x,y) = (230, 1.23). If Hp/A is on the x-axis and DFT is on the y-axis than every dot (x,y) represents a test specimen in the orthogonal x,y-axis system.

If the test specimen is subjected to the standard fire test, it will be heated up and it is expected that it will take a certain time in order to achieve a specific design temperature of, say 550°C. This time is the so called performance time t. By putting the performance time t on the z-axis a 3-dimensional space is created in which every combination of Hp/A, DFT and performance time t is represented by a dot (x,y,z) in the space formed by the x-, y-, and z-axis.

This 3-dimensional space is for one particular temperature only and shows for each of the test specimens the performance time achieved. This is illustrated in Figure 1.

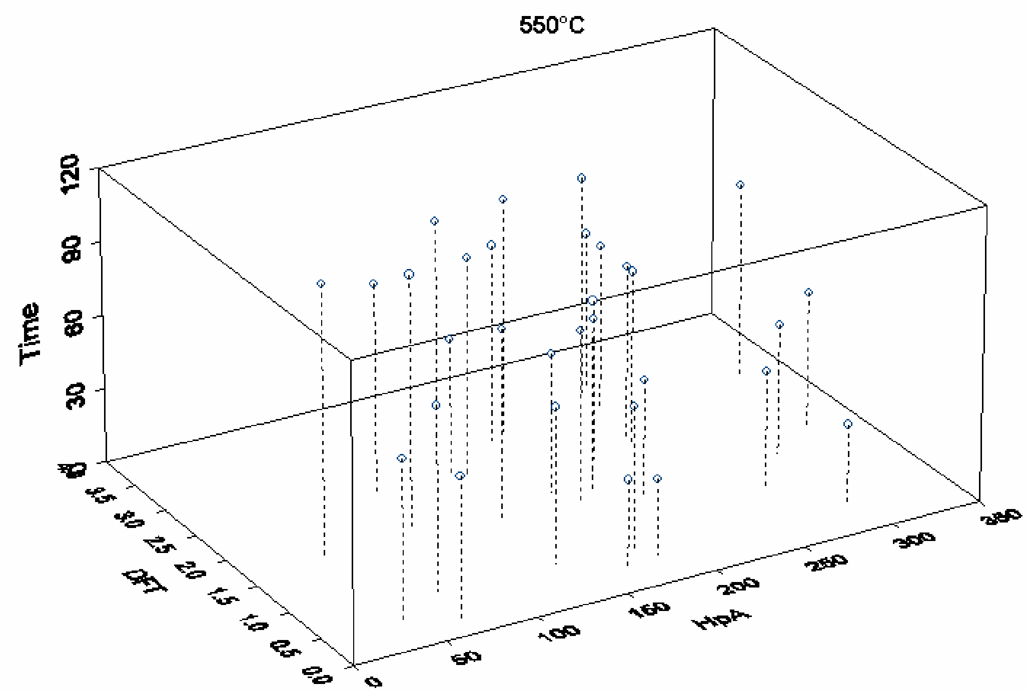


Fig. 1: 3D - Representation of data set for 550°C

This information is factual, i.e. these dots in the 3-dimensional space are measured values obtained from the fire tests. The position of the dots is the only factual information available to form the input for the assessment.

Forming triangles

It is now possible to identify three dots (x_1,y_1), (x_2,y_2) and (x_3,y_3), each of them representing a test specimen (x_i,y_i), to create a triangle. For simplicity, these three dots are in the x,y-plane (z=0). It is also possible to draw straight lines through the dots, intersecting at the corners of the triangle. The line equations have the form of:

$$y = ax + b \qquad [1]$$

The lines enclose an area in the x,y-plane, which is called the domain. The domain forms a collection of (x_i,y_i) dots for which the plane equation, that will be explained below, will be applicable. See Figure 2 and 3.

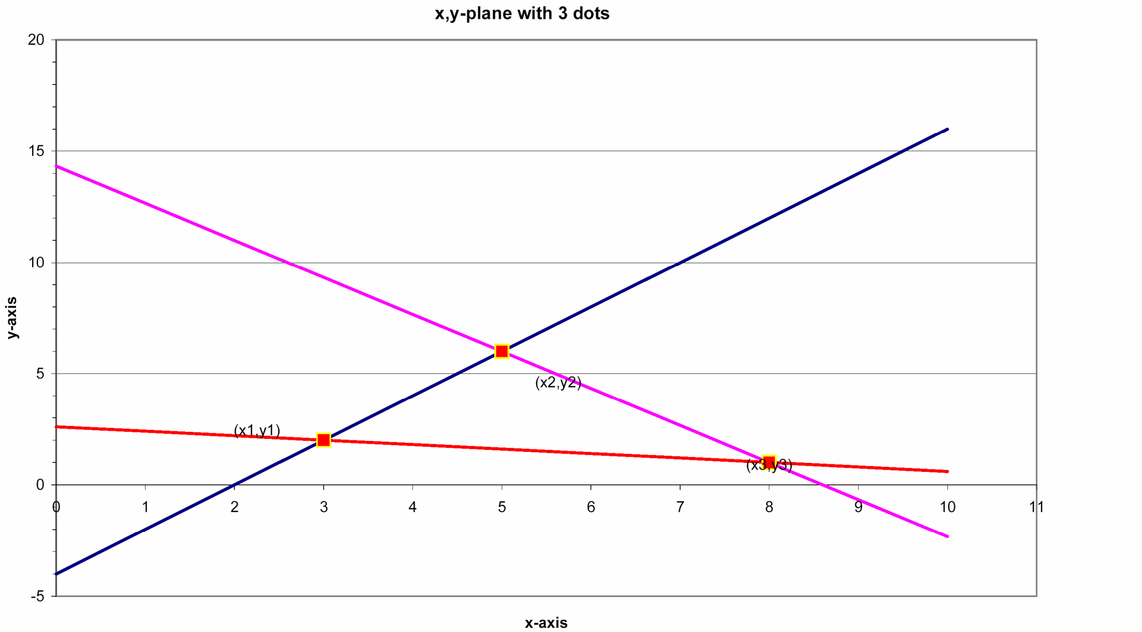


Figure 2

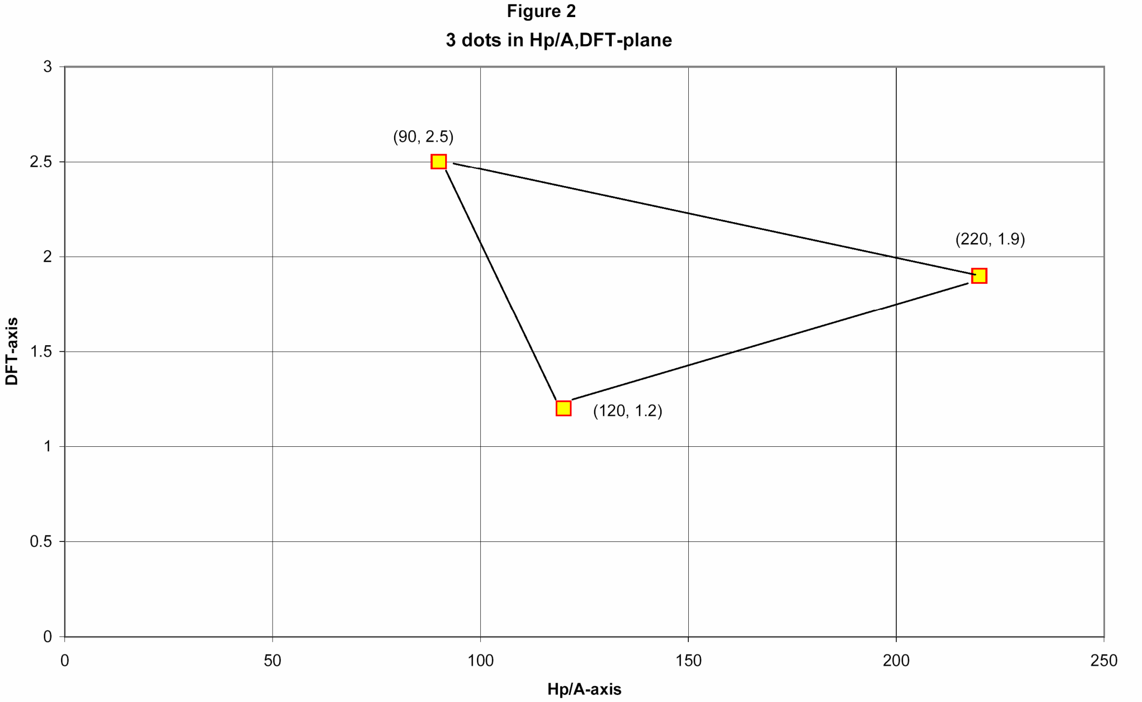
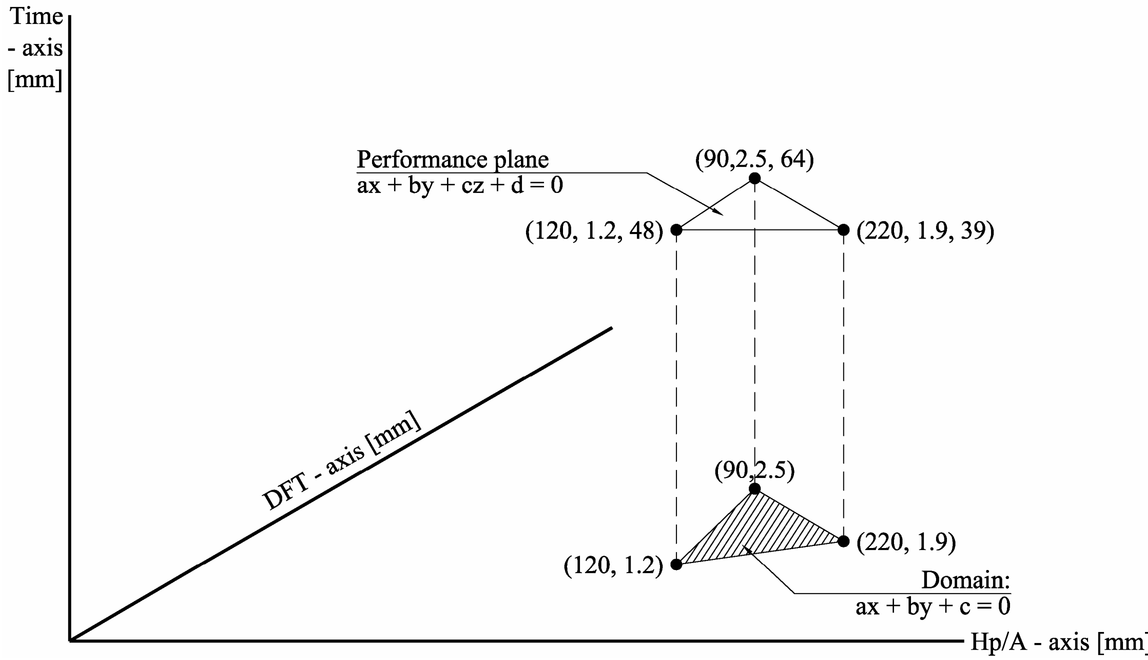


Figure 3

In the 3-dimensional space the three dots (x_1,y_1,z_1), (x_2,y_2,z_2) and (x_3,y_3,z_3), can be imagined to lay in one plane. The equation of the plane has the form of:

$$ax + by + cz + d = 0 \qquad [2]$$

This is illustrated in Figure 4.



By filling in a value for x and for y (x =Hp/A , y = DFT) in the plane equation the z-value can be obtained. In other words for all dots within the triangle in the x,y-plane (domain) the z can be calculated using the plane equation. This means that the performance time t can now be calculated for all combinations of (x_i,y_i), i.e. Hp/A and DFT values that are within the triangle with corners (x_1,y_1), (x_2,y_2) and (x_3,y_3). See Figure 2.

A more understandable form of the plane equation is:

$$a \bullet Hp/A + b \bullet DFT + c \bullet time + d = 0 \qquad [3]$$

See also Figure 4.

Test evidence with various data points

In most cases manufacturers have test evidence which contains many more data points than only three test specimens. The principle of forming triangles can be extended to create more triangles in the (x,y)-plane, i.e. the (Hp/A,DFT)-plane. In the previous section it was demonstrated that three dots form one triangle;

- 4 dots will form 2 triangles,
- 5 dots will form at least 4 triangles,
- 6 dots will form at least 5 triangles and so on. See Figure 5.

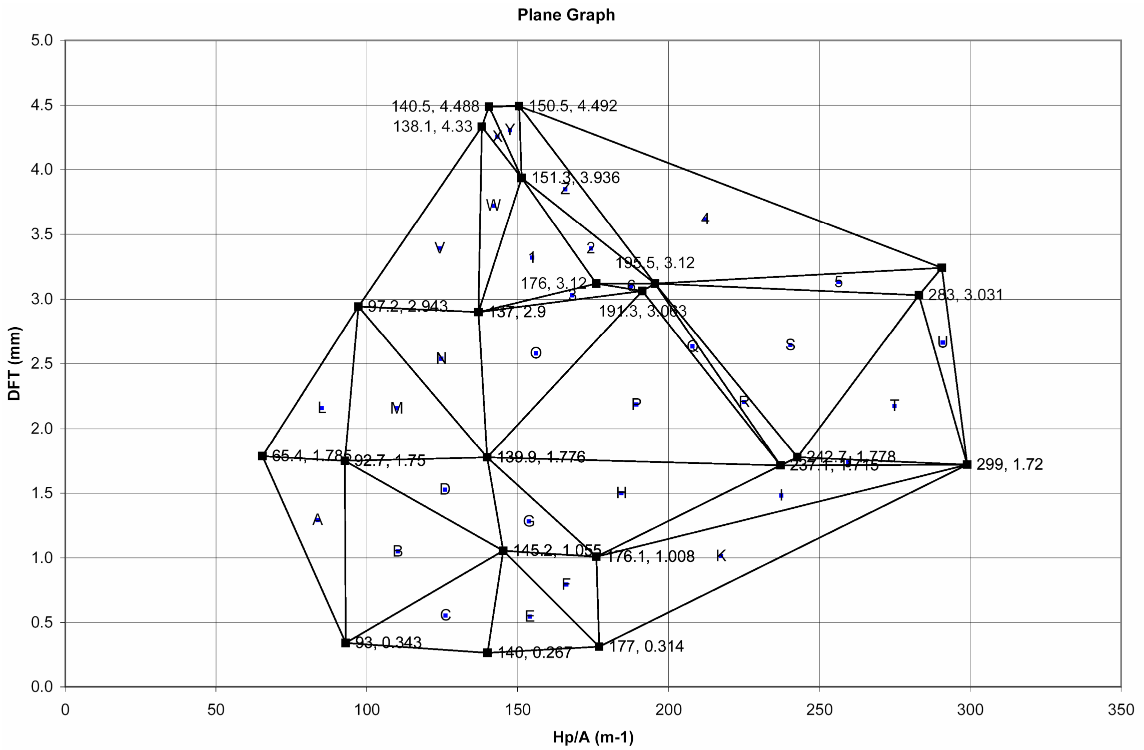


Figure 5

Each of the triangles form the domain for which (x_i,y_i)-dots within that triangle deliver the z-value by using the plane equation. i.e. each of the triangles in the (Hp/A,DFT)-plane forms the domain for which a combination of Hp/A and DFT within the triangle provides a performance time by using the plane equation [3].

The planes intersect at lines that connect the measured performance times in the 3-dimensional space. An example of a data set and its performance time to 550°C is given in Figure 6. This Figure 6 demonstrates that when all of the planes are combined they form a 3-dimensional landscape, like the rolling hills of England.

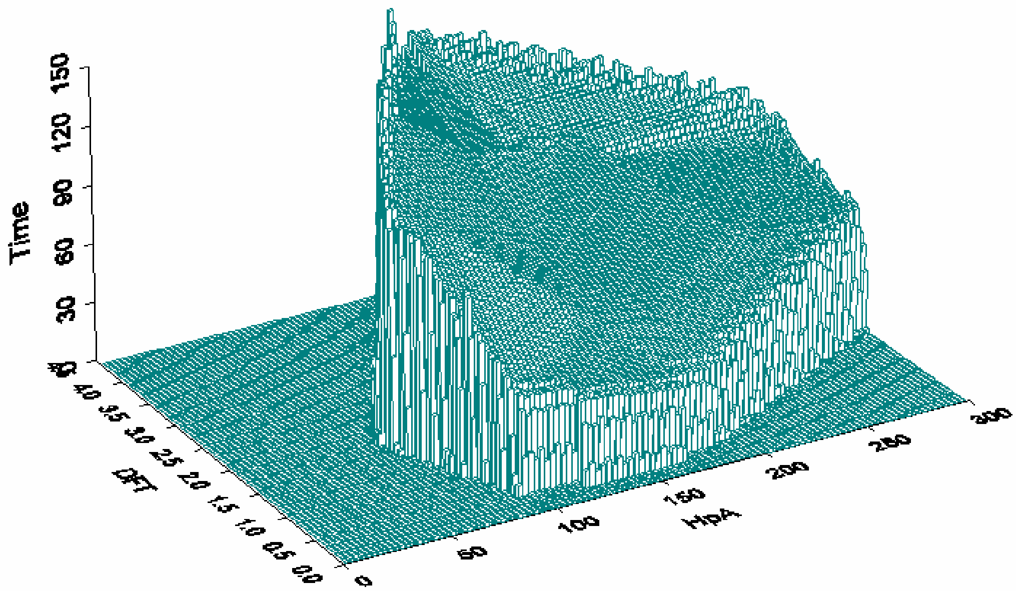


Figure 6

Output of the 3D Interpolation method
An assessment of the performance of an intumescent coating will involve;

- the performance time as a function of DFT (graphed for different values of Hp/A).
- the performance time as a function of Hp/A (graphed for different values of DFT).

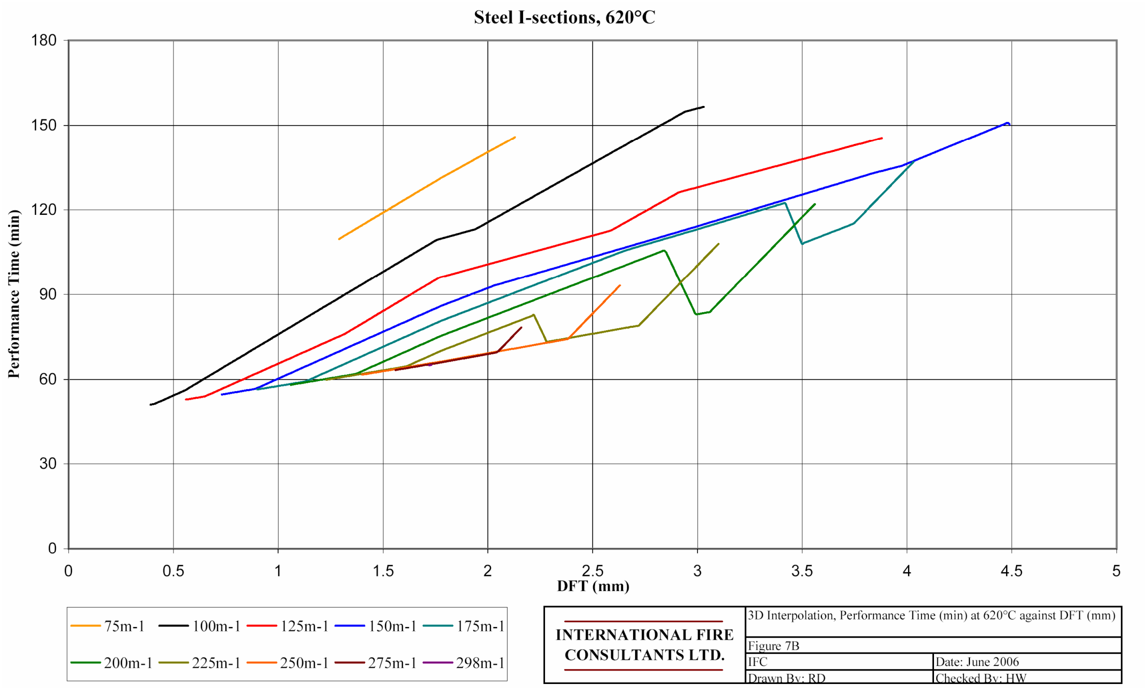
The performance time as a function of DFT is nothing else than a vertical cross section through the 'landscape' formed by the rolling hills. A vertical plane for a constant Hp/A produces the cross-section. A vertical cross-section using plane Hp/A = Constant can be taken for any value of Hp/A. This does not only show the performance time as a function of DFT, but also shows where applicable test evidence is available and where no test evidence exists. In other words it shows the lower and upper limitations of the DFT in the output directly, as performance time will be o (zero) if there is no applicable test evidence. The plane equation only returns z-values within the domain and therefore performance times will only be provided if Hp/A and DFT are both within the domain of the particular plane equation.

Also, the performance time expressed as a function of Hp/A is nothing more than a vertical cross-section through the landscape of rolling hills of a vertical plane for a constant DFT. A vertical cross-section using a plane for a constant DFT can be taken for any value of DFT. This vertical cross section will show the lower and upper limitations for Hp/A for that particular DFT value.

Previously unrevealed information about behaviour of intumescent coatings can now be visualised

The 3D Interpolation Method used to calculate the performance time as a function of Hp/A reveals that in some cases a higher DFT does not necessarily provide a higher performance time. This is illustrated by local dips in the 3D-landscape. The landscape of the rolling hills may unexpectedly reveal one or more local deep valleys.

Various cross-sections through the landscape combined in one graph may show that lines for different DFT's intersect. This is illustrated in Figures 7A and 7B. In Figures 7A and 7B the lines for DFT of 2.5mm and 3.0mm intersect, i.e. cross over, and this demonstrates that the behaviour is not as expected. For a certain range of Hp/A-values the 3.0mm DFT provides less performance than the 2.5mm DFT.



The 3D Interpolation Method allows identification of certain area's of both Hp/A and DFT where improvement of the intumescent recipe may be possible. This is a great tool for the chemists working on developing intumescent coatings.

Based on factual information

The 3D Interpolation method is based on factual measurements and 3-dimensional arithmetic (line and plane equations in the 3-dimensional space). It is the first time that predictive knowledge on the behaviour of intumescent coatings can be provided, without the blurring effect of statistical analysis, linear regression techniques or elaborate heat transfer calculations.

Criteria of acceptability satisfied by default

There is no need for correction techniques in order to satisfy criteria of acceptability. As the 3D Interpolation Method is based on facts, the error is 0 (zero) and the criteria for acceptability are automatically complied with. The measured data points form literally the planes, as the planes are constructed by using the data points, i.e. the planes are hung onto the data points. Therefore the difference between measured time and predicted time is 0 (zero), hence, the ratio calculated times / measured times = 1 by definition. Over-predictions or under-prediction does not exist as the calculated times cannot be higher or lower than the measured times. In fact the calculated times are identical to the measured times.

The number of individual values with a calculated performance time higher than the measured performance time is automatically 0 (zero). The ENV 13381-4 allows a maximum of 30% over-prediction, the Dutch Standard NEN 6072 allows 20%, the new ENV 13381-8 allow 15%.

Advantages of the 3D Interpolation Method

None of the available assessment methods (graphical methods ENV and UK, differential equation method with constant and variable lambda approach, linear regression methods) has so far been able to provide an assessment with 0 (zero) error or has been able to identify the lower and upper limit of the DFT's for a particular value of Hp/A, or has been able to provide predictive knowledge confirming that the performance of high DFT's is not always better than the performance of low DFT's.

The 3D Interpolation Method:

- is based only on facts
- provides assessment with 0 (zero) error
- complies with criteria of acceptability by default
- identifies the lower and upper limit of the DFT's for a particular value of Hp/A
- provides predictive knowledge of the performance.

Adding the fourth dimension

The 3D Interpolation Method can visualise the performance as a function of Hp/A, DFT, time and Temperature. Figures 8 to 10 show 3-dimensional graphs of an intumescent coating in the heating process at different stages at 350°C, 650°C and 750°C steel temperatures.

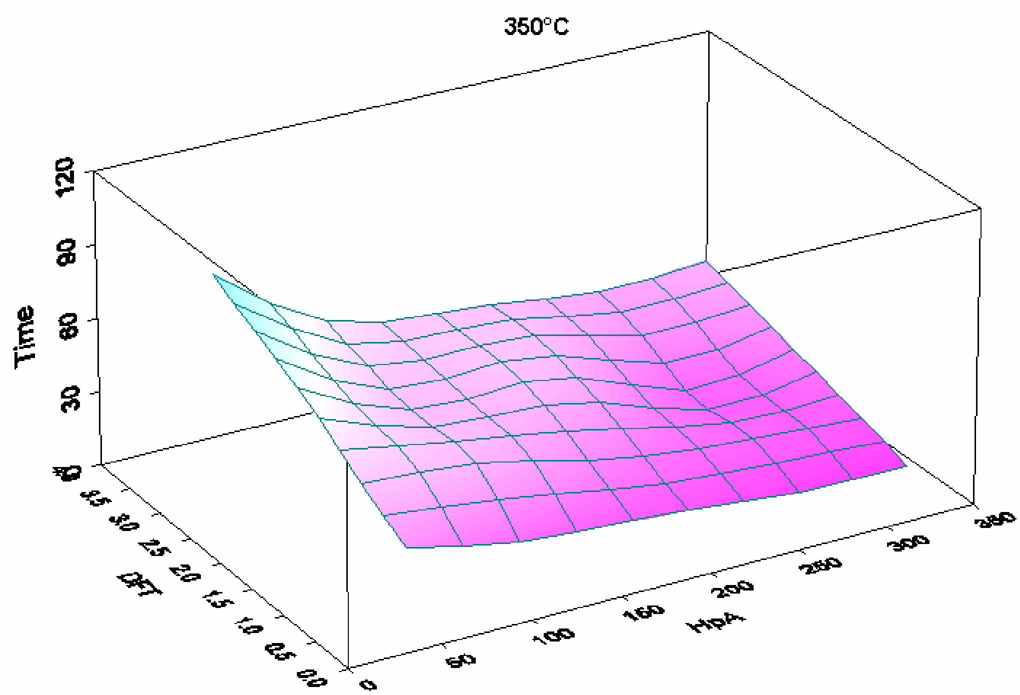
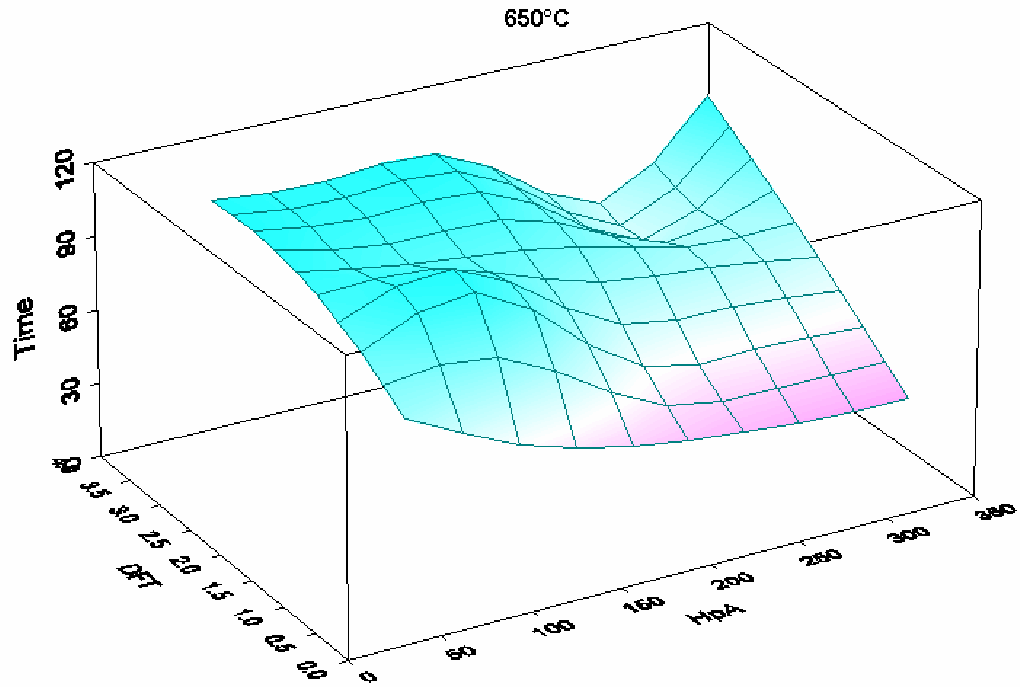


Figure 8



650°C
Time
120
90
60
30
0
DFT
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
HpA
0
50
100
150
200
250
300
350

Figure 9

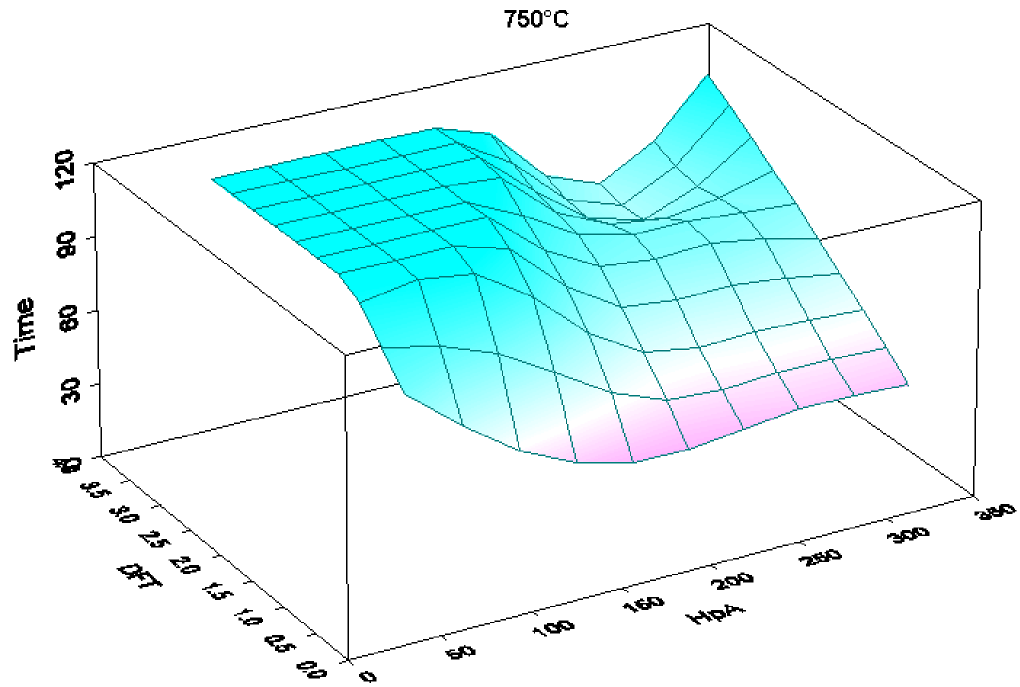


Figure 10

Conclusion

The 3D Interpolation Method is the only available assessment method so far that is based on facts only and will therefore render all discussions of pushing, pulling or manipulating the contribution of intumescent coatings to the fire resistance performance of structural steel work, redundant.

About the author

Hans van de Weijgert is Principal Engineer at International Fire Consultants Ltd (IFC) in Princes Risborough, United Kingdom. He studied the physics of the built environment and building construction in Eindhoven, The Netherlands in the early eighties. His fire testing and consultancy career started at TNO in The Netherlands in 1987 and he joined IFC Ltd in August 2000. He has performed more than 2600 full-scale fire tests in many different laboratories in Europe. The main responsibilities of Hans are the development of products, design advice for constructions on and offshore and the assessment of the fire resistance of building components and constructions.