EVALUATION OF ENCLOSURE TEMPERATURE EMPIRICAL MODELS

Society of Fire Protection Engineers Technical Report

November 9, 2010

Sean P. Hunt and John Cutonilli
Hughes Associates, Inc.
3610 Commerce Drive
Suite 817
Baltimore MD 21227

HUGHES ASSOCIATES, INC.
30 YEARS OF FIRE ENGINEERING LEADERSHIP

Morgan Hurley, P.E.
Technical Director
Society of Fire Protection Engineers
7315 Wisconsin Ave.
Suite 620E
Bethesda, MD 20814

SFPE
SOCIETY OF FIRE PROTECTION ENGINEERS

Table of Contents

1.0 Introduction

Performance-based design of structural fire resistance involves three primary tasks: (1) determination of the fires to which the structure could be exposed, (2) estimation of the heat transfer from the fire to the structure, and (3) prediction of the structural performance at elevated temperatures.

The fire scenario that is most frequently used in performance-based design of structural fire resistance is a fully developed enclosure fire. There can be variability in the fire size that results from which items is ignited first and how the fire grows and spreads during the growth phase of a fire. Focusing on fully-developed fires eliminates much of this variability, since a fully-developed (post-flashover) fire is less sensitive to which items is ignited first and how the fire grows.

For most structural fire resistance designs, neglecting the heating to the structure during the growth stage of a fire is reasonable. This is because the heating of the structure during the fully-developed stage is much greater than the heating during the growth stage.

Several methods have been published in the literature for estimating the time-temperature history of fully-developed compartment fires.[1] Most predictive methods assume a one-zone compartment, in which the temperature is modeled as being uniform throughout the compartment at any given time.

For engineering design purposes, it is generally desired to use a predictive method that provides an estimation of temperature and duration that would not be expected to be exceeded. Using a fire exposure that could be exceeded could result in a design that could fail under some combinations of conditions. The purpose of this document is to assess the available empirical models against the results of published full scale test data from multiple sources.

2.0 Full Scale Test Data

The *SFPE Engineering Guide to Fire Exposures to Structural Elements*[1] evaluated several predictive methods by comparing predictions to two sets of data. The first set of data was from 321 experiments conducted under the auspices of CIB.[2] To explicitly analyze the effect of long, narrow compartments, temperature data as a function of time from a series of experiments that were performed in a compartment that was approximately 23 meters long, 2.7 meters high and 5.5 meters wide[3] were also used to evaluate methods.

For the purpose of developing an engineering standard, a more comprehensive evaluation was desired. The test data from 381 additional fully-developed fire tests were assembled into a single database for use in comparing various time-temperature correlations. The database was dominated by wood fuel and wood crib type fires; however, about ten percent were chemical in nature and another twenty percent or so involved mixed Class A materials. Table 2 summarizes the data sources for the tests used to assess the various empirical models. Only tests where average compartment temperature data were available, the compartment is well described (materials, dimensions, ventilation), and the ventilation is constant, and the ventilation is natural and involves only vertical openings are used in this evaluation. A total of 146 of the 381 tests are retained in the database using the aforementioned criteria. Figure 1 - Figure 9 provide an overview of the nature of the tests that are included in the database. The ventilation factor histogram (Figure 15) depicts the relative ventilation to available heat loss ratio in an enclosure and is calculated using the total area and effective height of the natural ventilation and the internal surface area as follows:[1]

$$F = \frac{A_v \sqrt{H_v}}{A_T}$$

where F is the ventilation factor ($m^{1/2}$), A_v is the total area of the natural ventilation (m^2), H_v is the effective height of the natural ventilation (m), and A_T is the total internal boundary area of the enclosure (m^2).

Table 1 - Summary of Enclosure Fire Tests Reviewed and Selected for Comparison

Researcher(s)	Reference	Number of Tests Reported	Number of Tests Included in Database	Notes
Alam et al.	4	8	0	Excluded because tests involved forced ventilation, no ventilation, or ventilation changes during the test.
Arnault	5, 6	~96	38	Wood fuel. Excluded tests were not ventilation limited.
Arnault	5, 7	~20	10	Wood fuel. Excluded tests were not ventilation limited.
Andersson	8	24	0	Excluded because the tests were small scale.
Babrauskas	9	4	0	Excluded because temperature data was unavailable.
Blackmore et al.	10	20	5	Excluded tests were conducted in furnace or had corrupted data.
Bohm et al.	11	17	0	Excluded because tests involved either forced ventilation or results data was unavailable.
Bruce	12	6	6	Enclosure included glass windows.
Bryner et al.	13	6	0	Excluded because the fuel was a gas burner.
Butcher et al.	14	12	12	Wood fuel.
Bullen et al.	15	3	0	Excluded because results data was unavailable.
CTICM	5, 16	9	8	Excluded test involved variable ventilation.
Croce	17	1	0	Excluded because enclosure details were unavailable.
Durkin	18	13	0	Excluded because results data unavailable.
Fang et al.	19	16	9	Excluded tests involved forced ventilation.
Fang	20	7	7	Furniture fuel.

Researcher(s)	Reference	Number of Tests Reported	Number of Tests Included in Database	Notes
Fang	21	8	0	Excluded because results data unavailable.
Girgis	22	10	6	Furniture fuel.
Gross et al.	23	1	0	Excluded because enclosure details were unavailable.
Gross	24	3	0	Excluded because the ventilation state changed during the tests.
Hagen et al.	25	5	1	Results data was unavailable for excluded tests.
Hamins et al.	26	6	0	Excluded because enclosure details were unavailable.
Hamins et al.	27	5	0	Excluded because results data was unavailable.
Ingberg	28	10	0	Excluded because ventilation conditions changed during tests.
Kawagoe	29	10	7	Excluded tests because of multiple fires (1); undefined enclosure (1); and corrupted results data (1).
Kirby	30	9	9	Wood fuel.
Lee	31	6	0	Excluded because results data was unavailable (five tests) and forced ventilation was used (one test).
Leonard et al.	32	1	0	Excluded because results data was unavailable.
Lonnermark et al.	33	19	19	Polymer fuel.
Lougheed et al.	34	1	0	Excluded because enclosure details were unavailable.
McGarry et al.	35	2	0	Excluded because the test duration was too short.
Rodak et al.	36	5	0	Excluded because ventilation conditions changed during tests.
Roy	5, 37	3	3	Wood fuel.
Schaffer et al.	38	3	3	Wood fuel.
Shorter	39	8	0	Excluded because enclosure details were unavailable.
Su et al.	40	3	3	Thermoplastic fuel.
Tewarson	41, 42	3	0	Excluded because results data was unavailable.
Total		381	146	

FULLY DEVELOPED FIRE TEST DATABASE PROFILE

Dominant/Primary Fuel Package

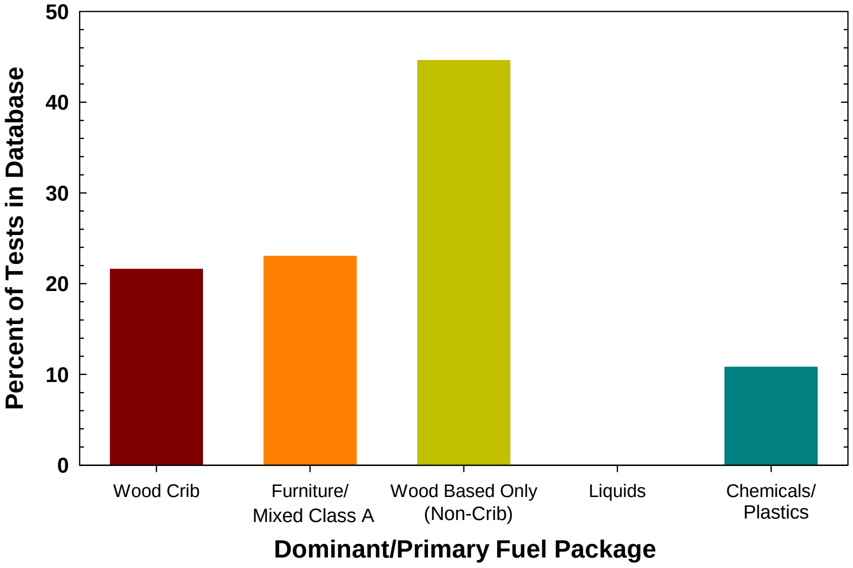


Figure 1 - Type of Fuels in Test Database.

Test Duration

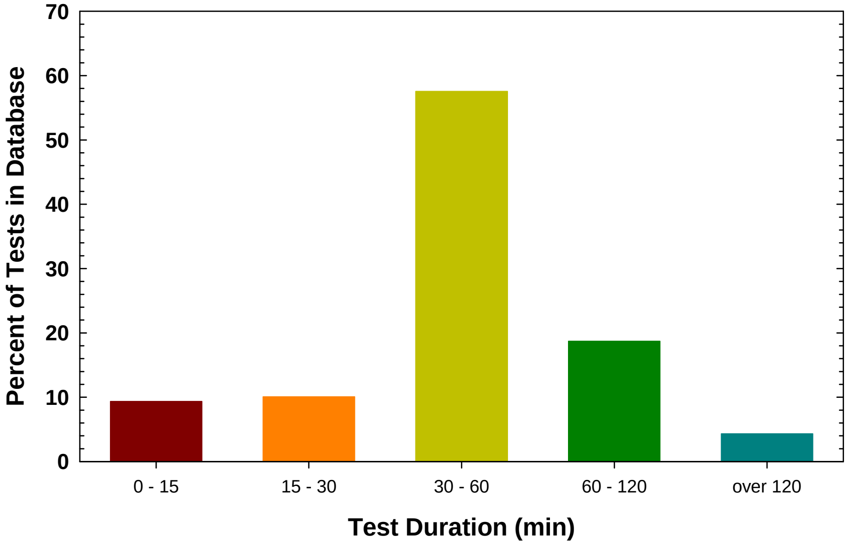


Figure 2 - Duration of Tests in Database.

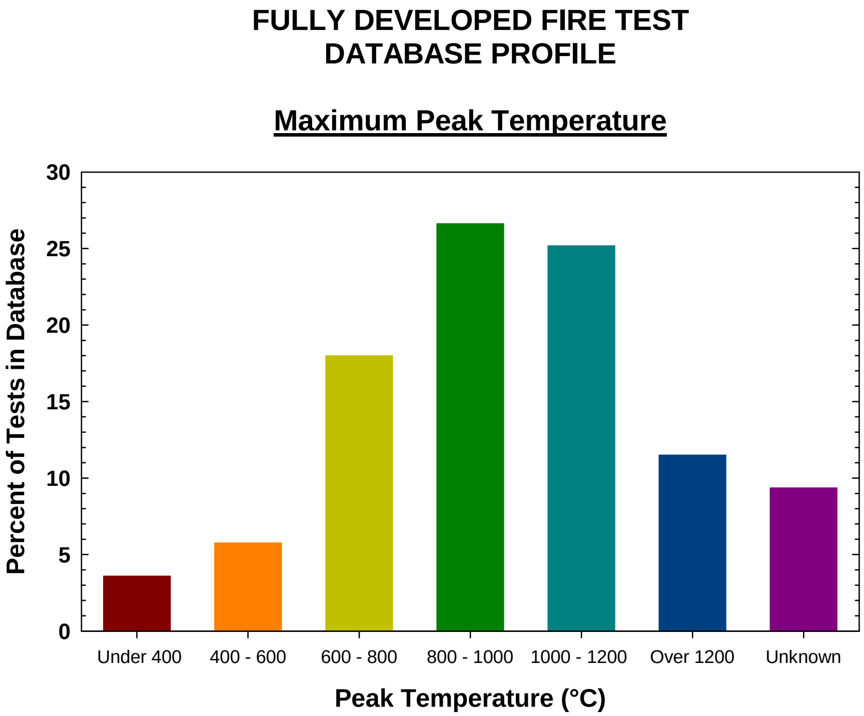


Figure 3 - Maximum Peak Temperature Measured in Tests in Database.

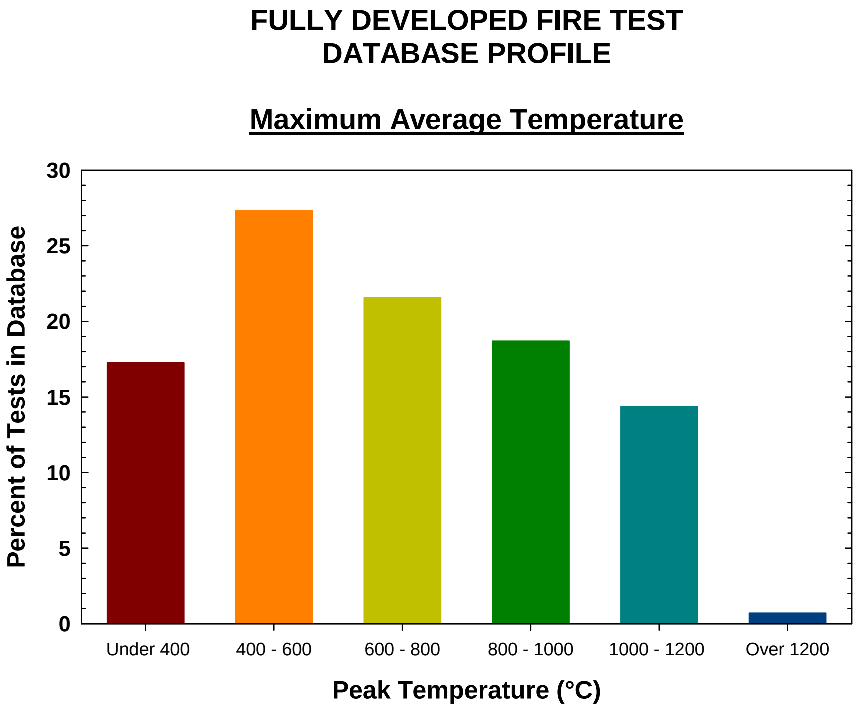


Figure 4 - Maximum Average Temperature in Reported for Tests in Database.

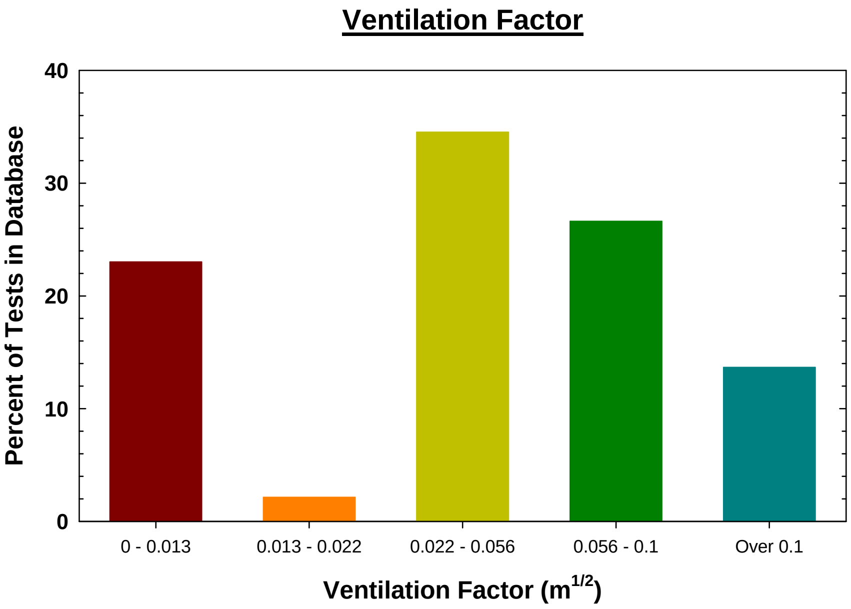


Figure 5 - Ventilation Parameter for Tests in Database.

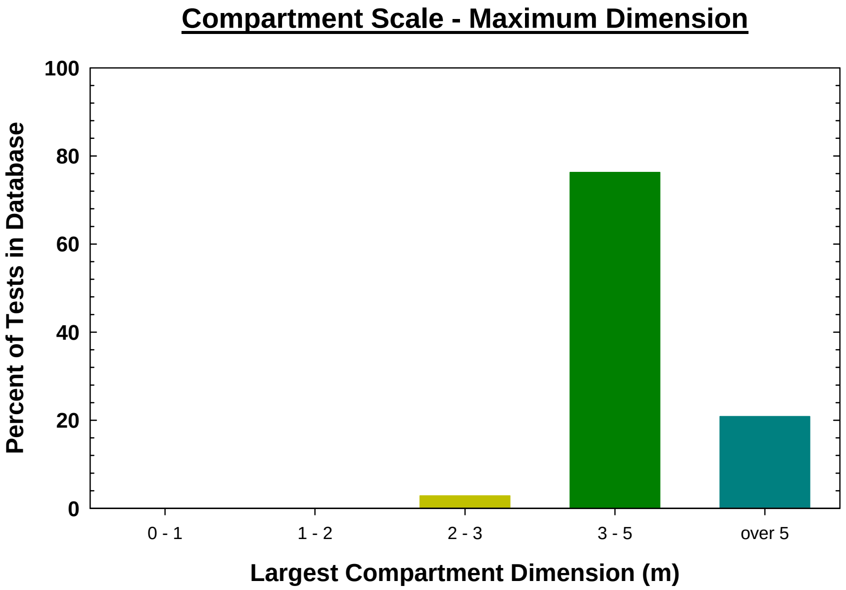


Figure 6 - Compartment Scale for Tests in Database – Largest Dimension.

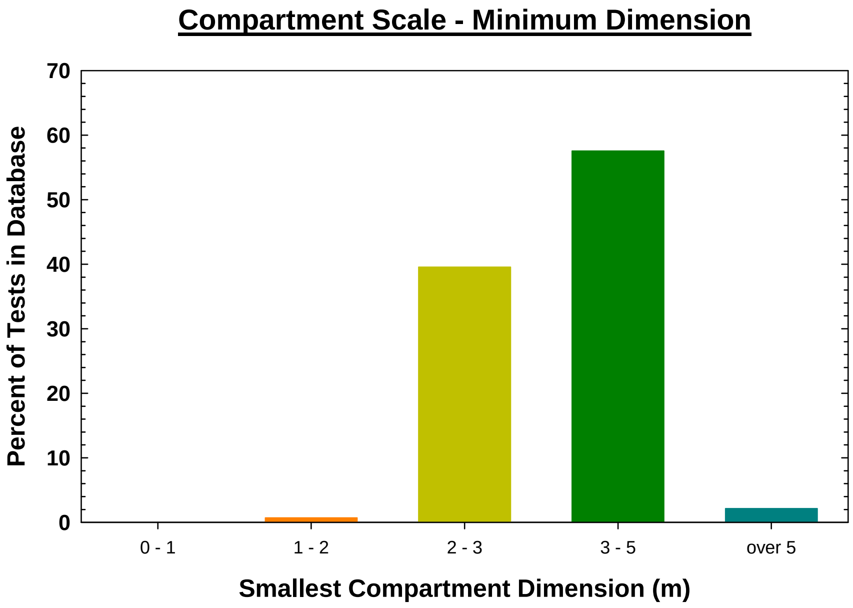


Figure 7 - Compartment Scale for Tests in Database – Smallest Dimension.

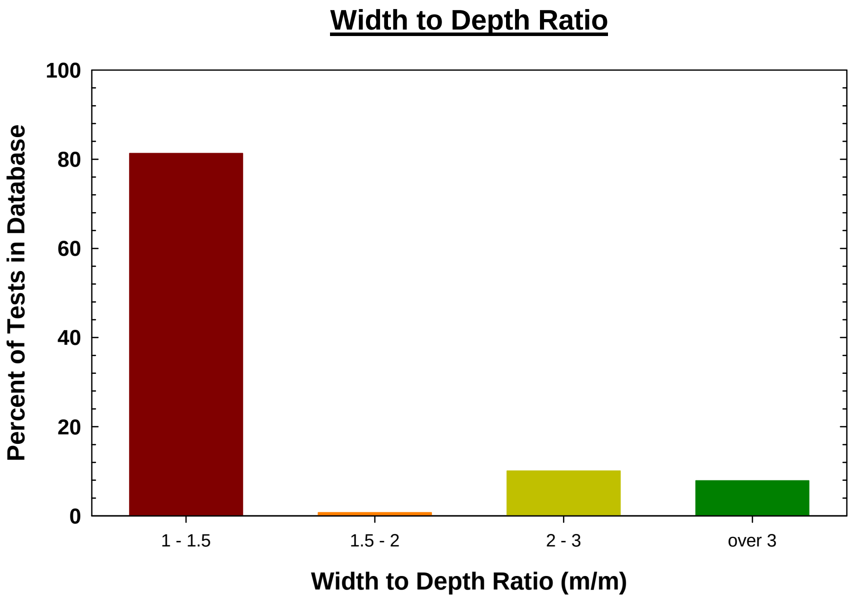


Figure 8 - Compartment Width to Depth or Depth to Width Ratio in Tests in Database.

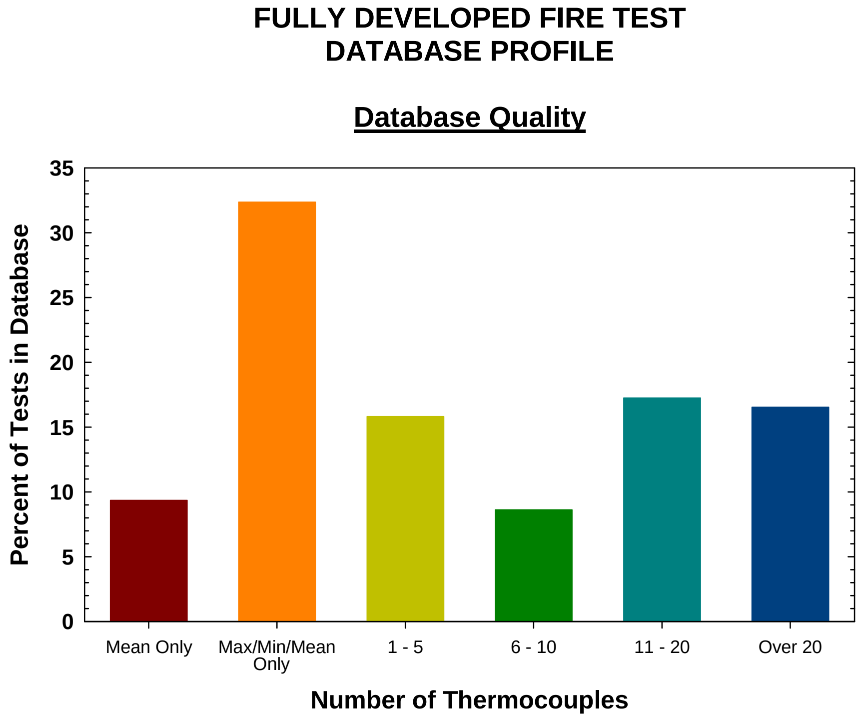


Figure 9 - Extent of Temperature Instrumentation/Documentation (Data Quality) for Tests in Database.

3.0 Methods Evaluated*

Twenty-four predictive methods were evaluated by comparing predictions with the test data in the database. To develop the comparisons, the experiments were modeled using input data based on the characteristics of the experiments. The output from the predictive methods was compared to the experimental data as described in subsequent sections of this document.

The predictive methods that were evaluated included eleven correlations with fourteen variations, two simplistic calculation approaches (an ASTM E119-10 Standard Time-Temperature Profile and 1,000 °C/1,200 °C constant temperature exposures), plus the recommended approach from the *SFPE Engineering Guide to Fire Exposures to Structural Elements*.[1] The methods evaluated are shown in Table 2. The details of the methods are addressed in the applicable referenced documents.

Table 2 - Predictive Methods Evaluated

Method	Variations
1. Eurocode	1991 version[43]
	Buchanan Modifications[44]
	Franssen Modifications[45]
	2002 version[46]
2. Method of Lie[47]	
3. Method of Tanaka[48]	Original
	Refined
4. Method of Magnussen[49]	
5. Method of Harmathy[50, 51]	
6. Method of Babrauskas[52]	
7. Method of Ma et al.[53]	
8. Method of CIB[54]	
9. Method of Law	Original[55]
	Modified[1]
10. Method of Cadorin[56]	Slow Fire
	Medium Fire
	Ultra Fast Fire
11. Method of Barnett[57]	Slow Fire
	Medium Fire
	Ultra Fast Fire
12. ASTM E119[58]	
13. Constant Temperature	1,000°C constant temperature
	1,200°C constant temperature
14. SFPE Engineering Guide to Fire Exposures to Structural Elements[1]	Combines Modified Law, Method of Magnussen, and Method of Lie

---

* Portions of the descriptions of the predictive methods are adapted from reference **Error! Bookmark not defined.**

3.2 Eurocode Parametric Fire Exposure Method

The Eurocode 1 Part 2.2[44] provides three "standard" fire curves and a parametric fire exposure. The standard fire curves include the ISO 834 curve, an external fire curve, and a hydrocarbon fire curve. The parametric fire exposure in the Eurocode was originally developed by Wickstrom.[59] Wickstrom stated[59] that this method assumes that the fire is ventilation controlled and all fuel burns within the compartment.

The Swedish building code contained an approximation of the ISO 834 standard fire curve. Wickstrom modified this method by altering the time scale based on the ventilation characteristics and enclosure thermal properties. The modified time scale compares the enclosure of interest to Magnusson and Thelandersson's "type A" enclosure with an opening factor of 0.04 $m^{1/2}$. Wickstrom found that the resulting curve approximated the ISO 834 standard fire curve.

The Eurocode states that this parametric exposure may be used for fire compartments up to 100 m^2 only, without openings in the roof and for a maximum compartment height of 4 m.

Buchanan[46] suggested that the temperatures in the Eurocode are often too low, and suggested that it would be more accurate to scale based on a different reference lining material. Franssen[45] noted two shortcomings of the Eurocode procedure for accounting for layers of different materials. These were:

1. The Eurocode procedure does not distinguish which material is on the side exposed to a fire.
2. The contribution of each material to the linings factor is weighted by thickness, so the adjusted linings factor for an enclosure with a nominal thickness of an insulating material over a much thicker, heavier material will be biased towards the linings factor of the thicker, heavier material.

Franssen therefore suggested alternate methods of accounting for layers of different materials than was provided in the Eurocode. Franssen also observed**Error! Bookmark not defined.** that as the ratio between the fuel load and the ventilation factor decrease, the Eurocode predicts unrealistically short burning durations. Therefore, Franssen suggested additional modifications to alleviate this shortcoming.

3.3 Lie's Parametric Method

Lie[47] suggested that if the objective is to develop a method of calculating fire resistance requirements, then it is necessary only to find a fire temperature-time curve "whose effect, with reasonable probability, will not be exceeded during the use of the building."[47] Lie developed an expression based on the series of temperature-time curves computed by Kawagoe and Sekine[60] for ventilation controlled fires, which he proposed could be used as an approximation for the most severe fire that is likely to occur in a particular compartment.[47]

3.4 Method of Tanaka

Tanaka[48] extended the equation for pre-flashover room fire temperature developed by McCaffrey et al.[61] to obtain equations for ventilation controlled fire temperatures of the room of origin and the corridor connected to the room.[48]

Tanaka studied the effect of an opening between the corridor and the outdoors when the corridor was connected to the room of origin. His equations can be reduced where there is no opening between the room of origin and the connected corridor and can be used for predicting the temperature of a single fire room. Tanaka uses Kawagoe and Sekine's[60] method of predicting the mass burning rate. Following comparison of the results of the simple equations to results of more detailed computer model, Tanaka refined the equations to improve accuracy.

3.5 Magnusson and Thelandersson Parametric Curves

Magnusson and Thelandersson[49] studied the variations in the development of energy, the effects of air supply and the resulting evolution of gases with time in the course of a fire. They determined the temperature of the combustion gases from wood fuel fires, in an enclosed space as a function of time, under different conditions.

Magnusson and Thelandersson made adjustments to Kawagoe's[60] work to accommodate the effect of a cooling phase.

Magnusson and Thelandersson evaluated eight specific types of enclosures and developed temperature time curves for each, assuming wood fuel. The opening factor and the fuel load were varied for each of the eight types of enclosures, and temperature as a function of time was presented in both graphic and tabular formats.

They suggest choosing the type of enclosed space most similar to one of the eight types in respect to the thermal properties of the bounding structure, then determining the opening factor and the fuel load for case of interest, and finally interpolating linearly, if necessary. Alternatively, one can choose a curve which is determined without interpolation, so as to be on the safe side (i.e., the next higher value of opening factor and fuel load).

3.6 Method of Harmathy

Harmathy published a method for predicting burning rates and heat fluxes in compartment fires with cellulosic fuels.[50,51] Harmathy's method is based on theory, with a number of simplifications and comparisons of data to define constants. The methods that Harmathy presented are applicable to fully developed fires in compartments that are ventilation limited or fuel controlled.

Harmathy established the duration of the fully developed burning period as the time that the combustible mass remaining in the compartment is eighty percent or more of the initial mass.

Harmathy states that where boundary materials are not homogeneous, a weighted average can be used. Also, Harmathy suggests that where lining materials are layered, the properties of the inner layer may be used.

Harmathy's method results in two equations and two unknowns. Harmathy suggests using an iterative procedure to solve the two equations. Harmathy provides a correlation for predicting the temperature during the decay period.

3.7 Method of Babrauskas

Babrauskas[52] developed an empirical post-flashover temperature model using the temperature predictions from the post-flashover computer model COMPF. The program COMPF was completed and released in 1975.[62] A comprehensive presentation of the theory was then presented as part of Babrauskas' Ph.D. dissertation.[63] The portions of the dissertation pertinent to COMPF theory were subsequently made available as a pair of journal articles. [64,65]

The original COMPF program treated only wood crib fuels or arbitrary fuels for which burning rate data were known and could be inputted. A second version, COMPF2,[66] allowed treatment of liquid and thermoplastic pools.

During the development of COMPF, it was realized that not all the input data that might be desired would necessarily be available. Thus, the idea of "pessimization" was introduced. In addition to running in a purely deterministic mode, there were two other modes of computation available. In one case, the fuel mass loss rate would be computed as usual, but window ventilation would not be set to the maximum open area. Instead, the instantaneous open area was computed by the program to always be such a value that would lead to the highest room temperature (up to the maximum full-opening size). In a second pessimization mode, the window ventilation would have a fixed value, but the fuel mass loss rate would be instantaneously adjusted to give the highest room temperature.

Babrauskas used COMPF2 to create a series of closed-form algebraic equations that can be used to estimate temperatures resulting from fully-developed fires. According to Babrauskas, estimations made using the closed-form equations are accurate to within three to five percent of COMPF2 predictions, typically closer to three percent.[54]

3.8 Ma and Mäkeläinen Method

Ma and Mäkeläinen[53] developed a parametric time-temperature curve for compartments that are small or medium in size (floor area less than 100 m^2). The method was developed for use mainly with cellulosic fires. Their aims were to develop a simple calculation procedure that would reasonably estimate the temperature, with time, of a fully-developed compartment fire.

Ma and Mäkeläinen noted that fires generally only impact the structures during the fully developed and decay stages. They developed a general shape function to define the temperature history of a compartment fire that is a function of fuel loading, ventilation conditions, and geometry and material properties of the compartment.

The general shape function was developed by non-dimensionalizing temperature-time data from twenty-five different data sets was based on the maximum gas temperature (T_{gm}) and the time to reach the maximum temperature, (t_m).

For ventilation-controlled fires, Ma and Mäkeläinen use Law's correlation to describe the duration of the fully-developed stage. For fuel-controlled fires, Ma and Mäkeläinen use Harmathy's correlation for burning rate of fuel controlled fires.

3.9 CIB Method

In 1958, under the auspices of CIB W014, laboratories from several countries investigated the factors that influence the development of enclosure fires.[54] Compartments with width:length:height dimension ratios of 211, 121, 221 & 441 (where the first number denotes compartment width, the second number denotes compartment depth, and the last number denotes compartment height normalized by the shortest dimension) with length scales of 0.5 m, 1.0 m and 1.5 m were analyzed. A total of 321 experiments were conducted in still air conditions. The fuel loading in the compartments ranged from 10-40 kg/m^2 of wood cribs with stick spacing to stick width ratios of 1/3, 1 and 3. Test data was modified through statistical analysis to account for systematic differences between test laboratories.

Average temperature and normalized burning rate were presented in graphical form. Separate graphs were presented for cribs with 20 mm thick wood sticks spaced 20 mm apart and for cribs with 20 mm wide sticks spaced 60 mm apart and cribs with 10 mm wide cribs spaced 30 mm apart. Because the cribs with 20 mm thick wood sticks spaced 20 mm apart resulted in higher compartment temperatures and lower normalized burning rates (and hence, longer predicted burning durations), these graphs were used in the analysis described herein.

The graphs were used to develop predictions of temperature and burning rate by determining the compartment geometry and determining the temperature and burning rate from the graphs.

3.10 Method of Law

Law[55] derived a method of predicting compartment temperatures resulting from fully-developed fires based by developing correlations to fit the data from tests conducted under the auspices of CIB.[54] The method was modified to improved the predictive capability for other test data as described in *SFPE Engineering Guide to Fire Exposures to Structural Elements*.[1]

3.11 Method of Cadorin

Cadorin[56] developed a model called "OZone" that was intended to predict the temperatures in a compartment fire during both the pre-flashover stage of fire growth and also post-flashover. The model was specifically written for use in structural fire resistance applications.

Ozone is comprised of a two-zone model and a one-zone model. OZone switches from a two-zone model to a one-zone model if flashover is determined to occur, if the gasses surrounding fuel that is not ignited have a higher temperature than the ignition temperature of the fuel, if the interface height descends to a defined height (the default is twenty percent of the ceiling height), or if the fire area is equal to or greater than a defined area (the default is twenty-five percent of the floor area.)

3.12 Method of Barnett

Barnett[57] developed the "BFD Curve" by curve fitting the results of one hundred forty-two fire tests. The fire tests generally used wood cribs, although seven percent used fuels other than wood cribs. The BFD Curve requires predicting the maximum temperature by using a separate correlation; for the comparisons described in this analysis, the maximum temperature was calculated using the Method of Law[54] as described in Section 3.10. "Slow," "medium" and "ultra fast" t^2 fire growth rates were assumed.

3.13 ASTM E119-10 Standard Time-Temperature Profile

The ASTM E119 Time-Temperature Profile[58] is a standardized exposure that is used to test and certify fire resistant elements. A burning duration was calculated as follows:

$$\tau_b = \frac{E \cdot A_f}{90 A_O \sqrt{H_O}}$$

Where:
τ_b = The burnout time for the enclosure fire (minutes)
E = Energy load per unit floor area of the enclosure (MJ/m^2)
A_f = Floor area of the enclosure over which combustibles are present (m^2)
A_o = Opening area (m^2)
H_o = Opening height (m)

The burning duration is determined by equating the mass loss rate of the fuel given a ventilation controlled condition to the total mass of fuel available. The exposure temperature was that of the standard time-temperature curve, and the length of the exposure was set equal to the calculated burning duration. A decay rate of 7 °C/min was also applied to the temperature profile after the fuel was consumed or the fire was stopped.

3.14 SFPE Engineering Guide to Fire Exposures to Structural Elements

Based on a more limited analysis than that contained herein, the SFPE Engineering Guide to Fire Exposures to Structural Elements[1] recommended using a either a modified Law method or the methods of Magnussen or Lie based on the compartment characteristics.

3.15 Constant Temperature

Constant temperature exposures of 1,000 °C and 1,200 °C were used as the exposure temperature. The length of the exposure was set as the burning duration, which was calculated in the same manner as described in the section on the ASTM E-119-10 Standard Time Temperature Profile. A temperature decay rate of 7 °C/min was also applied to the temperature profile after the fuel was consumed.

4.0 Basis for Comparison

Four summary measures were developed to assist with the comparisons of model predictions to test data. These summary measures were intended to reduce the results of modeling each experiment to a single point on a graph of predictions vs. measurements. Specifically, the following summary measures were used: maximum predicted temperature vs. the maximum average measured temperature, an integrated average that is derived from the mass (thickness) of steel required to prevent the steel from exceeding a temperature of 538 °C, an integrated average that is derived from the thickness of concrete required to prevent a 1.3 cm thick steel plate from exceeding a temperature of 538 °C, and an integrated average that is derived from the thickness of insulation required to prevent a 1.3 cm thick steel plate from exceeding a temperature of 538 °C. These comparison metrics are expected to provide a broad sense of the correlation predictive capability in actual applications. The straight peak and average temperature comparisons demonstrate the gross accuracy of the correlations against the data. The integrated average comparison metrics are intended to reflect the model use in predicting steel temperature increases and allows for some error compensation (i.e., if the peak temperature is over-predicted but the duration of the temperature above the measured values is short, the results will deviate less than a case in which the peak temperature is over-predicted and the temperature persists for a considerable time period).

4.1 Maximum Predicted Temperature vs. Maximum Average Measured Temperature

Predictions of temperature were compared to measured temperatures. A summary measure of the maximum predicted temperature during a fully-developed fire was compared to the maximum measured temperature during an experiment. When there were multiple thermocouples in an experimental compartment, the temperatures measured by each thermocouple were averaged at each time when measurements were taken, and the peak of the averaged temperatures was used for comparison.

Figure 10 - Figure 27 represents plots of the maximum predicted temperature and the maximum average measured temperature by correlation for all tests in the database. Also shown in Figure 10 - Figure 27 are the lines corresponding to plus or minus five and ten percent of the line of perfect agreement. The five and ten percent lines were computed using the temperature increase above ambient.

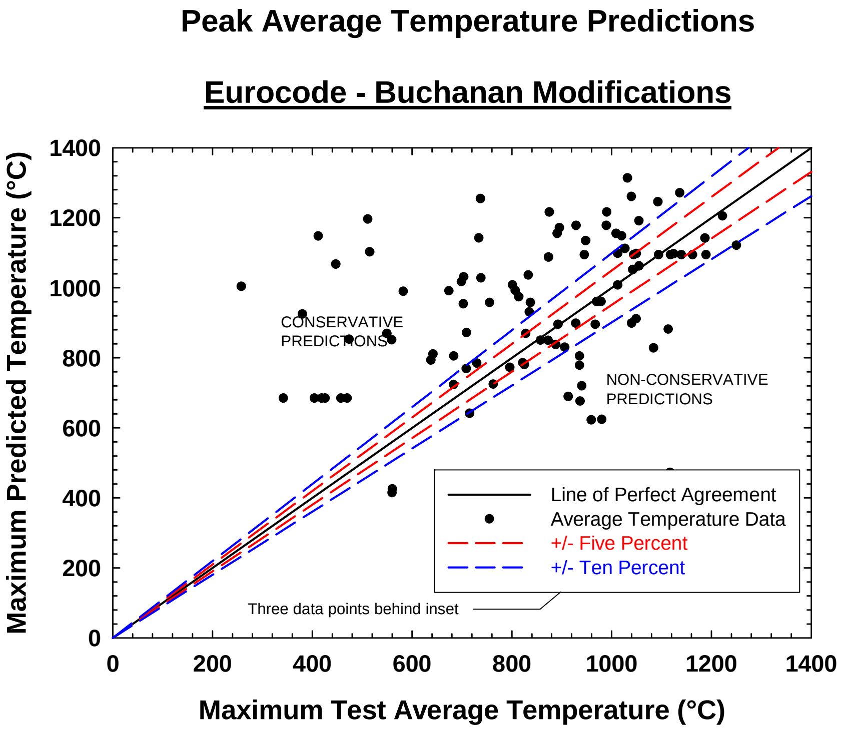


Figure 10 - Peak Temperature Analysis - Eurocode (Buchanan Modifications).

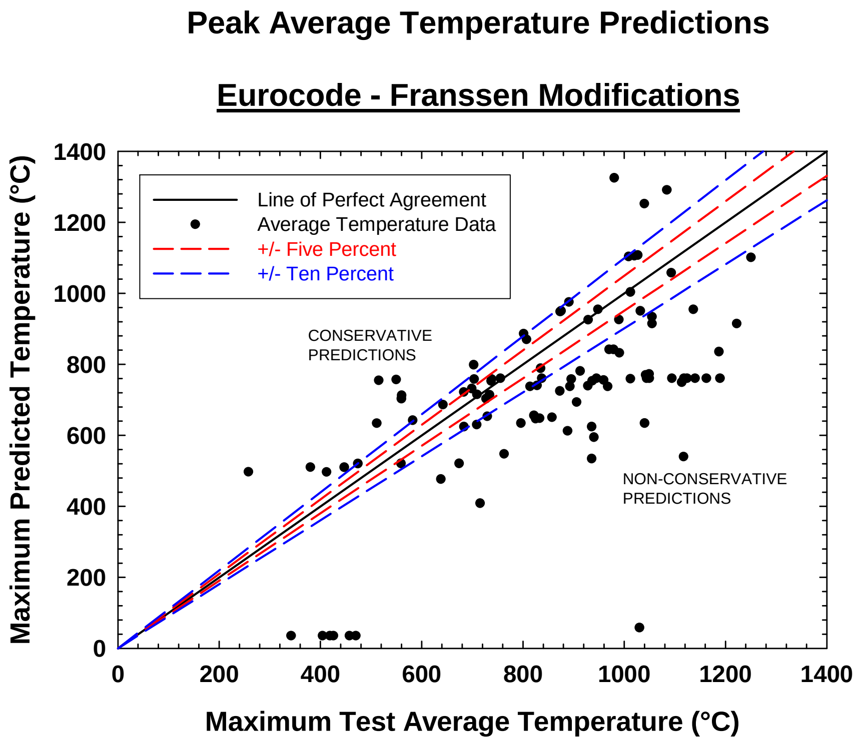


Figure 11 - Peak Temperature Analysis – Eurocode (Franssen Modifications).

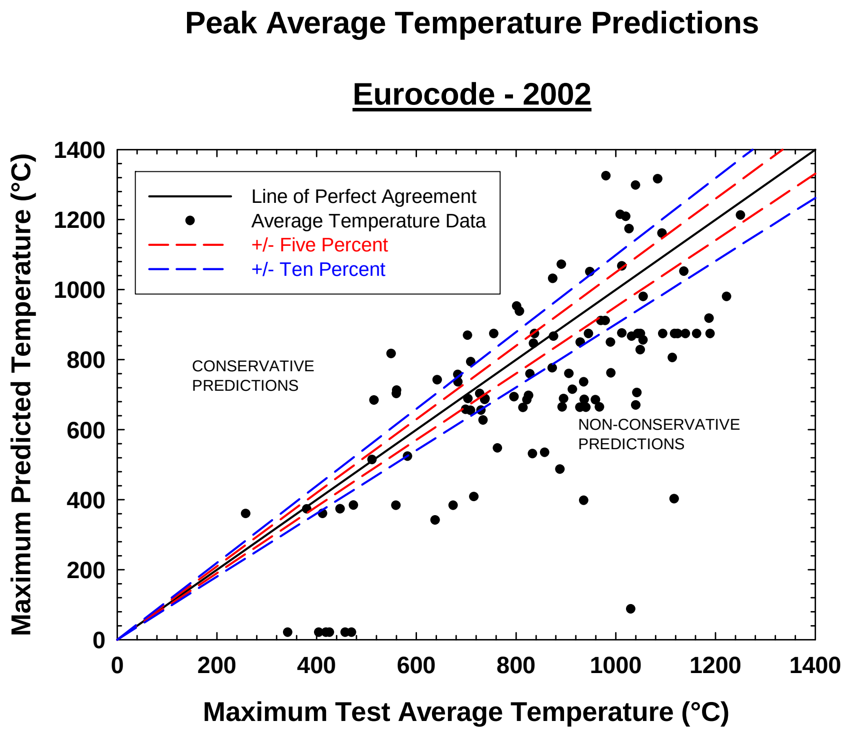


Figure 12 - Peak Temperature Analysis – Eurocode 2002.

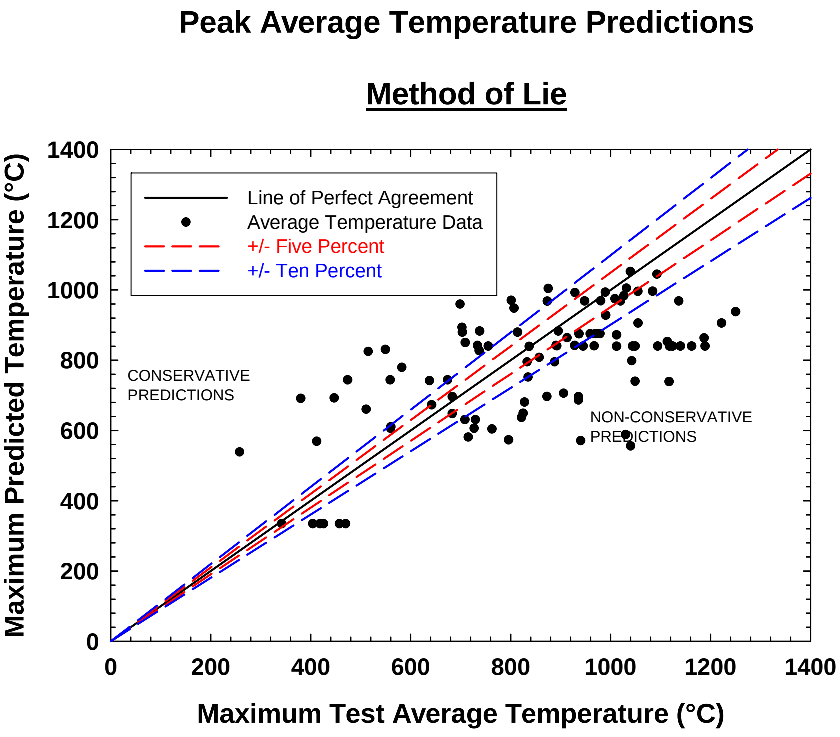


Figure 13 - Peak Temperature Analysis – Method of Lie.

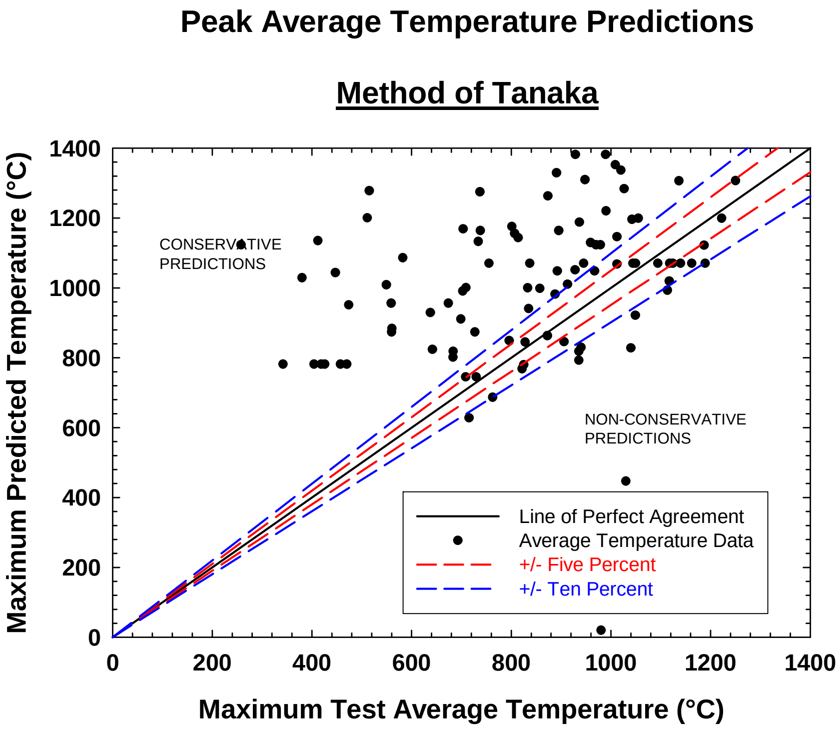


Figure 14 - Peak Temperature Analysis – Method of Tanaka.

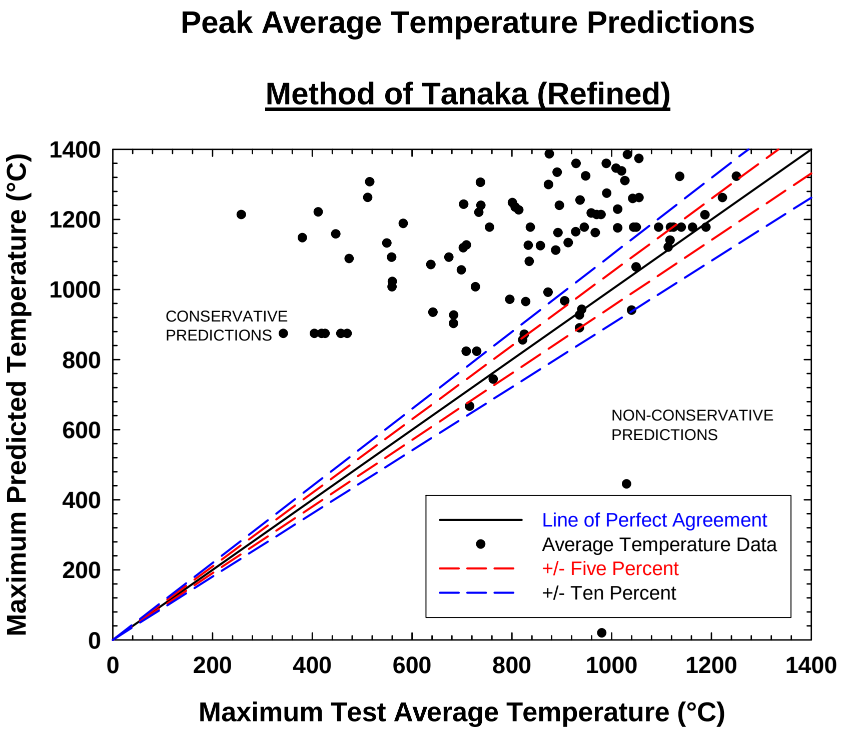


Figure 15 - Peak Temperature Analysis – Method of Tanaka (Refined).

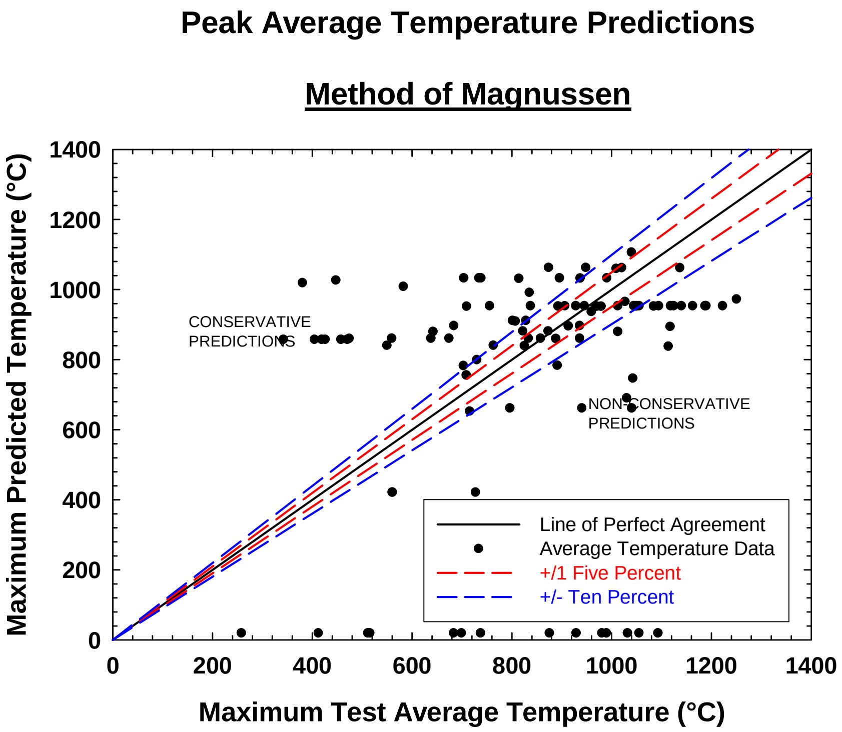


Figure 16 - Peak Temperature Analysis – Method of Magnussen.

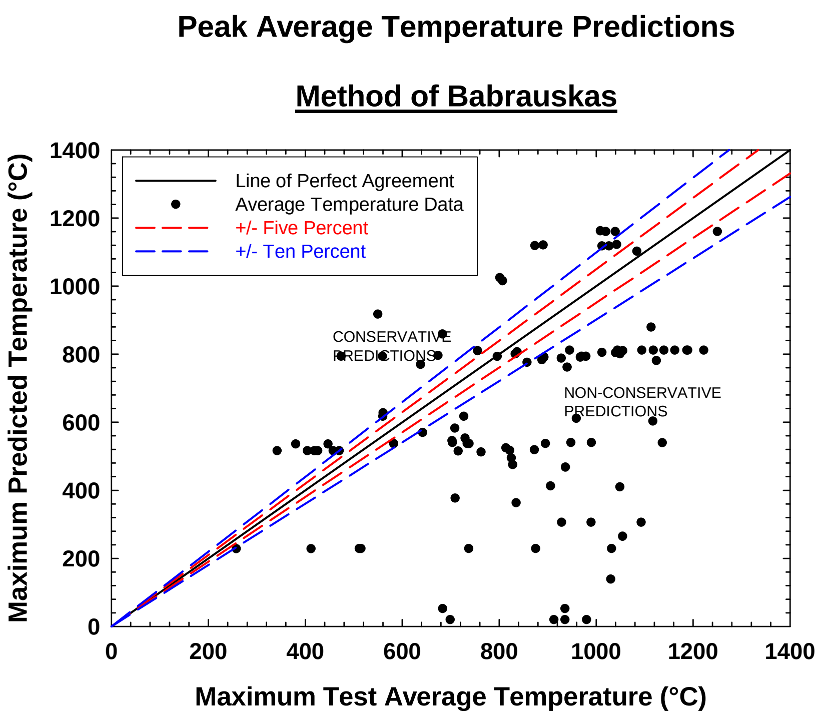


Figure 17 - Peak Temperature Analysis – Method of Babrauskas.

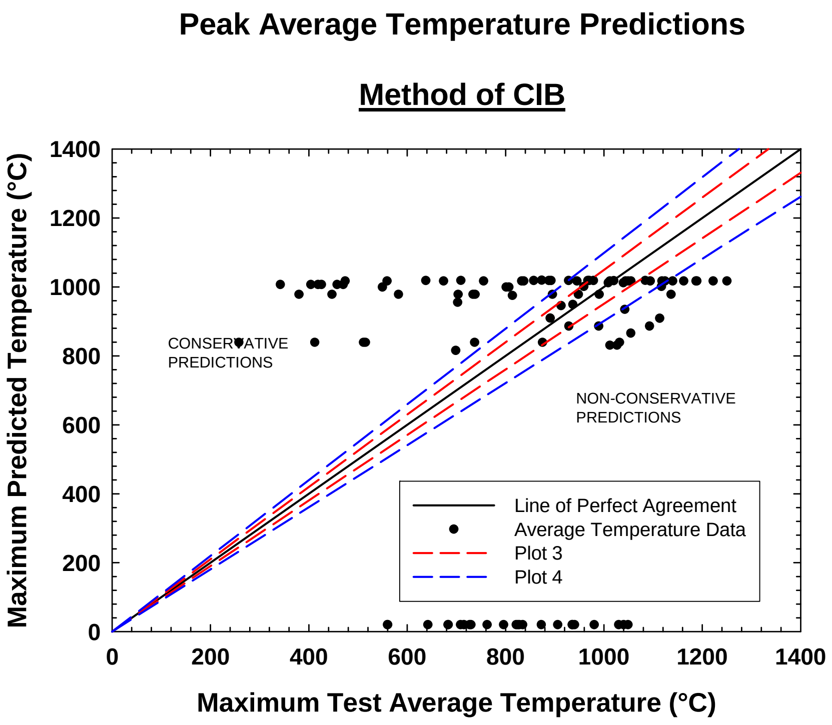


Figure 18 - Peak Temperature Analysis – Method of CIB.

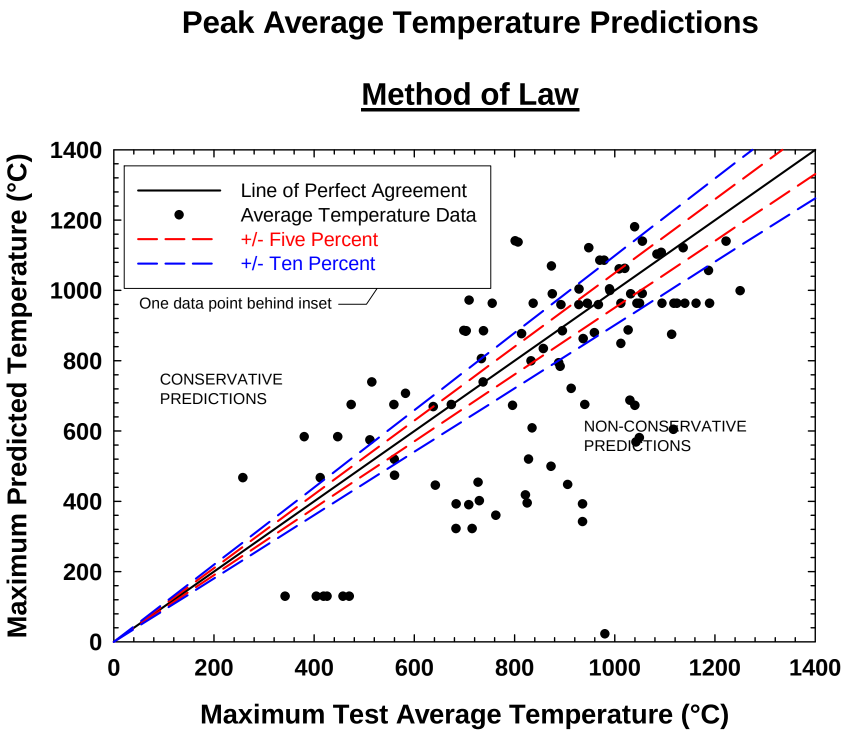


Figure 19 - Peak Temperature Analysis – Method of Law.

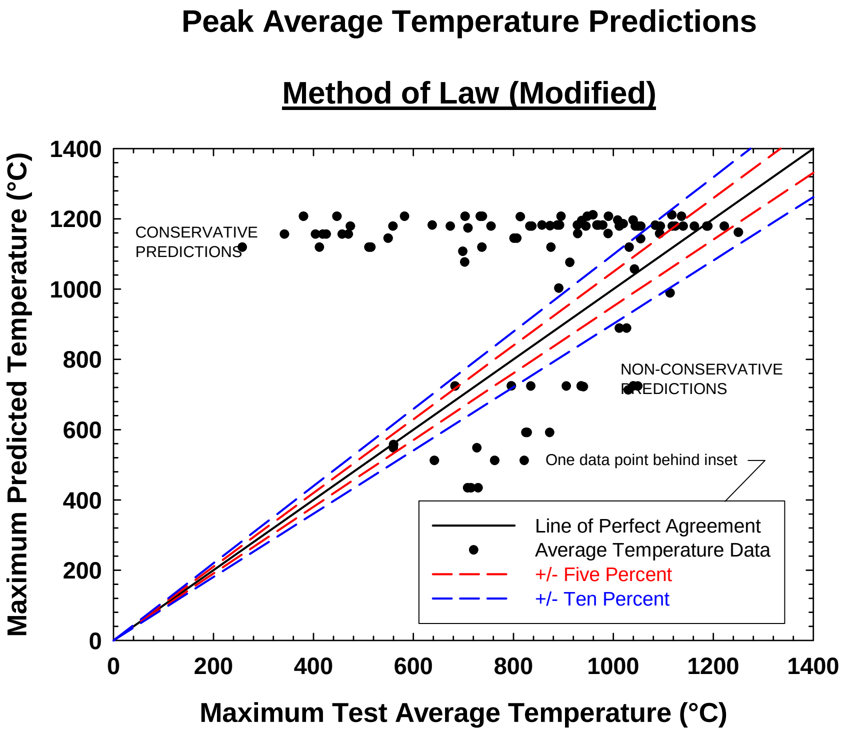
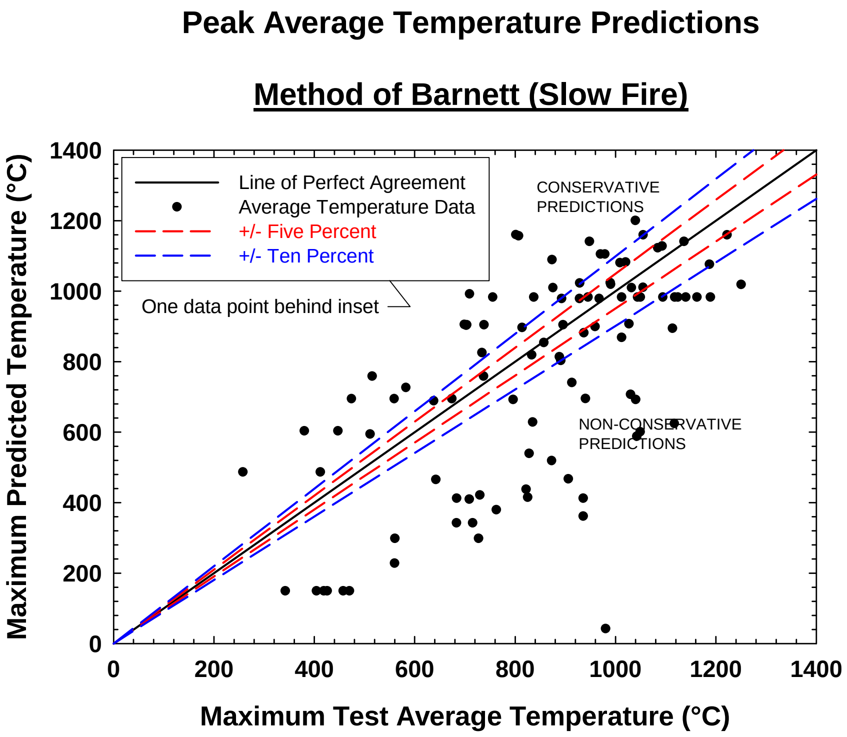
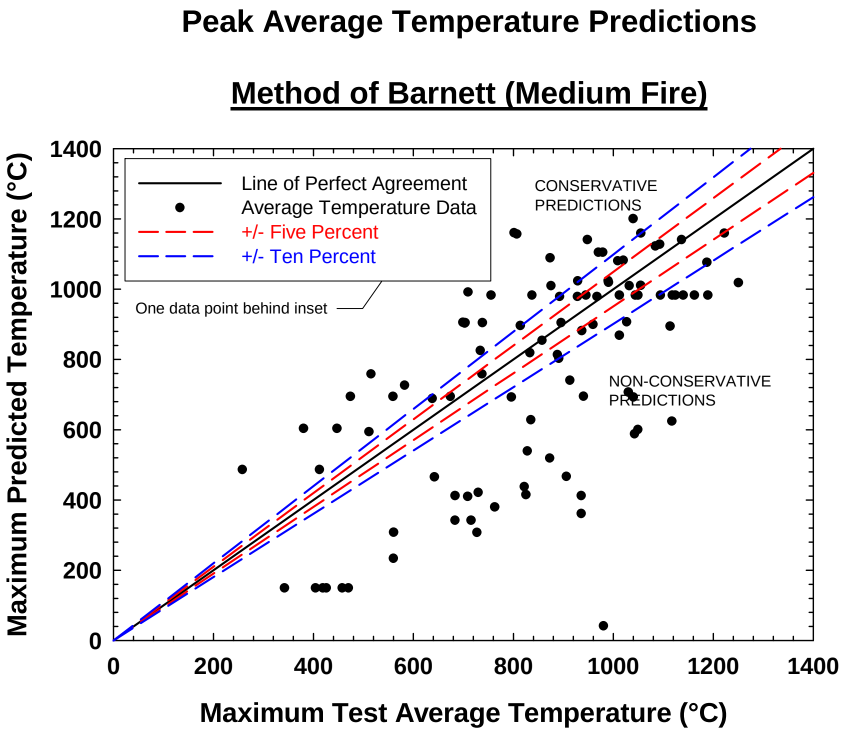


Figure 20 - Peak Temperature Analysis – Method of Law (Modified).


Peak Average Temperature Predictions

Method of Barnett (Slow Fire)

Figure 21 - Peak Temperature Analysis – Method of Barnett (Slow Growth Rate Fire).


Peak Average Temperature Predictions

Method of Barnett (Medium Fire)

Figure 22 - Peak Temperature Analysis – Method of Barnett (Medium Growth Rate Fire).

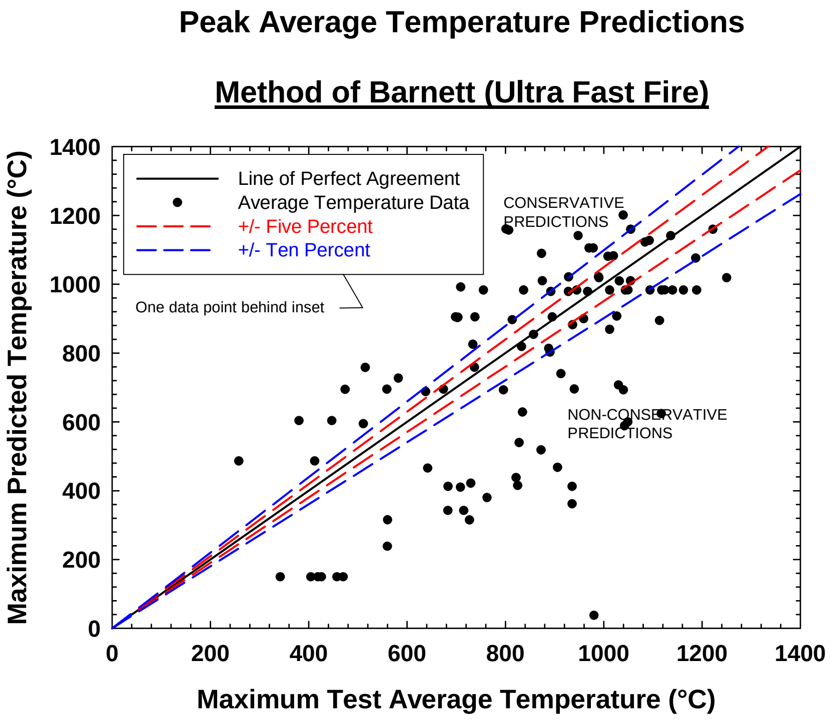


Figure 23 - Peak Temperature Analysis – Method of Barnett (Ultra Fast Growth Rate Fire).

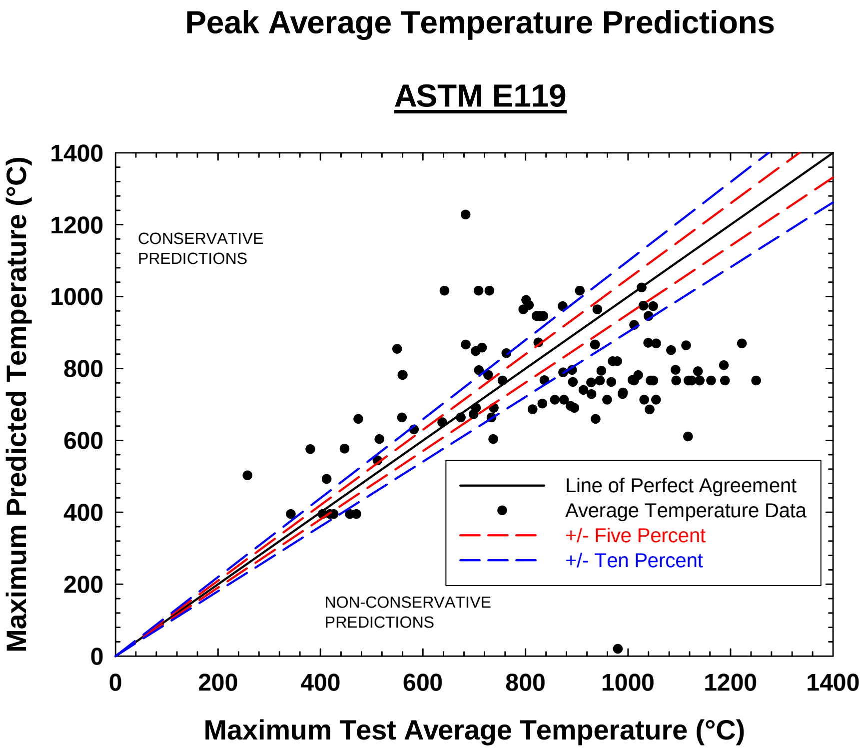


Figure 24 - Peak Temperature Analysis – ASTM E119 Fire Exposure.

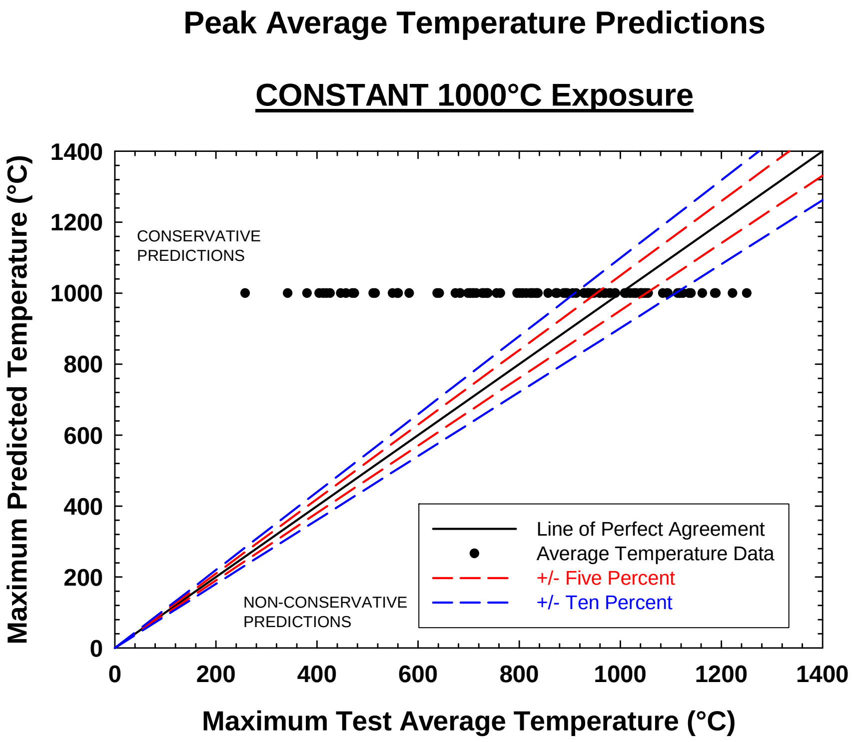


Figure 25 - Peak Temperature Analysis – Constant Exposure Temperature (1,000 °C).

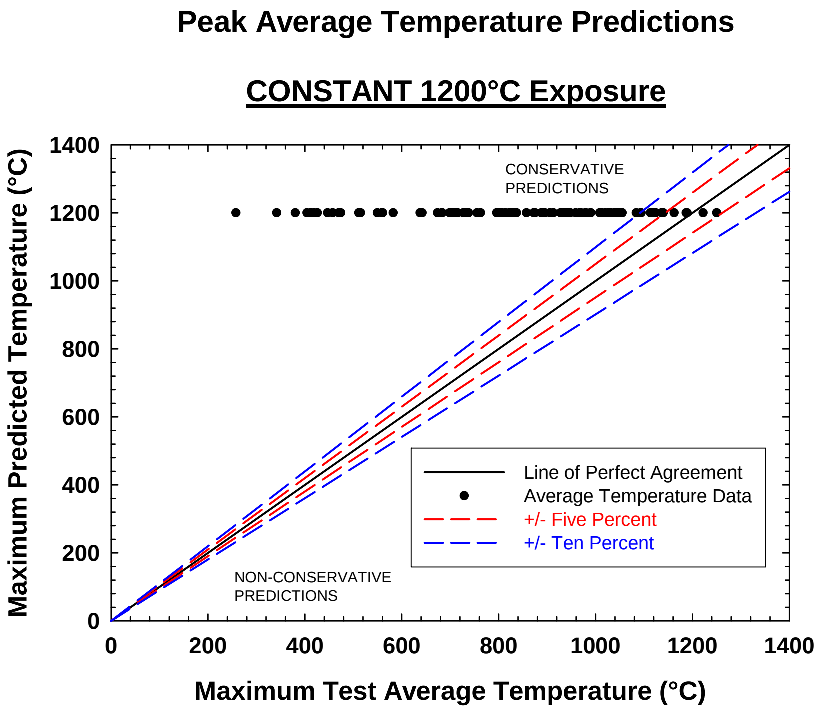


Figure 26 - Peak Temperature Analysis – Constant Exposure Temperature (1,200 °C).

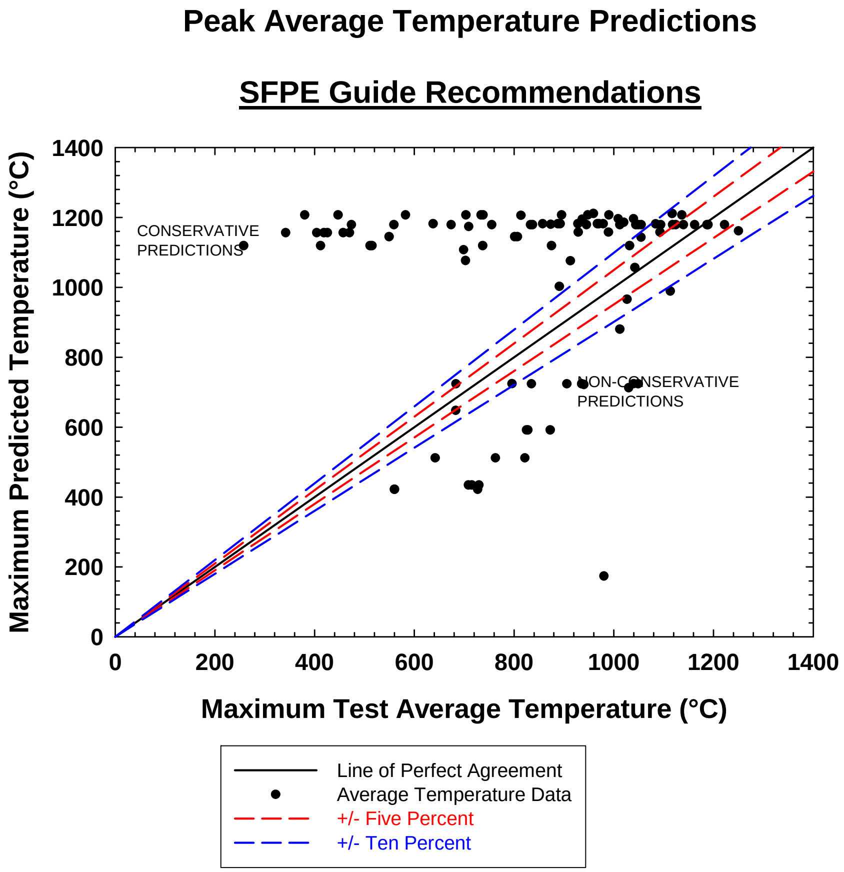


Figure 27 - Peak Temperature Analysis – SFPE Guide Recommendation.

The temperature results provide a direct indication of the performance of the correlations. Some correlations tend to predict compartment temperatures within a narrow band:

- Magnussen: 800 to 1,000 °C
- Harmathy: 200 to 400 °C
- Ma and Makelainen: 100 to 200 °C and ~1,000 °C
- CIB: 800 to 1,000 °C
- Modified Law: 1,000 to 1,200 °C
- Cadorin: 600 °C
- SFPE Guide Recommended Approach: 1,100 to 1,200 °C

- 1,000 °C and 1,200 °C constant exposures: by definition predict 1,000°C and 1,200 °C, respectively)

The Eurocode methods, Tanaka methods, Method of Law, Method of Barnett, and the ASTM E119-10 exposure predictions exhibit a great deal of scatter about the line of perfect agreement. Other than a constant 1,200°C exposure, only the method of Tanaka and the Tanaka Refined method provide predictions of peak temperatures that are generally greater than those measured.

Methods that appear to trend in the correct direction include Eurocode 2002, Method of Barnett (any fire growth rate), and the ASTM E119-10 Standard Time-Temperature Profile.

If the prediction of the peak temperature were the only metric of concern, the results of this analysis indicate that the most logical selection would be either Tanaka Refined or a 1,200 °C constant exposure.

4.2 Bare Steel Lumped Mass Evaluation

An integrated measure of temperature was developed by determining the thickness of steel that would be required to prevent the steel from exceeding a temperature of 538 °C. Bare steel was modeled as being exposed to predicted temperatures using each method and to the temperatures from experiments. When there were multiple thermocouples in an experimental compartment, the peak temperatures measured at each time during the exposure were used as the exposure temperature. If the peak temperatures measured among the thermocouples were not available, then the temperatures measured by each thermocouple were averaged at each time when measurements were taken, and these average temperatures were used as the exposure temperature.

The predicted temperatures and the measured temperatures from experiments were used as input into a heat transfer analysis. An imaginary, one-dimensional (Cartesian) sample was exposed on one side to predicted temperatures and to the measured temperatures. The temperatures were converted to a heat flux using a radiation boundary condition and an emissivity and absorbtivity of 1.0 and a convection boundary condition using a convective heat transfer coefficient of 30 W/m^2K. Thermal properties for A36 steel were used as presented by Abrams.[67] The steel was modeled as a lumped mass; thus there was no temperature gradient across the steel regardless of the computed thickness. The steel effectively functioned as an energy absorber.

Based on the radiation and convection boundary conditions, the thickness of steel required to prevent the steel from exceeding a temperature of 538 °C was determined. The basis for comparison was the thickness of steel determined using the model predictions and the thickness of steel determined using the test data.

Comparisons of the calculated steel thicknesses are shown in Figure 28 - Figure 45. Points falling above the line of perfect agreement are conservative insofar as the steel thickness predicted by the correlation is greater than that predicted using the test data. The reverse is true for data falling below the line of perfect agreement. Also shown in Figure 28 - Figure 45 are the lines corresponding to plus or minus five and ten percent of the line of perfect agreement.

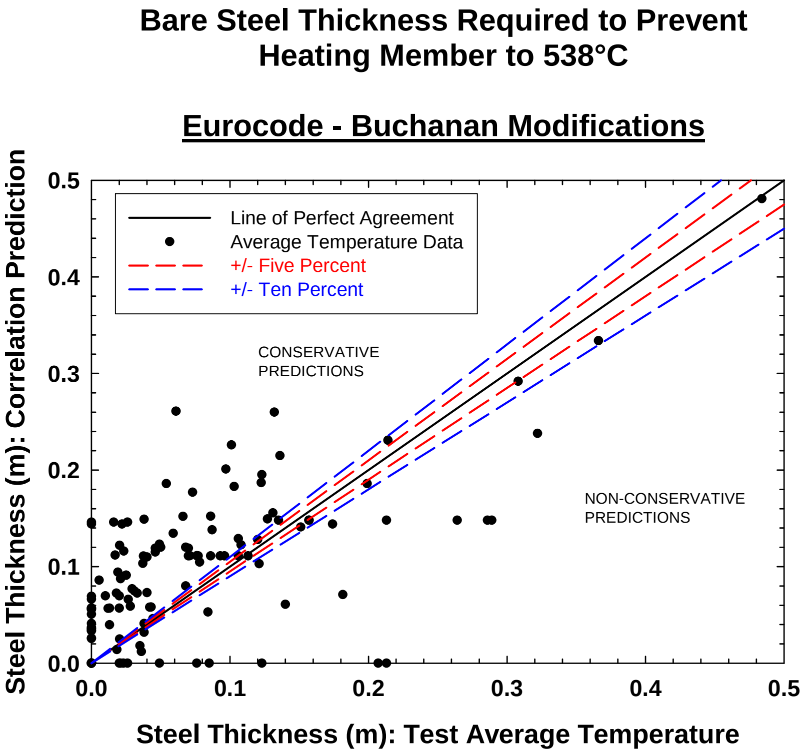


Figure 28 - Bare Steel Lumped Mass Evaluation Results – Eurocode– Buchanan Modifications.

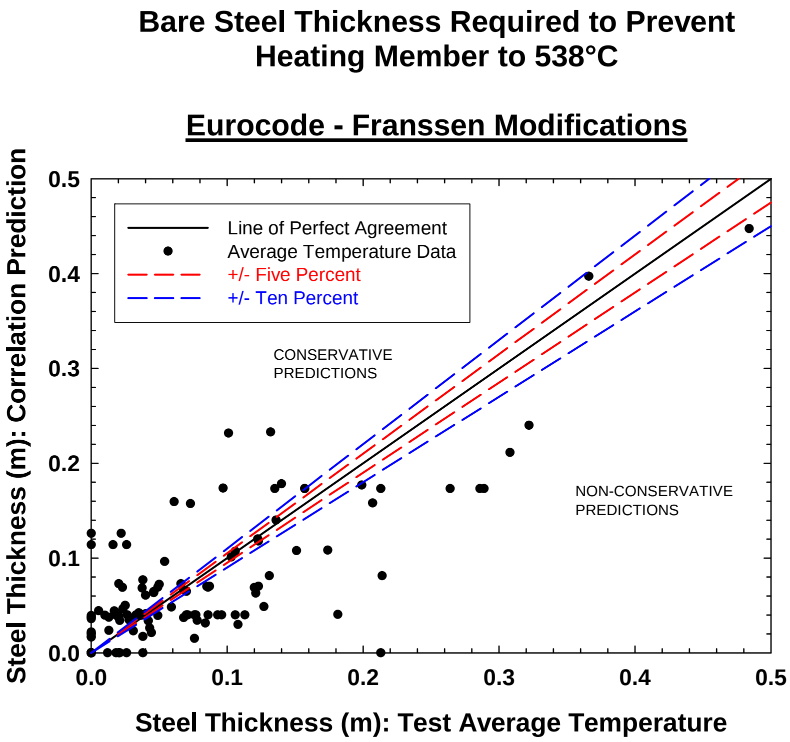


Figure 29 - Bare Steel Lumped Mass Evaluation Results – Franssen Modifications.

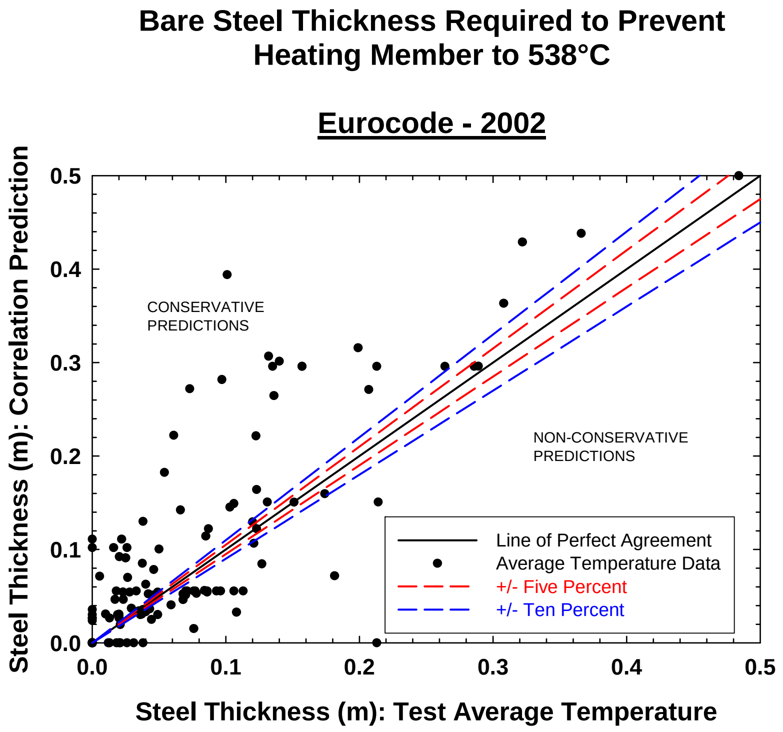


Figure 30 - Bare Steel Lumped Mass Evaluation Results – Eurocode 2002.

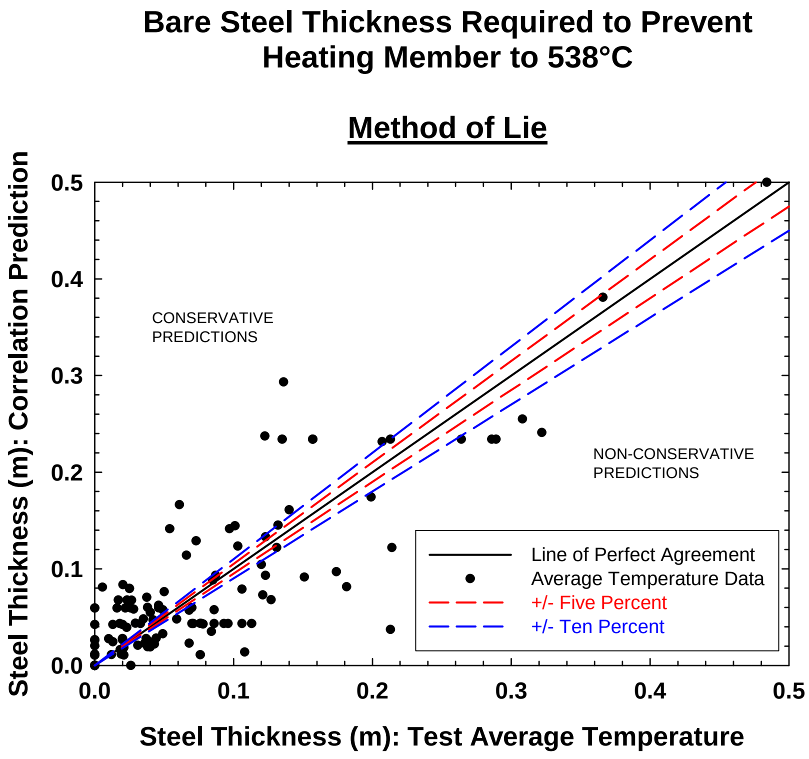


Figure 31 - Bare Steel Lumped Mass Evaluation Results – Method of Lie.

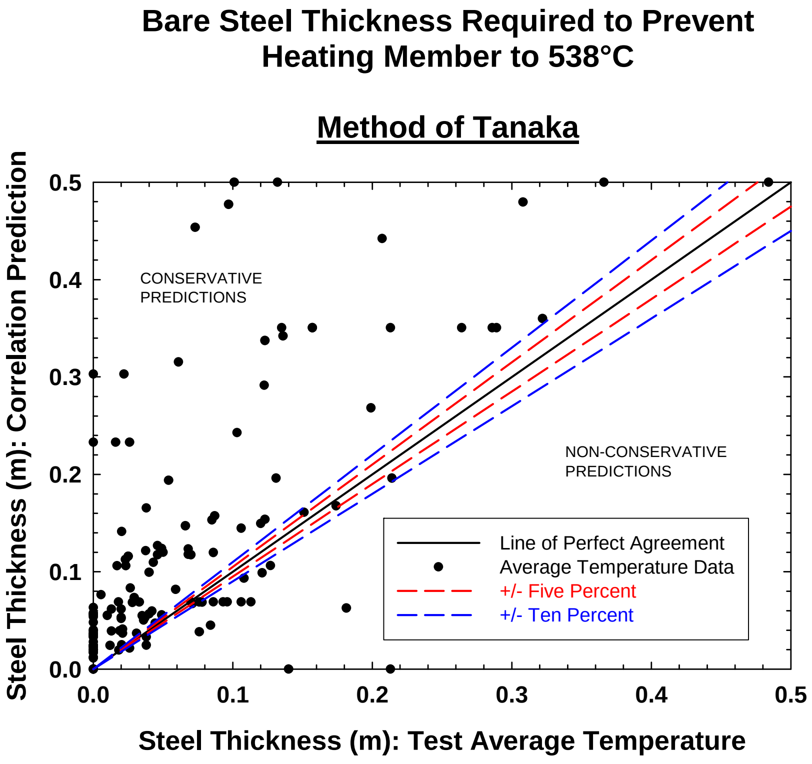


Figure 32 - Bare Steel Lumped Mass Evaluation Results – Method of Tanaka.

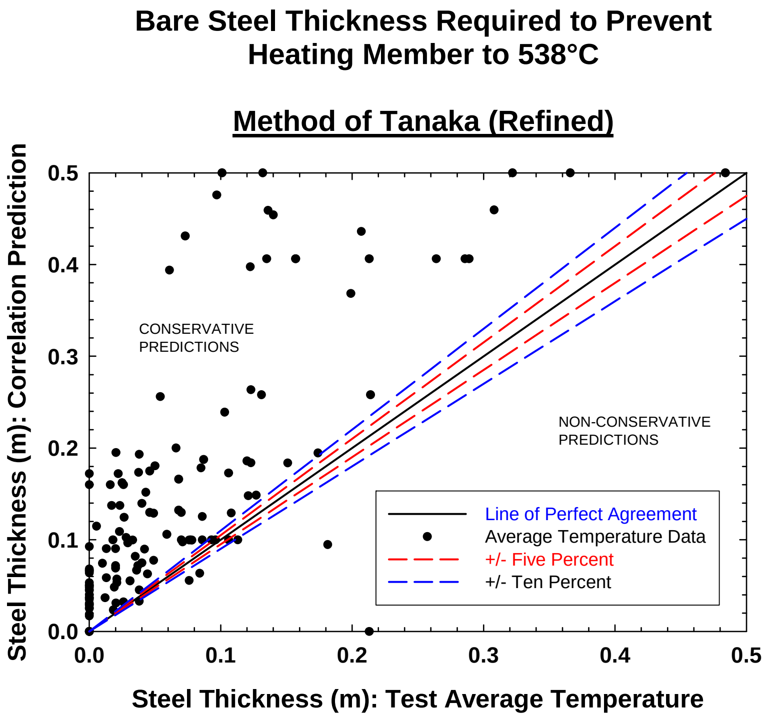


Figure 33 - Bare Steel Lumped Mass Evaluation Results – Method of Tanaka (Refined).

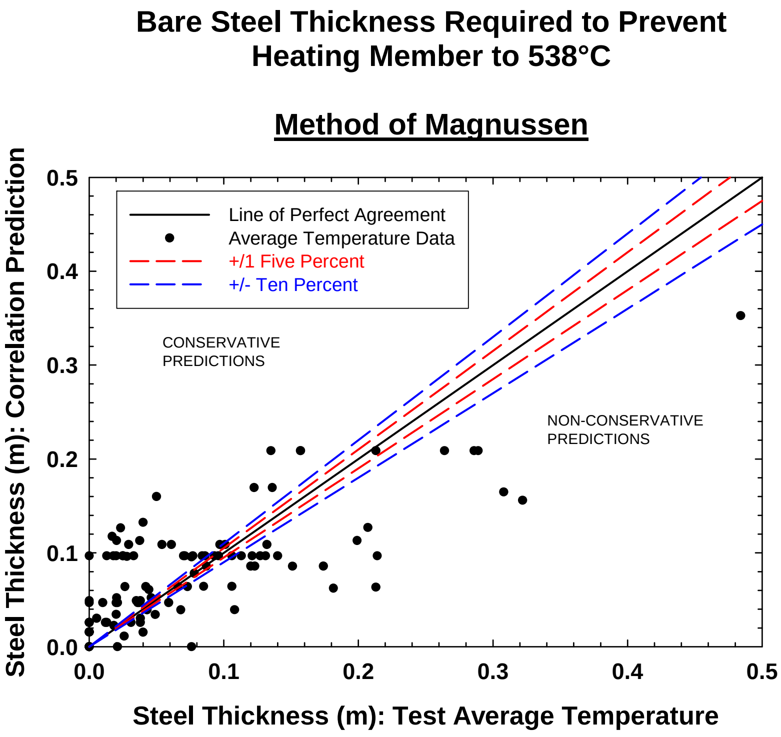


Figure 34 - Bare Steel Lumped Mass Evaluation Results – Method of Magnussen.

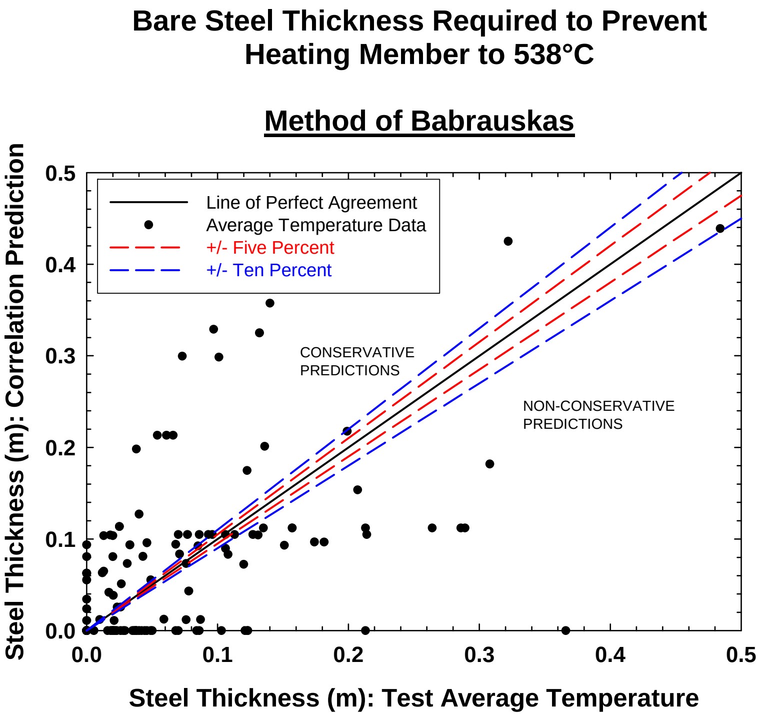


Figure 35 - Bare Steel Lumped Mass Evaluation Results – Method of Babrauskas.

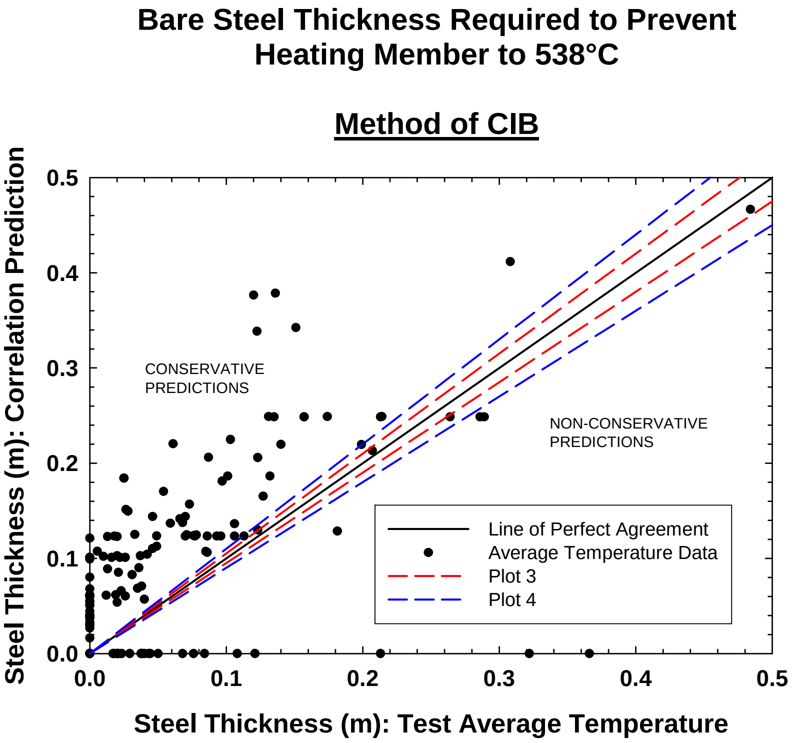


Figure 36 - Bare Steel Lumped Mass Evaluation Results – Method of CIB.

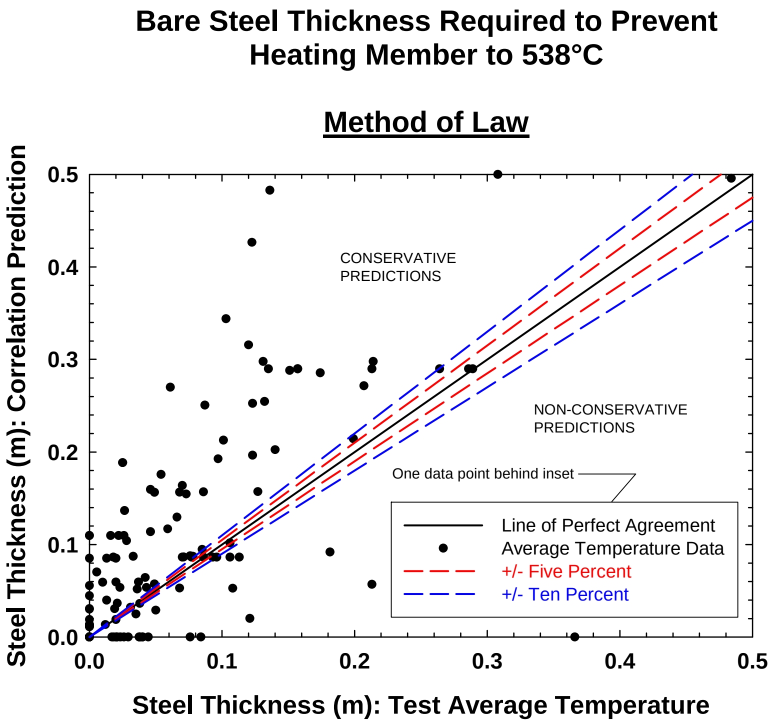


Figure 37 - Bare Steel Lumped Mass Evaluation Results – Method of Law.

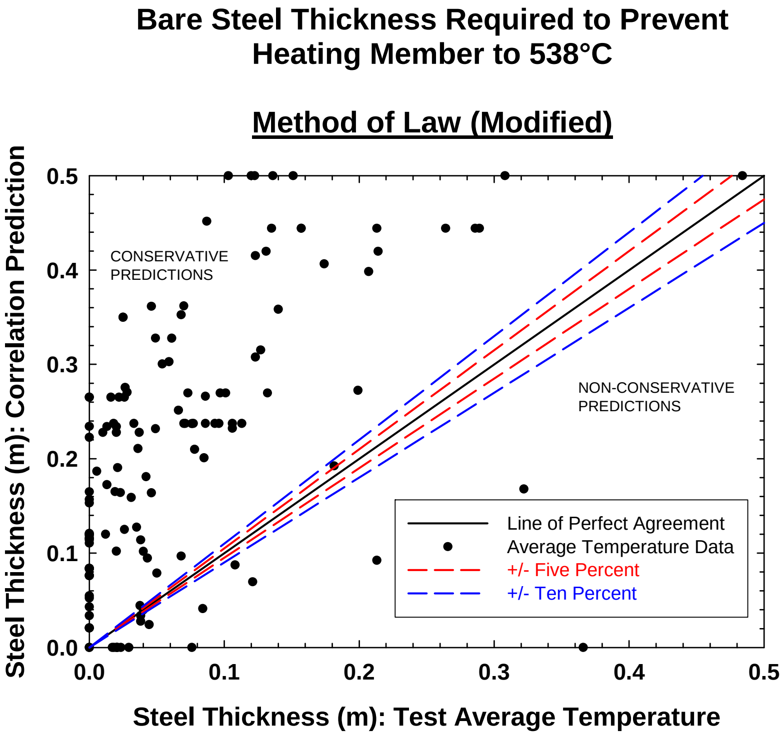


Figure 38 - Bare Steel Lumped Mass Evaluation Results – Method of Law (Modified).

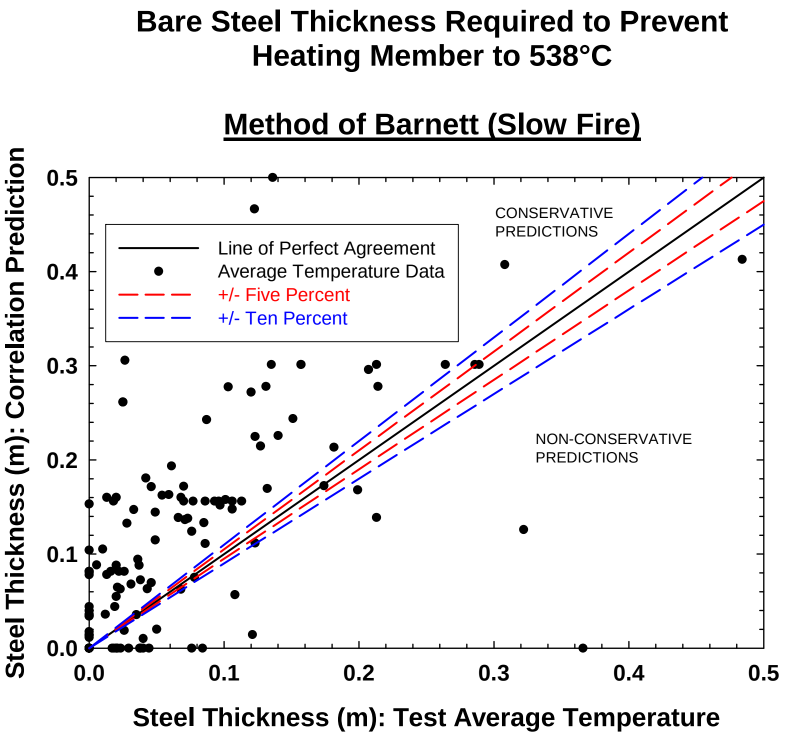


Figure 39 - Bare Steel Lumped Mass Evaluation Results – Method of Barnett (Slow Fire).

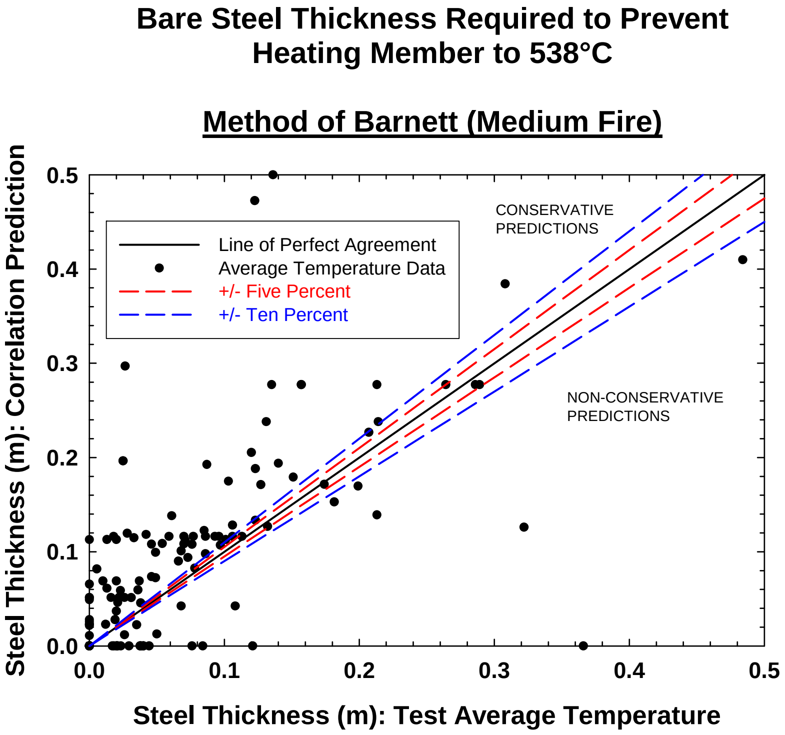


Figure 40 - Bare Steel Lumped Mass Evaluation Results – Method of Barnett (Medium Fire).

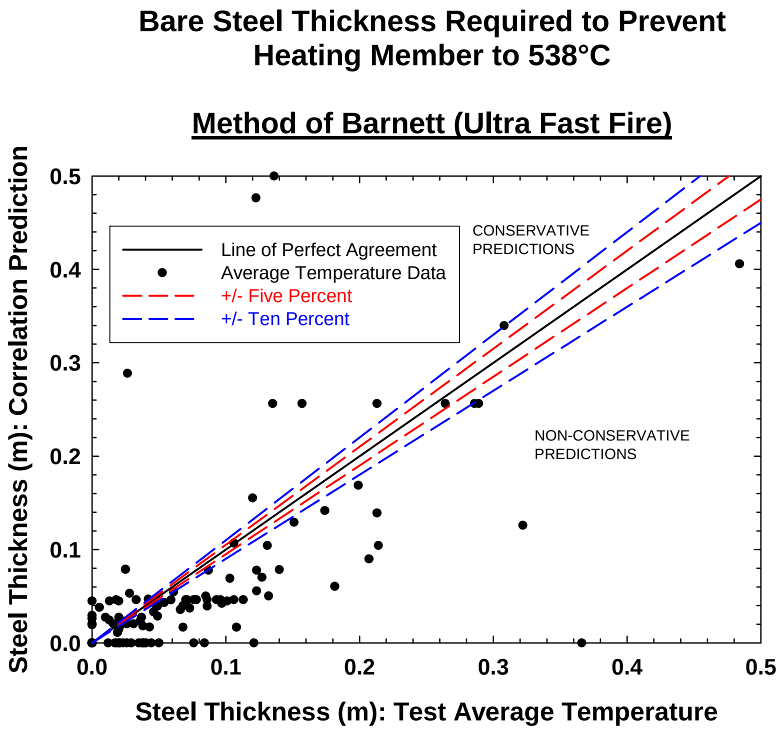


Figure 41 - Bare Steel Lumped Mass Evaluation Results – Method of Barnett (Ultra Fast Fire).

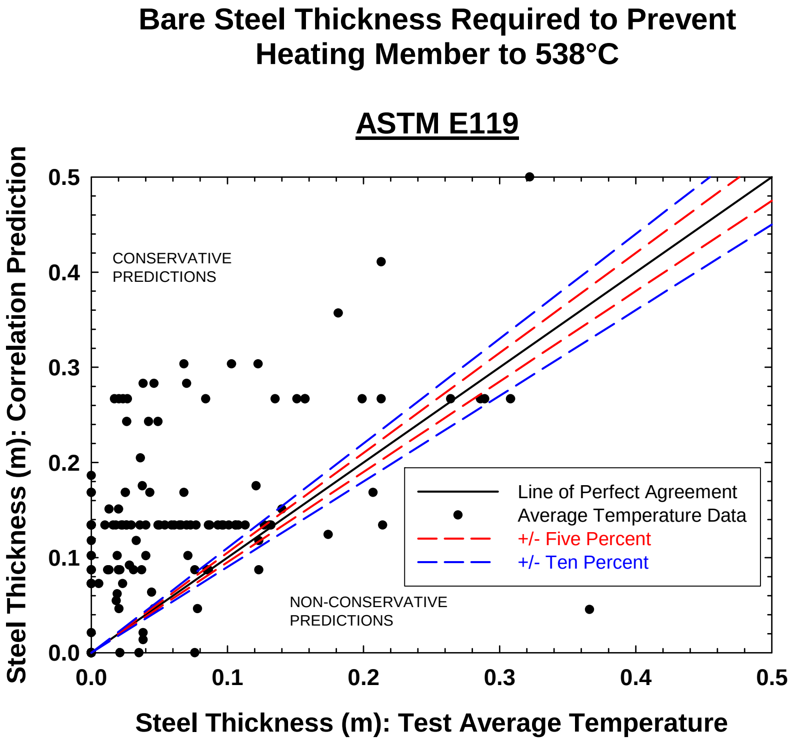


Figure 42 - Bare Steel Lumped Mass Evaluation Results – ASTM E119 Fire Exposure.

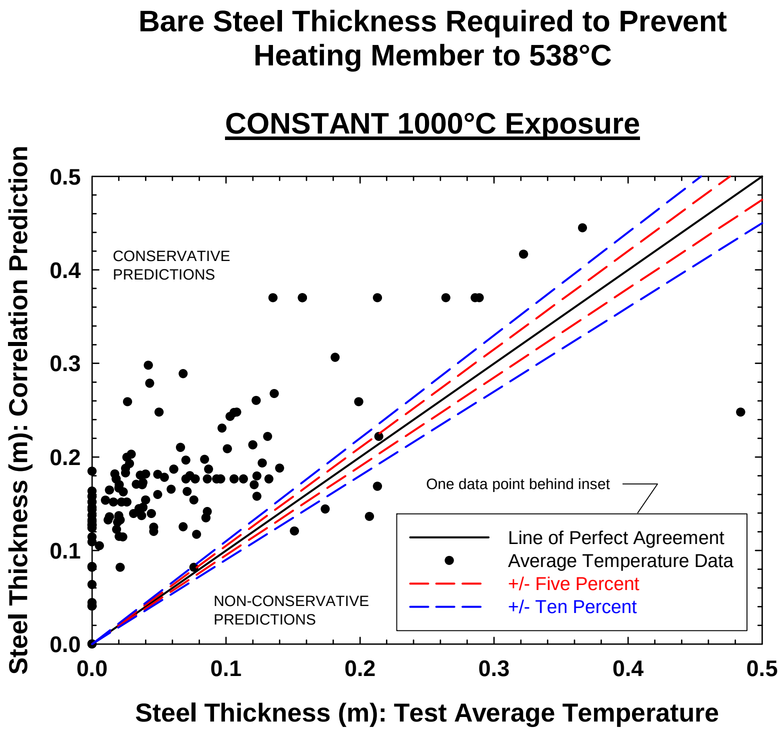


Figure 43 - Bare Steel Lumped Mass Evaluation Results – Constant Fire (1,000 °C).

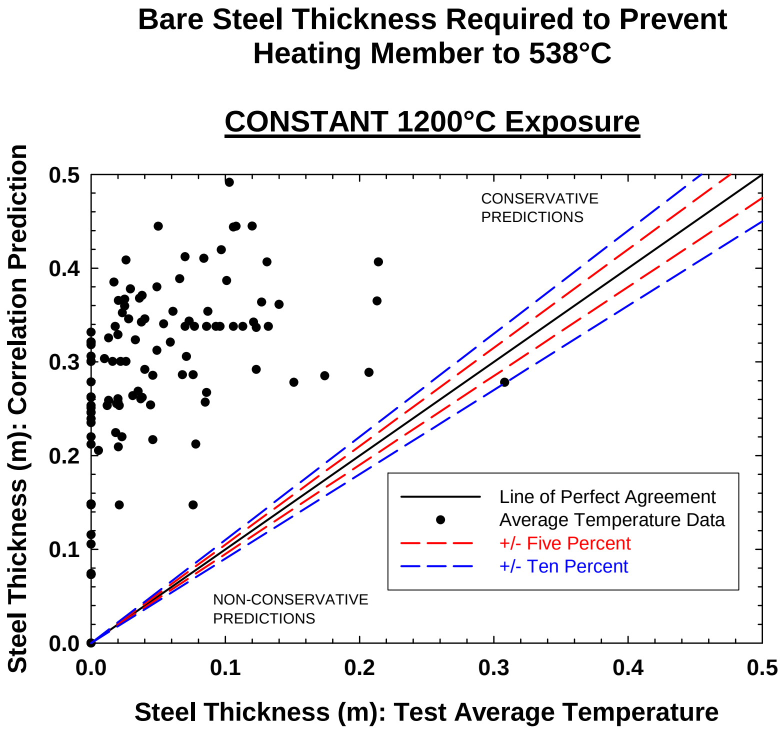


Figure 44 - Bare Steel Lumped Mass Evaluation Results – Constant Fire (1,200 °C).

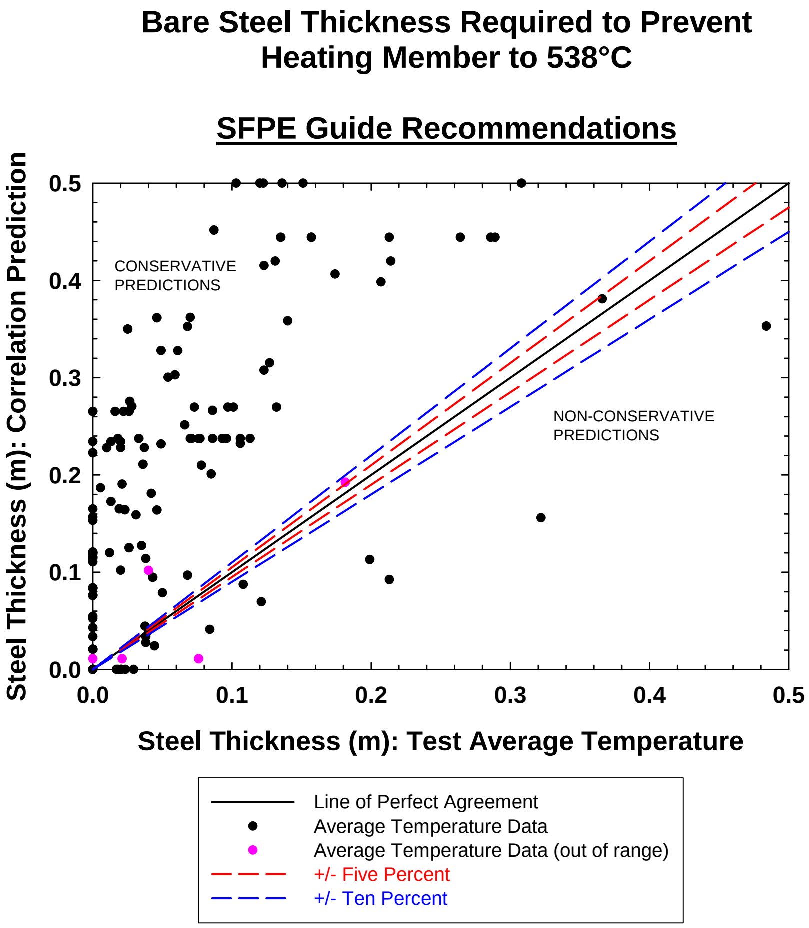


Figure 45 - Bare Steel Lumped Mass Evaluation Results – SFPE Guide Recommendations

From the bare steel lumped mass comparison of predictions and test data, no single method systematically predicted the thickness of steel required to keep the temperature below 538 °C to a high degree of accuracy. Deviations from the line of perfect agreement range from zero to many hundred percent for each method.

No single method consistently provided predictions of steel thickness that was equal to or greater than the steel thickness calculated based on the experimental data. The only exception was the constant 1,200 °C exposure. There was significant variation in the number of tests that are conservatively predicted among the methods evaluated.

There was no substantial difference between the correlations and the ASTM E119 or constant 1000 ^{o}C exposure with regard to predicting the thickness of bare steel necessary to prevent heating to a temperature of 538 °C. As such, the correlations offer no improvement relative to the simplistic approach. The ASTM E119 and constant 1000 °C exposure both resulted in an over-prediction of approximately the same number of data points as the other correlations considered; however, the ASTM E119 and constant 1000 °C exposure were less conservative.

A 1,200 °C constant exposure yielded the most conservative results based on the number of cases in which the calculated steel thickness based on the predictive method is equal to or greater than that calculated based on experimental data. The methods of Law (modified), Tanaka and Barnett were the most conservative among the correlations evaluated. The method of Babrauskas had lower scatter in the data than other methods evaluated.

4.3 Insulation-Protected Steel Plate Finite Difference Computation

For this analysis, an integrated measure of temperature was developed by determining the thickness of insulation required to prevent a 1.2 cm thick steel plate from exceeding a temperature of 538 °C. The insulation was modeled as being exposed to predicted temperatures using each method and to the temperatures from experiments. When there were multiple thermocouples in an experimental compartment, the peak temperatures measured at each time during the exposure were used as the exposure temperature. If the peak temperatures measured among the thermocouples were not available, then the temperatures measured by each thermocouple were averaged at each time when measurements were taken, and these average temperatures were used as the exposure temperature.

The predicted temperatures and the measured temperatures from experiments were used as input into a heat transfer analysis. An imaginary, one-dimensional (Cartesian) sample was exposed on the insulated side to predicted temperatures and to the measured temperatures. Blazeshield D-C/F was the insulation used in this comparison metric. The thermal conductivity and heat capacity vary with temperature as presented by Harmathy.[68]

The exposure temperatures were converted to a heat flux using a radiation boundary condition and an emissivity and absorbtivity of 1.0 and a convection boundary condition using a convective heat transfer coefficient of 30 W/m^{2}K. Thermal properties for A36 steel were used as presented by Abrams.[67]

An adiabatic boundary condition was applied on the unexposed steel surface and zero contact resistance was assumed at the steel-insulation interface. A finite difference heat transfer analysis was conducted where the insulation thickness was optimized (set equal to the thickness that allowed the steel to reach 538 °C at the conclusion of the exposure) to the nearest millimeter. The steel was modeled as having no thermal gradients. Figure 46 depicts the geometry modeled.

The basis for comparison was the thickness of insulation determined using the model predictions and the thickness of insulation determined using the test data.

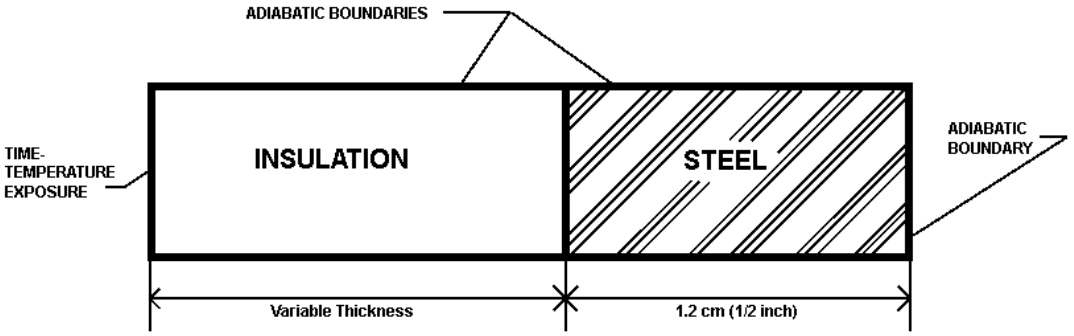


Figure 46 - Insulation-Steel System Model.

The calculated insulation thickness results are shown in Figure 47 - Figure 64. The insulation thickness predicted using experimental temperature data was plotted against the insulation thickness predicted for each method or method variation. Points falling above the line of perfect agreement are conservative insofar as the insulation thickness predicted by the correlation temperature profile was greater than that predicted using the measure test temperature profile. The reverse is true for data falling below the line of perfect agreement. Also shown in Figure 47 - Figure 64 are the lines corresponding to plus or minus five and ten percent of the line of perfect agreement.

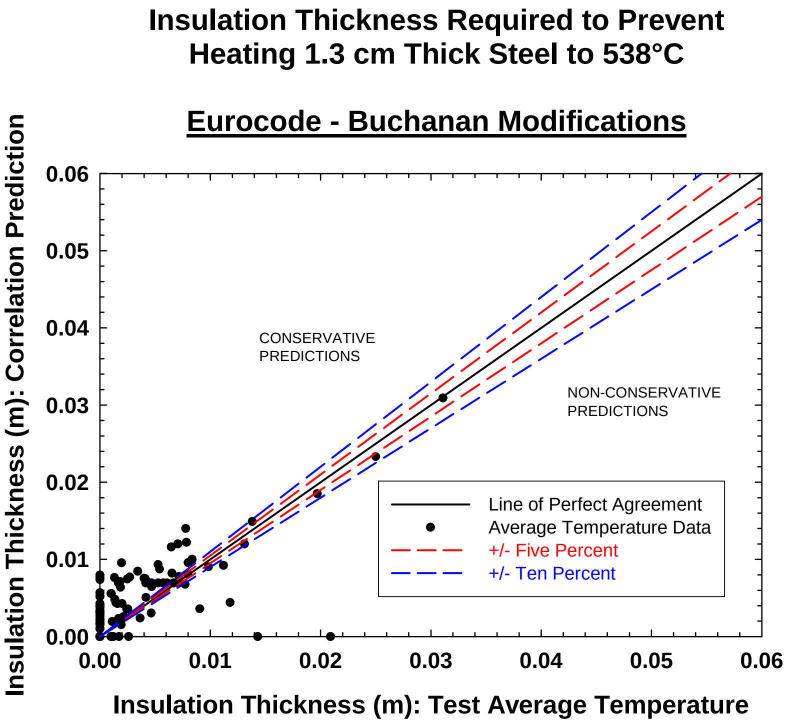


Figure 47 - Insulated Steel Results – Eurocode (Buchanan Modifications).

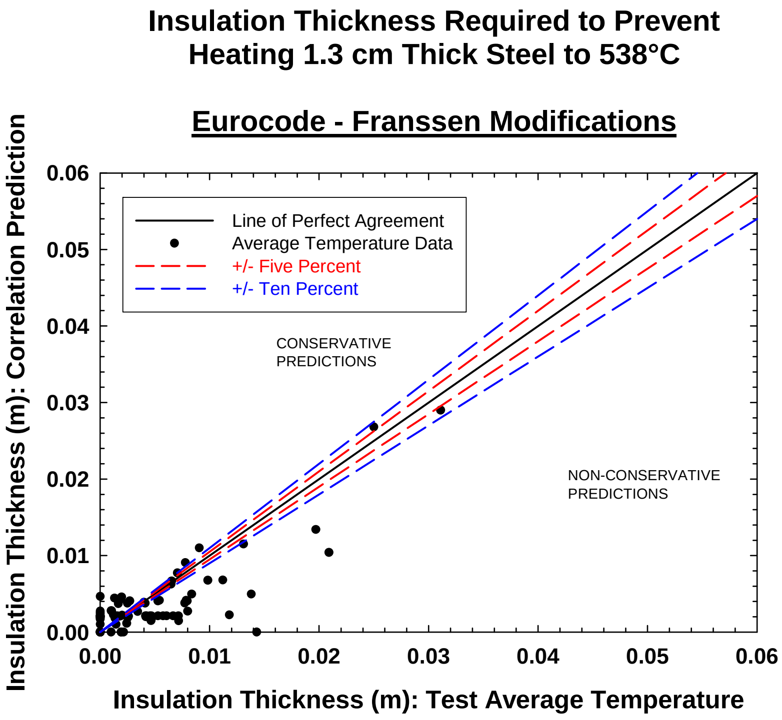


Figure 48 - Insulated Steel Results – Eurocode (Franssen Modifications).

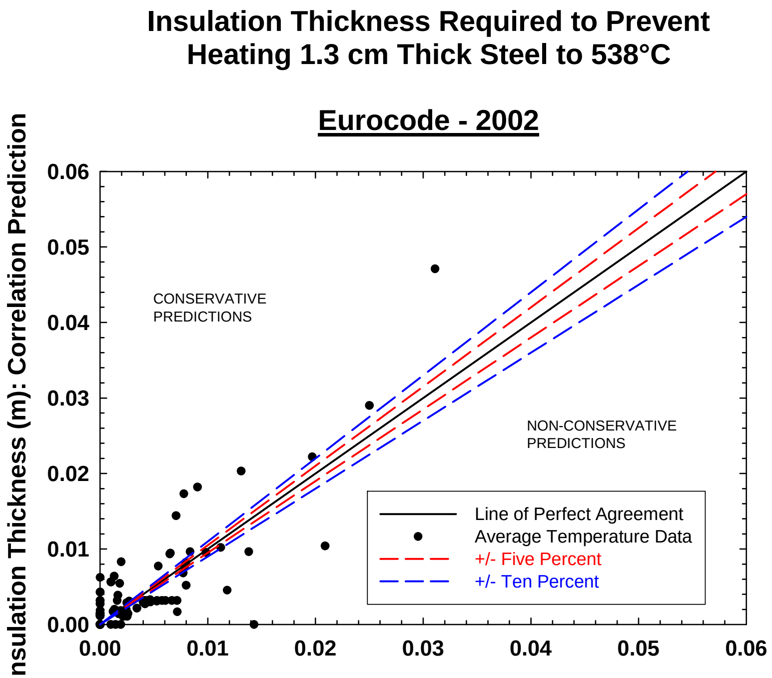


Figure 49 - Insulated Steel Results – Eurocode 2002.

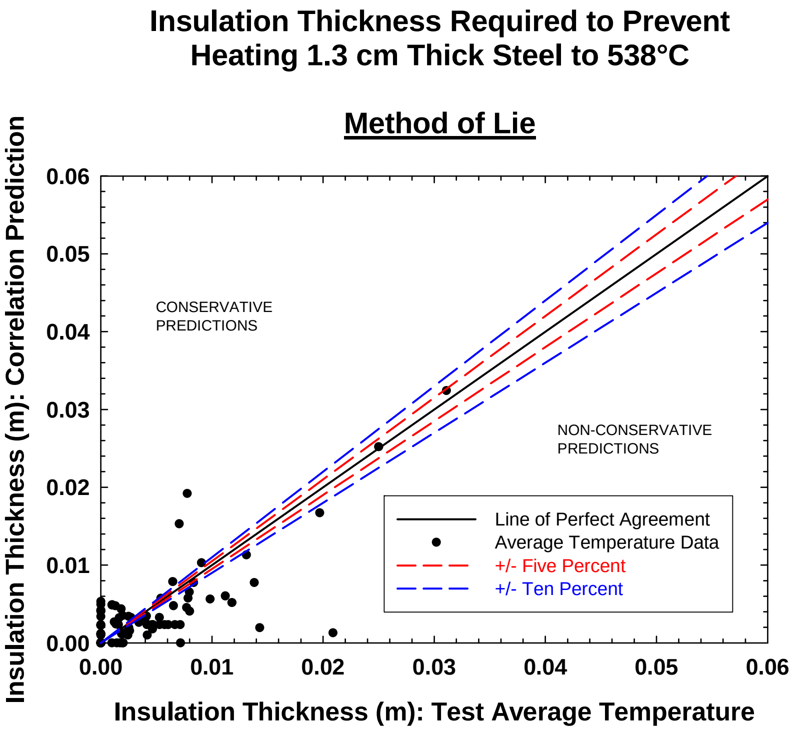


Figure 50 - Insulated Steel Results – Method of Lie.

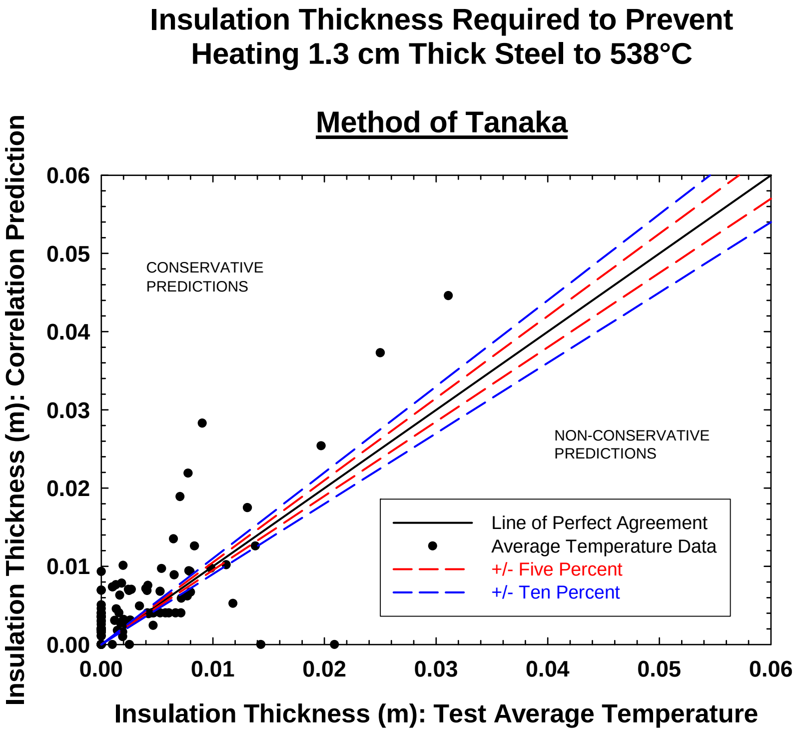


Figure 51 - Insulated Steel Results – Method of Tanaka.

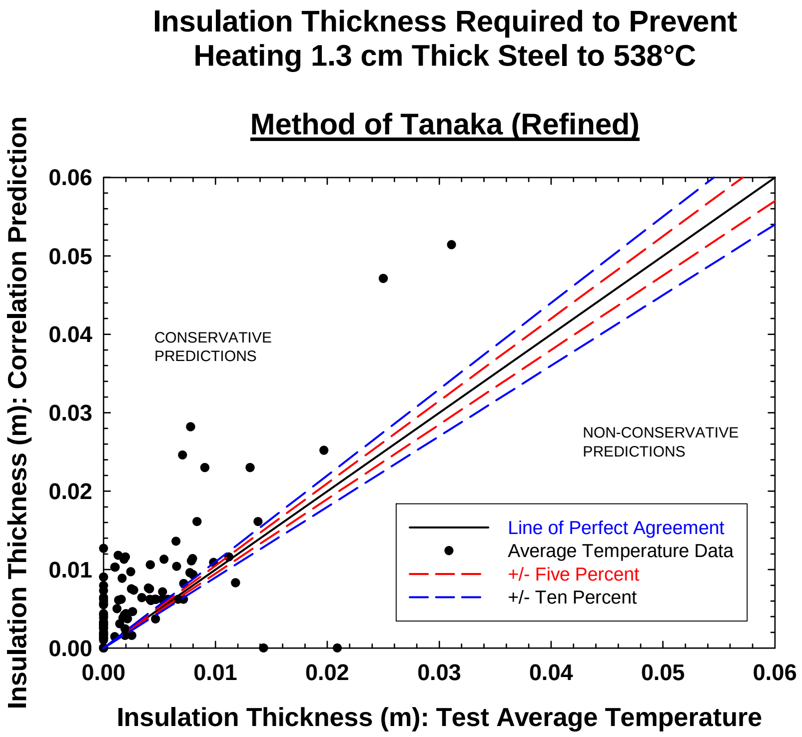


Figure 52 - Insulated Steel Results – Method of Tanaka (Refined).

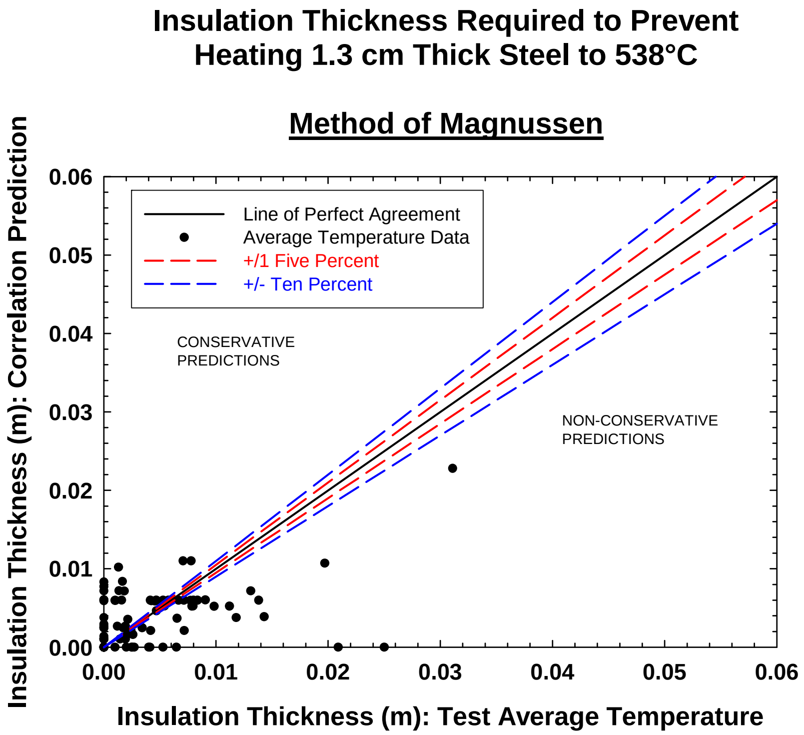


Figure 53 - Insulated Steel Results – Method of Magnussen.

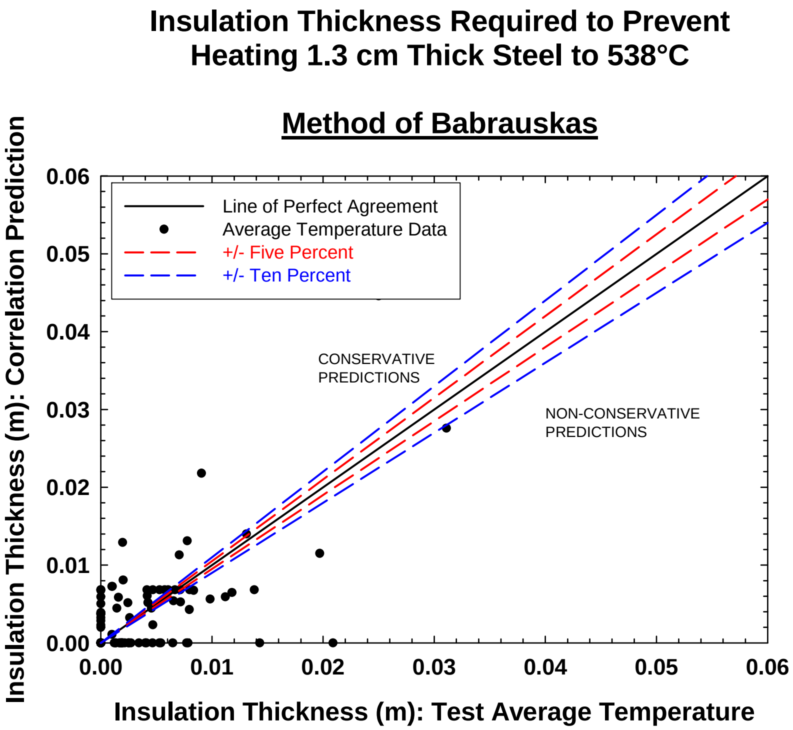


Figure 54 - **Insulated Steel Results – Method of Babrauskas.**

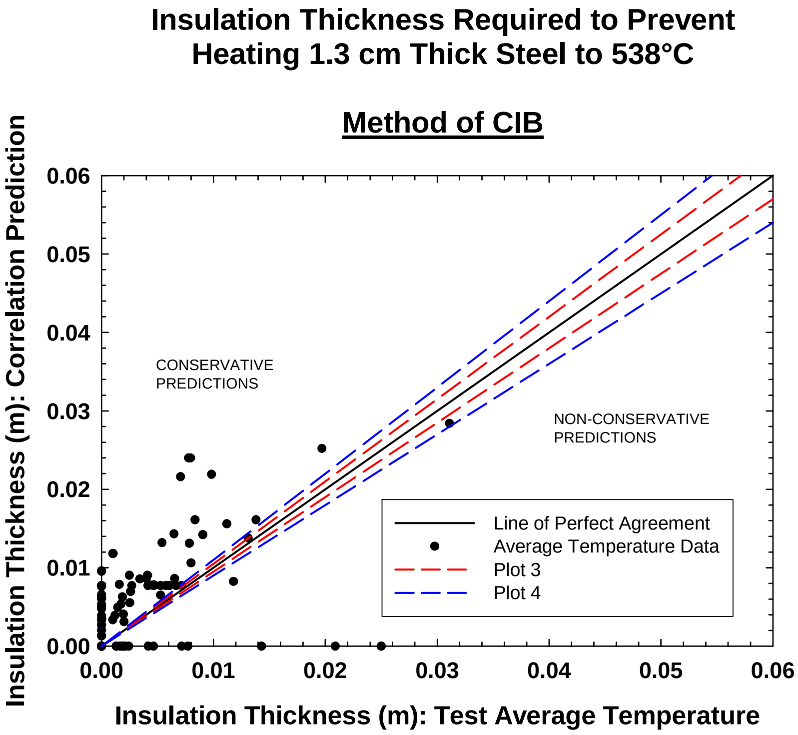


Figure 55 - **Insulated Steel Results – Method of CIB.**

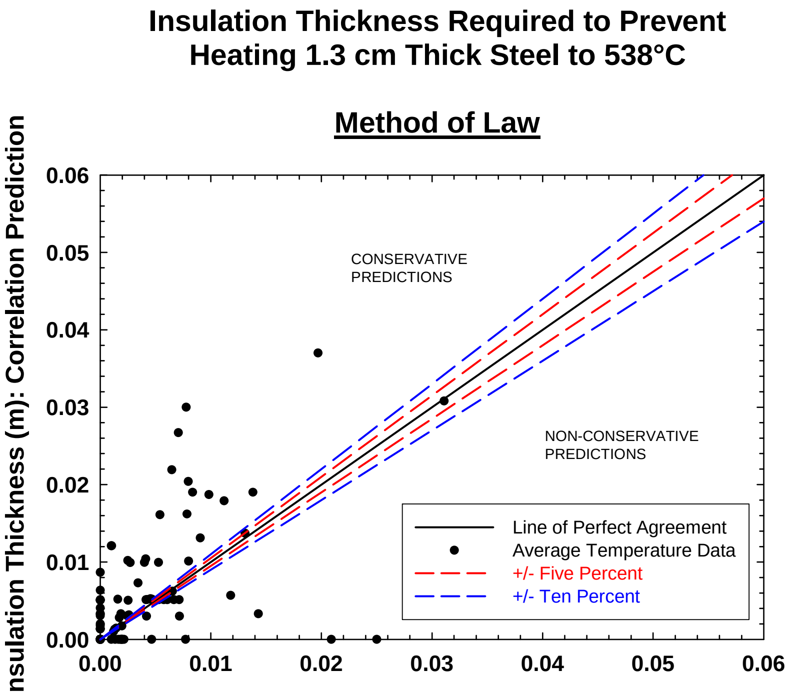


Figure 56 - Insulated Steel Results – Method of Law.

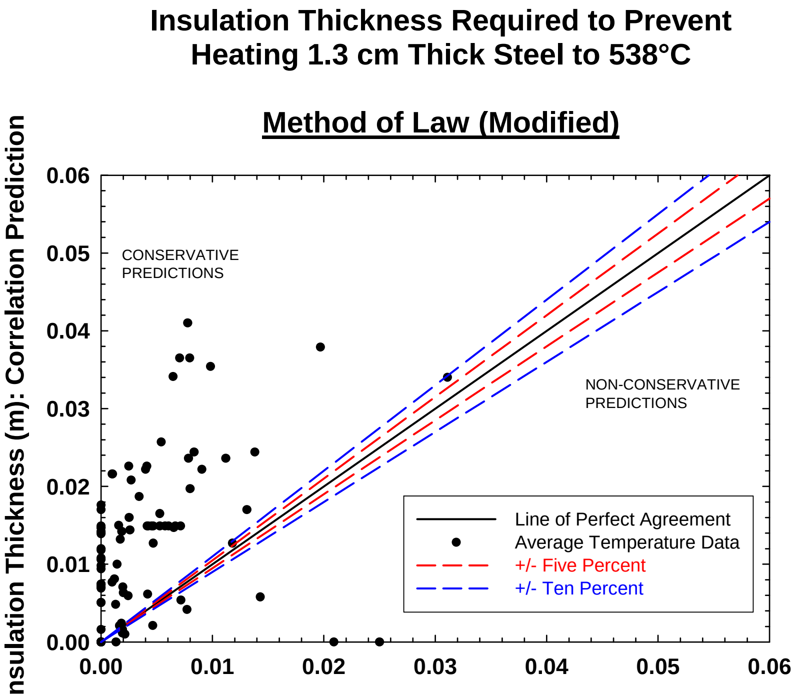


Figure 57 - Insulated Steel Results – Method of Law (Modified).

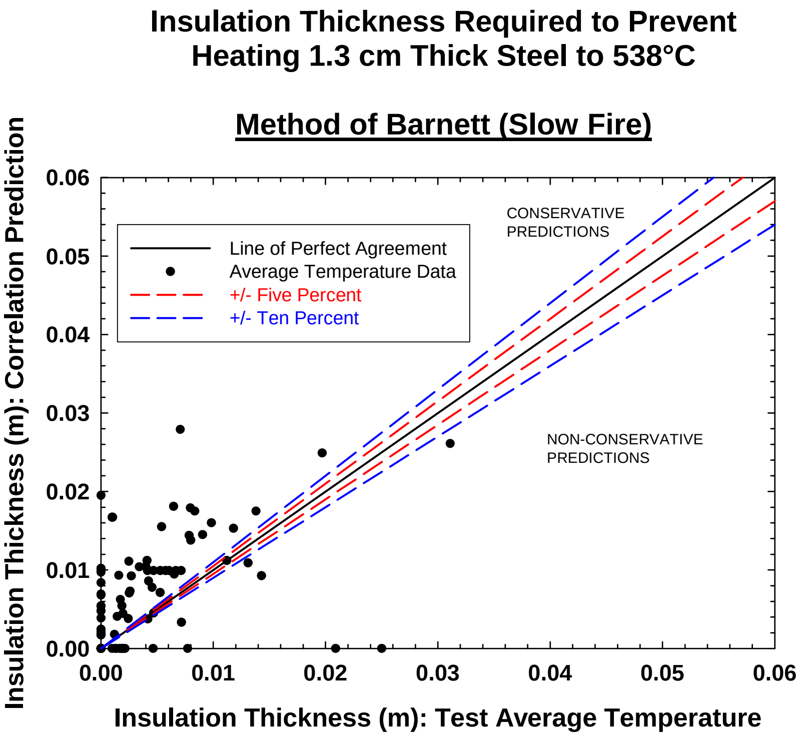


Figure 58 - Insulated Steel Results – Method of Barnett (Slow Growth Rate Fire).

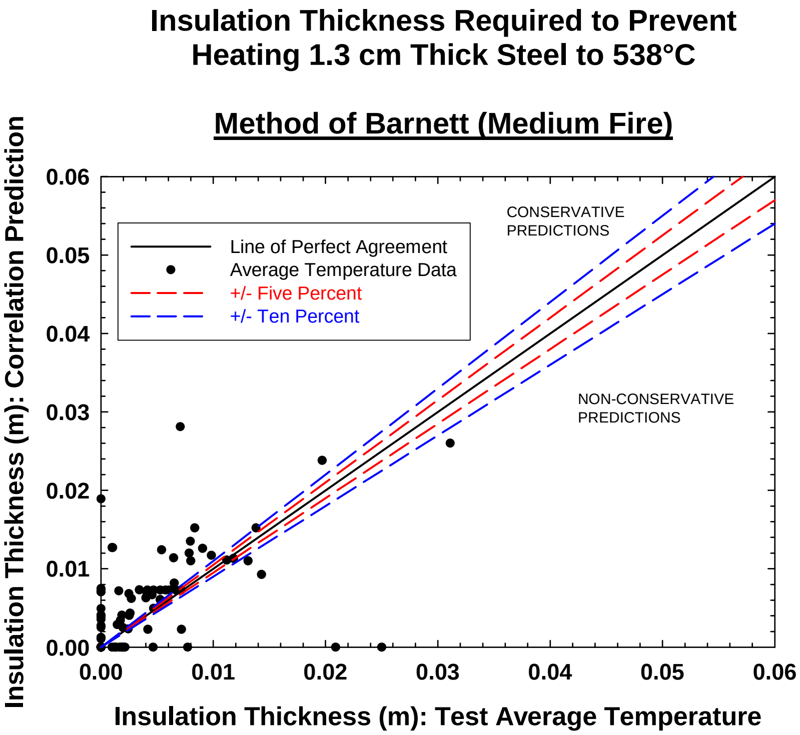


Figure 59 - Insulated Steel Results – Method of Barnett (Medium Growth Rate Fire).

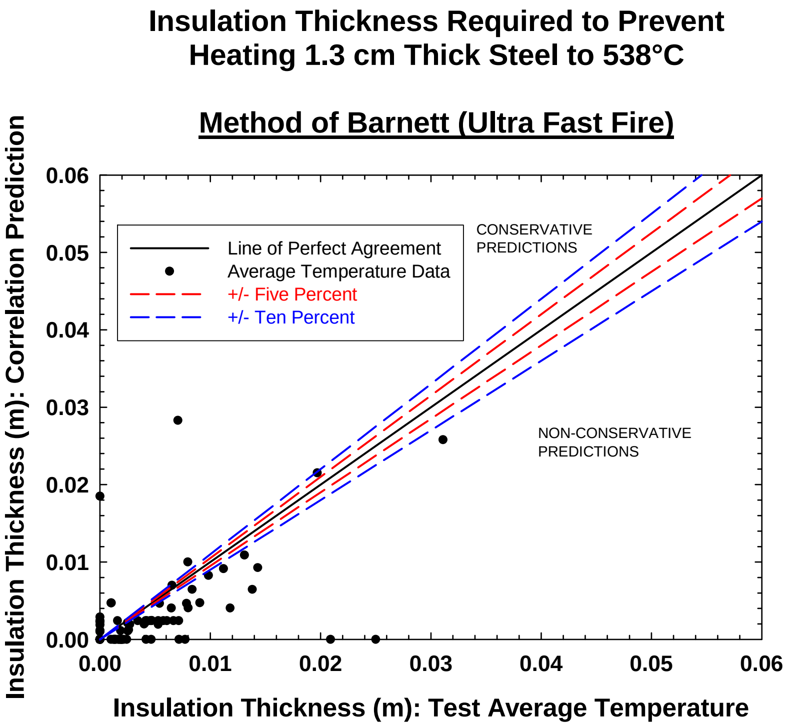


Figure 60 - **Insulated Steel Results – Method of Barnett (Ultra Fast Growth Rate Fire).**

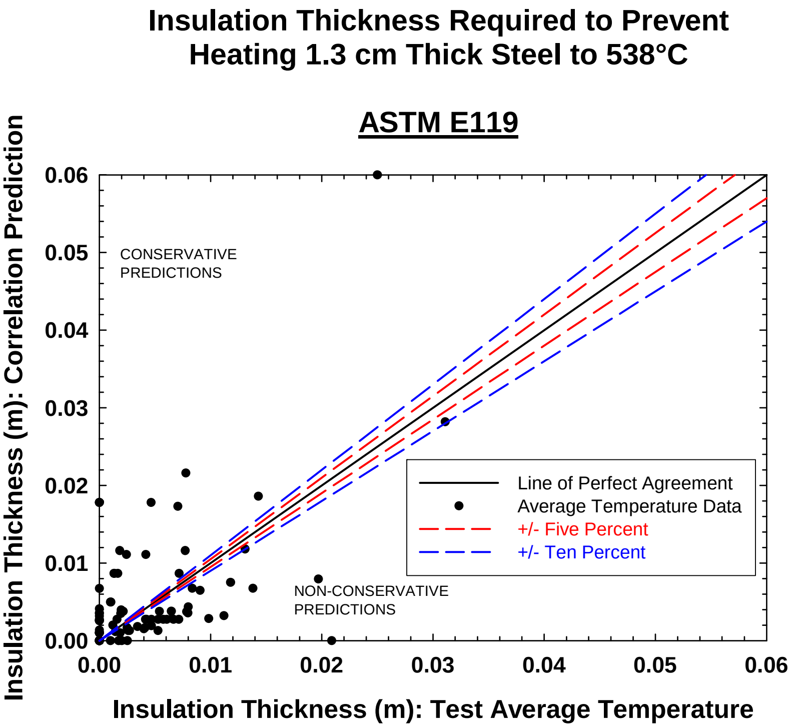


Figure 61 - **Insulated Steel Results – ASTM E119 Fire Exposure.**

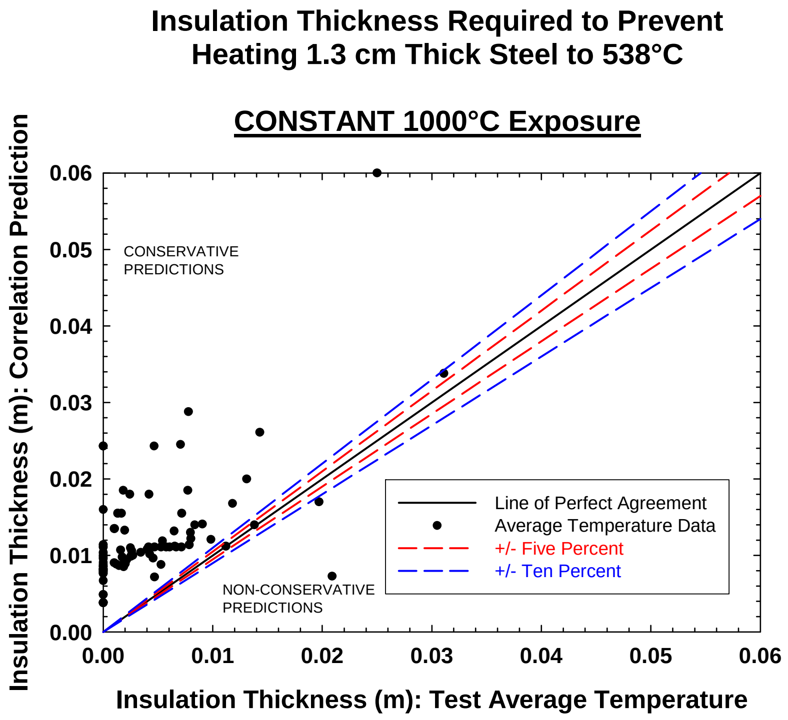


Figure 62 - **Insulated Steel Results – Constant Exposure Temperature (1,000 °C).**

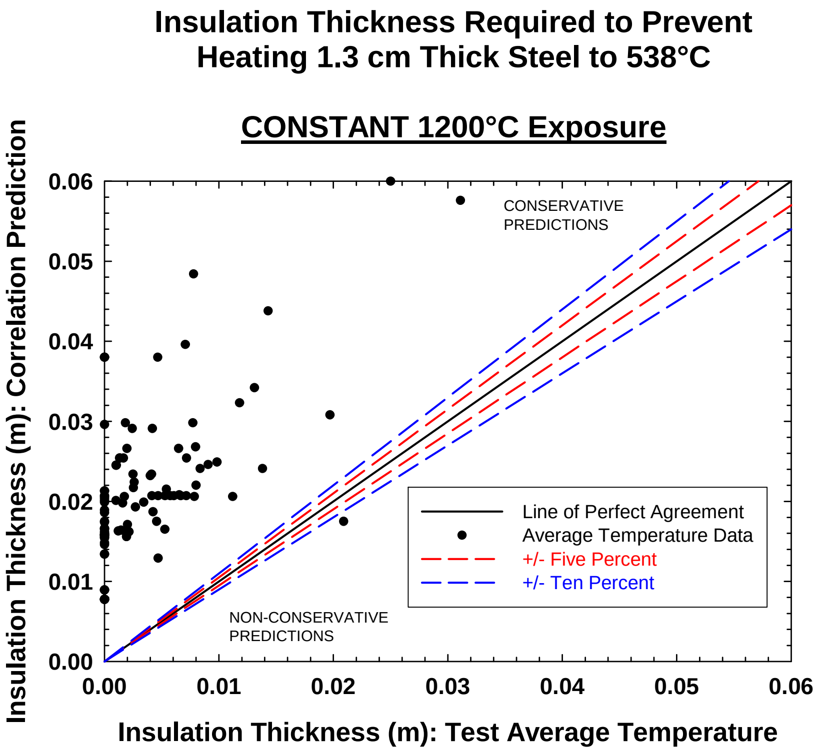


Figure 63 - **Insulated Steel Results – Constant Exposure Temperature (1,200 °C).**

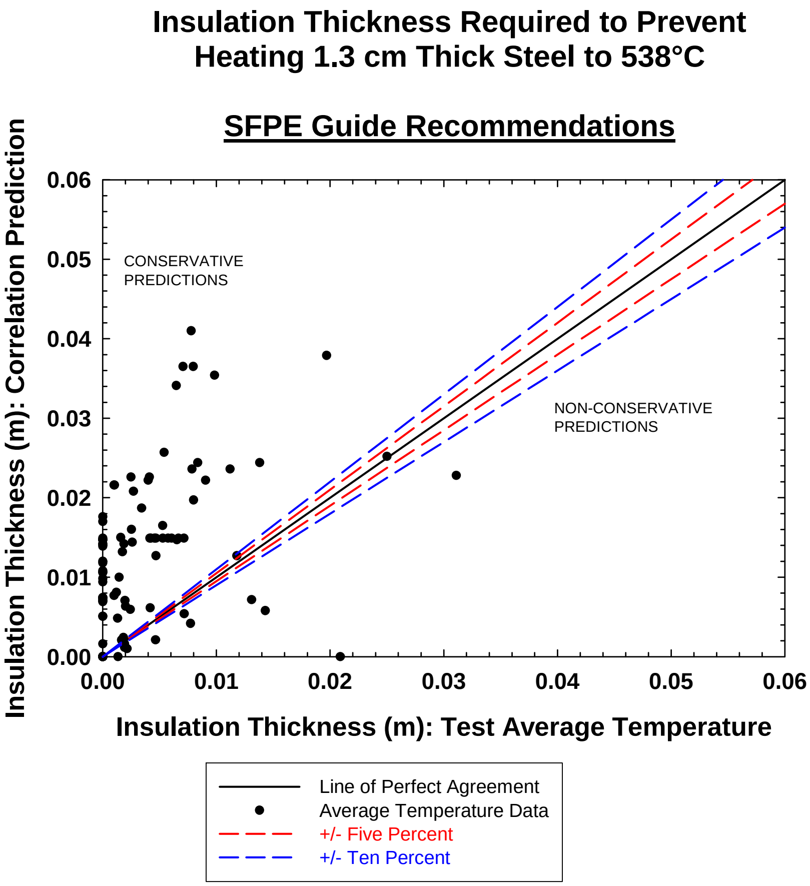


Figure 64 - Insulated Steel Results – SFPE Guide Recommendation.

Based on this comparison, the methods that consistently provided greater predictions of insulation thickness than was calculated using experimental temperature data were the constant temperature exposures and the methods of Barnett, and Tanaka.

In addition, a constant 1,200 °C exposure had the fewest points falling below the line of perfect agreement (only one point fell below the line.)

4.4 Concrete-Covered Steel Plate Finite Difference Computation

The analysis of a steel plate covered by concrete is similar to the analysis of a steel plate covered by insulation. An integrated measure of temperature was developed by determining the thickness of insulation required to prevent a 1.2 cm thick steel plate from exceeding a temperature of 538 °C. The concrete was modeled as being exposed to predicted temperatures using each method and to the temperatures from experiments. When there were multiple thermocouples in an experimental compartment, the peak temperatures measured at each time during the exposure were used as the exposure temperature. If the peak temperatures measured among the thermocouples were not available, then the temperatures measured by each thermocouple were averaged at each time when measurements were taken, and these average temperatures were used as the exposure temperature.

The predicted temperatures and the measured temperatures from experiments were used as input into a heat transfer analysis. An imaginary, one-dimensional (Cartesian) sample was exposed on the concrete-covered side to predicted temperatures and to the measured temperatures. Normal weight, siliceous aggregate concrete was the concrete used in this comparison metric. The thermal conductivity and heat capacity varied with temperature as presented by Lie.[69]

The exposure temperatures were converted to a heat flux using a radiation boundary condition and an emissivity and absorbtivity of 1.0 and a convection boundary condition using a convective heat transfer coefficient of 30 W/m^{2}K. Thermal properties for A36 steel were used as presented by Abrams.[67]

An adiabatic boundary condition was applied on the unexposed steel surface and zero contact resistance was assumed at the steel-concrete interface. A finite difference heat transfer analysis was conducted where the concrete thickness was optimized (set equal to the thickness that allowed the steel to reach 538°C at the conclusion of the exposure) to the nearest millimeter. The steel was modeled as having no thermal gradients. Figure 65 depicts the geometry modeled.

The basis for comparison was the thickness of concrete determined using the model predictions and the thickness of concrete determined using the test data.

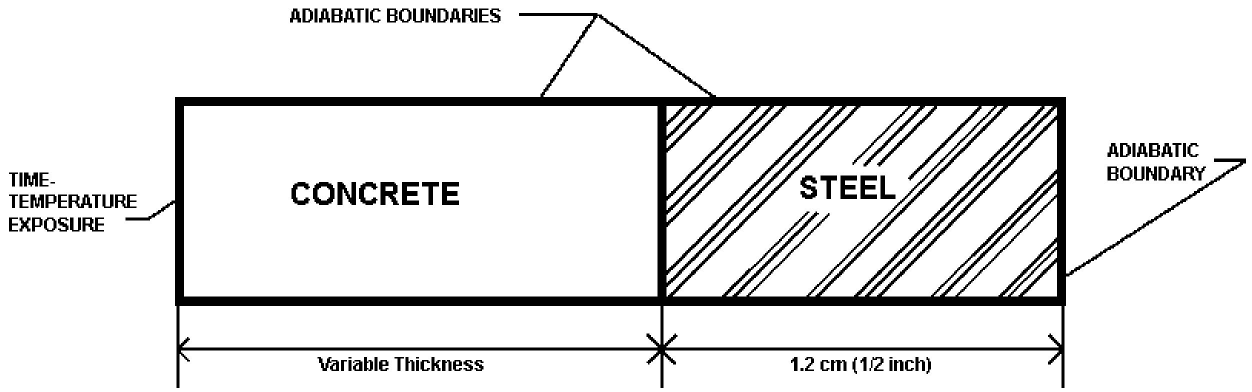


Figure 65 - Insulation-Steel System Model.

The calculated concrete thickness results are shown in Figure 66 - Figure 83. The concrete thickness predicted using experimental temperature data was plotted against the concrete thickness predicted for each method or method variation. Points falling above the line of perfect agreement are conservative insofar as the concrete thickness predicted by the correlation temperature profile is greater than that predicted using the measure test temperature profile. The reverse is true for data falling below the line of perfect agreement. Also shown in Figure 66 - Figure 83 are the lines corresponding to plus or minus five and ten percent of the line of perfect agreement.

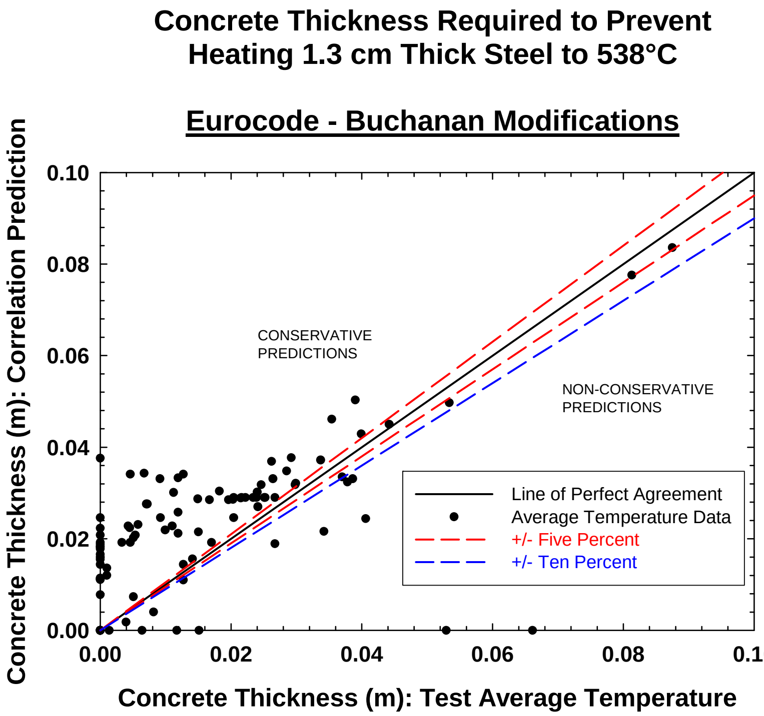


Figure 66 - Concrete-Steel Results – Eurocode (Buchanan Modifications).

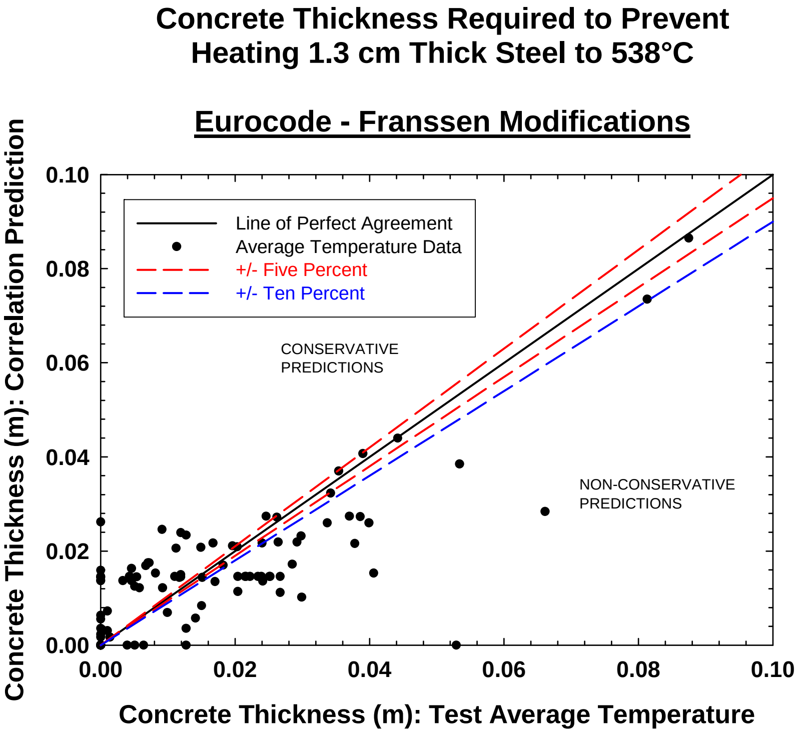


Figure 67 - Concrete-Steel Results – Eurocode (Franssen Modifications).

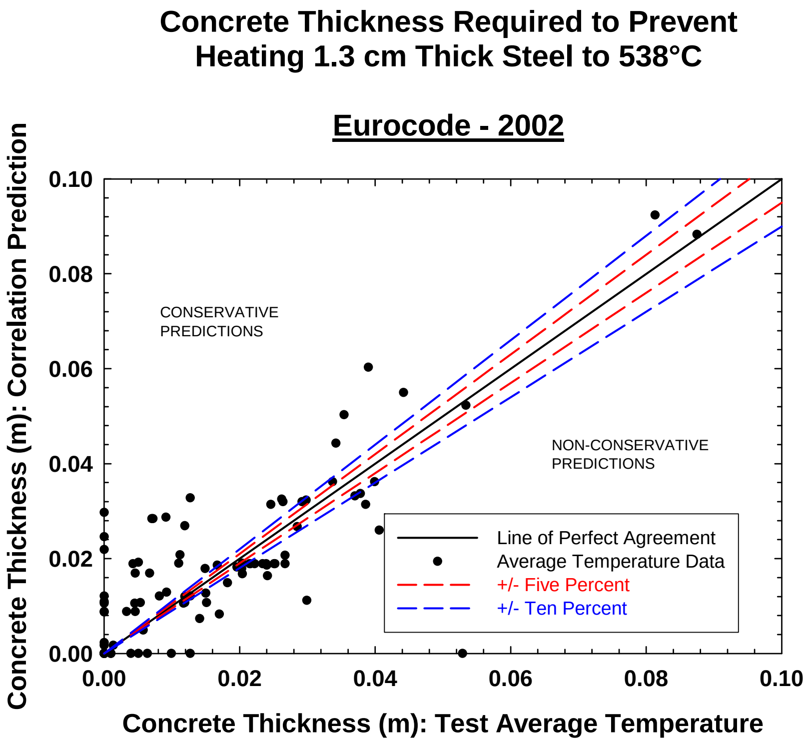


Figure 68 - Concrete-Steel Results – Eurocode 2002.

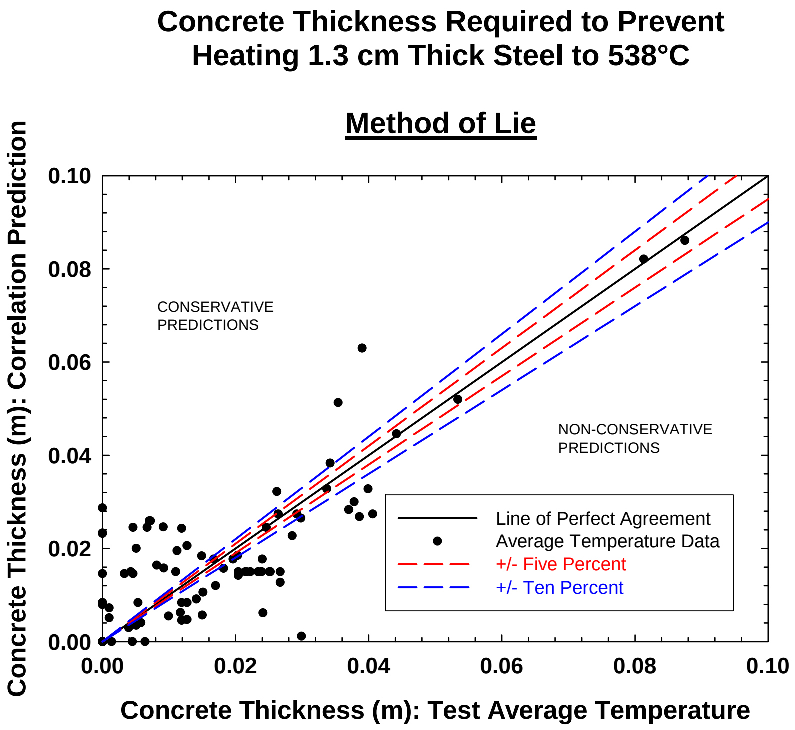


Figure 69 - Concrete-Steel Results – Method of Lie.

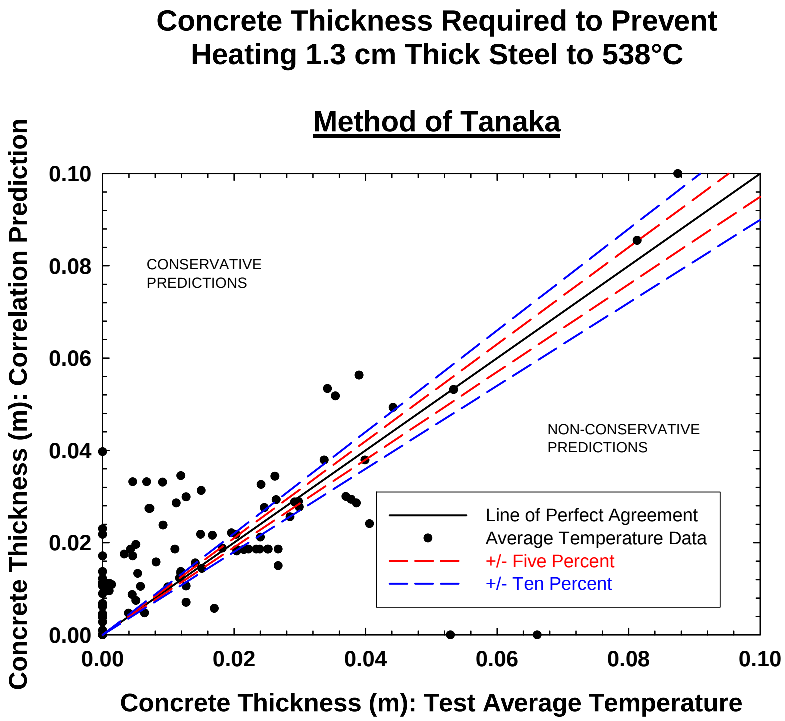


Figure 70 - Concrete-Steel Results – Method of Tanaka.

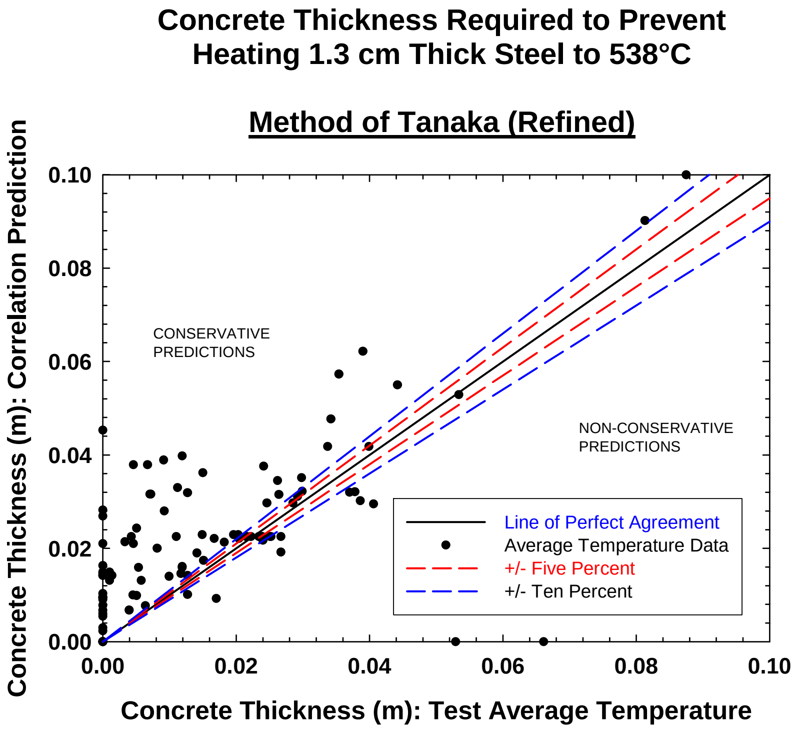


Figure 71 - Concrete-Steel Results – Method of Tanaka (Refined).

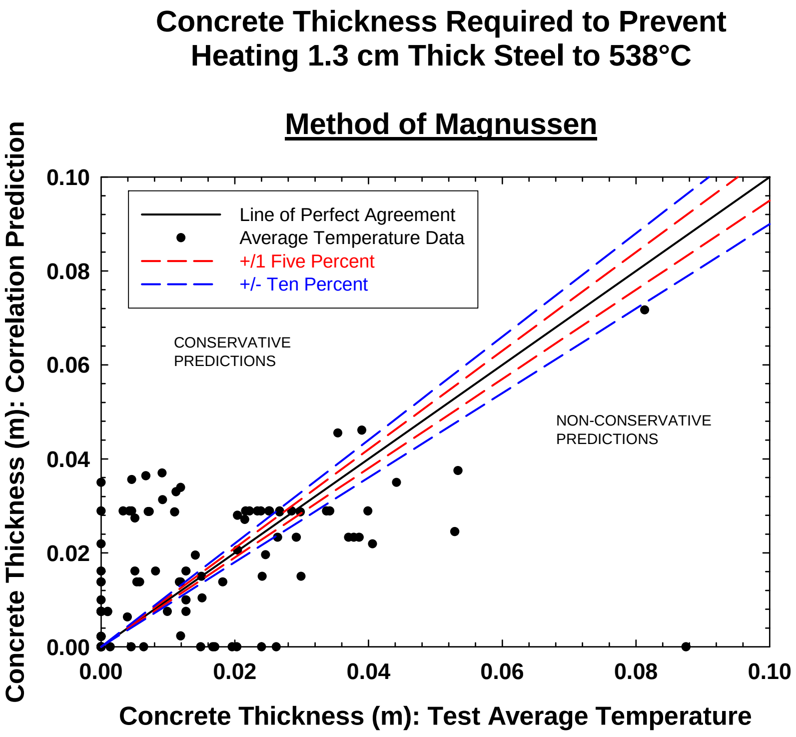


Figure 72 - Concrete-Steel Results – Method of Magnussen.

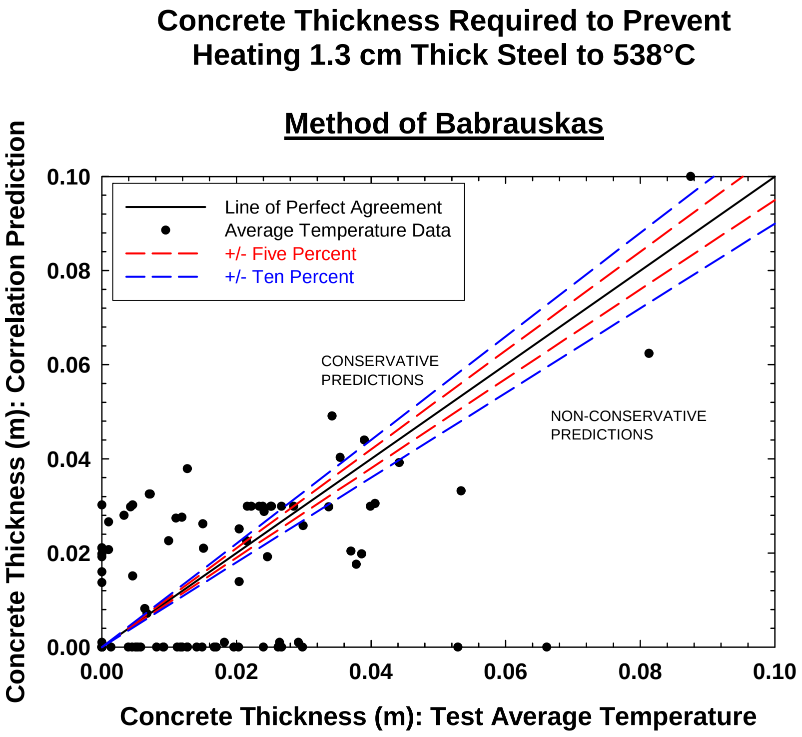


Figure 73 - Concrete-Steel Results – Method of Babrauskas.

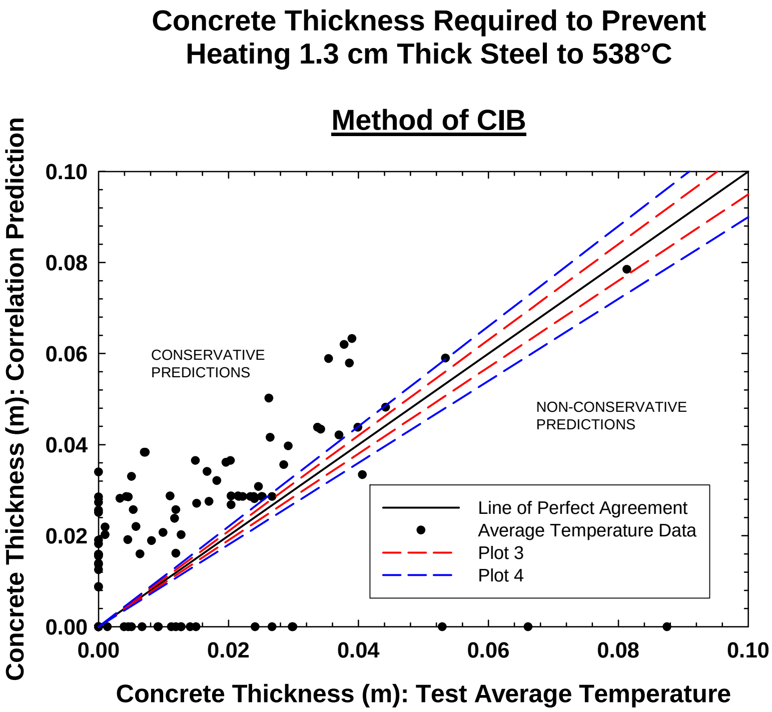


Figure 74 - Concrete-Steel Results – Method of CIB.

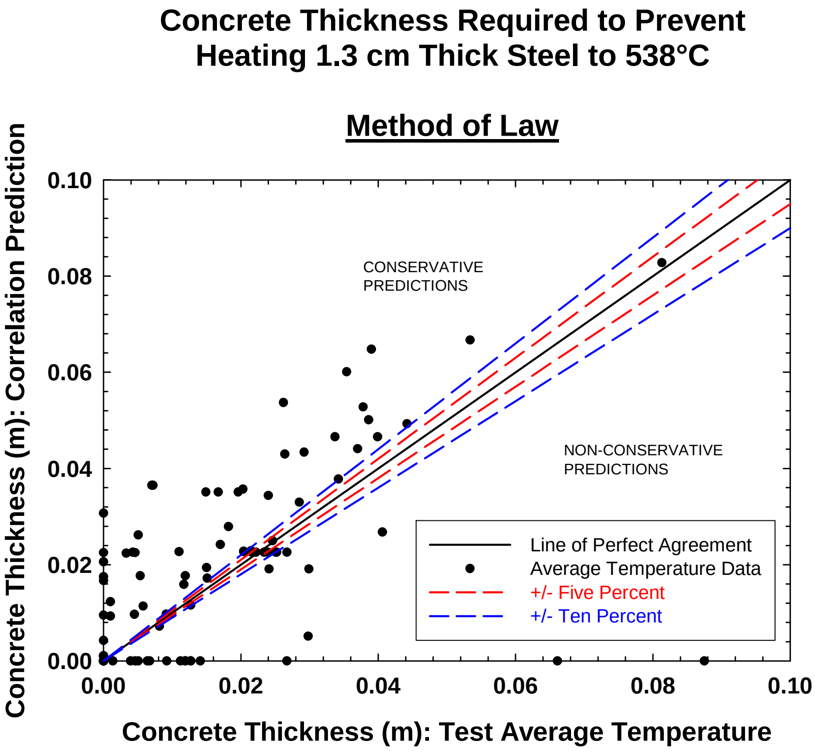


Figure 75 - Concrete-Steel Results – Method of Law.

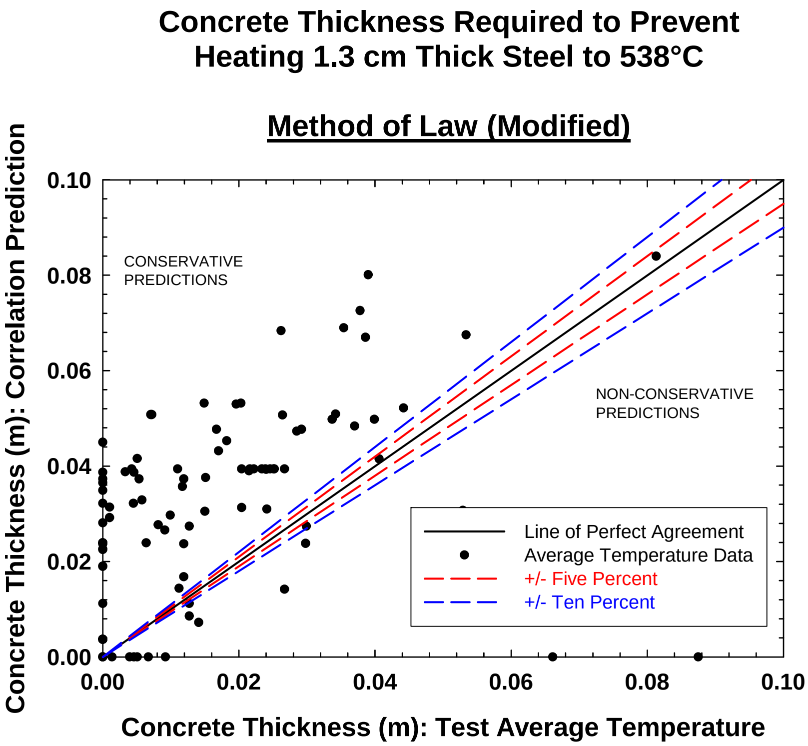


Figure 76 - Concrete-Steel Results – Method of Law (Modified).

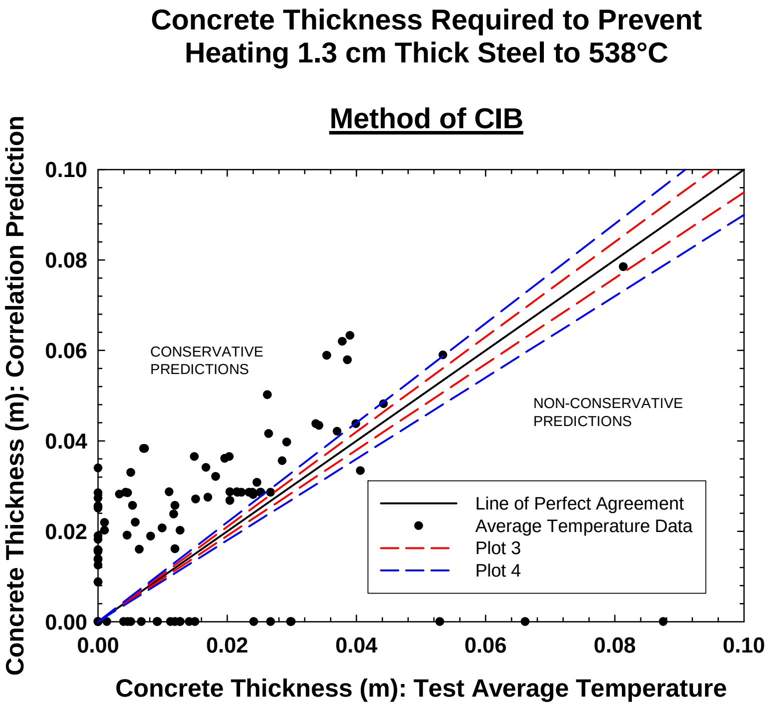


Figure 77 - Concrete-Steel Results – Method of Barnett (Slow Growth Rate Fire).

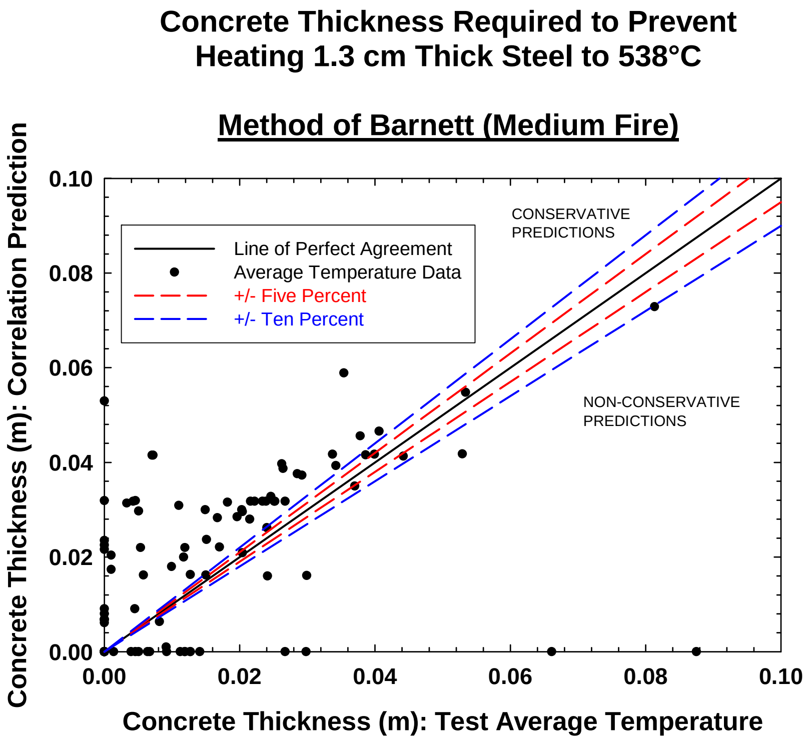


Figure 78 - Concrete-Steel Results – Method of Barnett (Medium Growth Rate Fire).

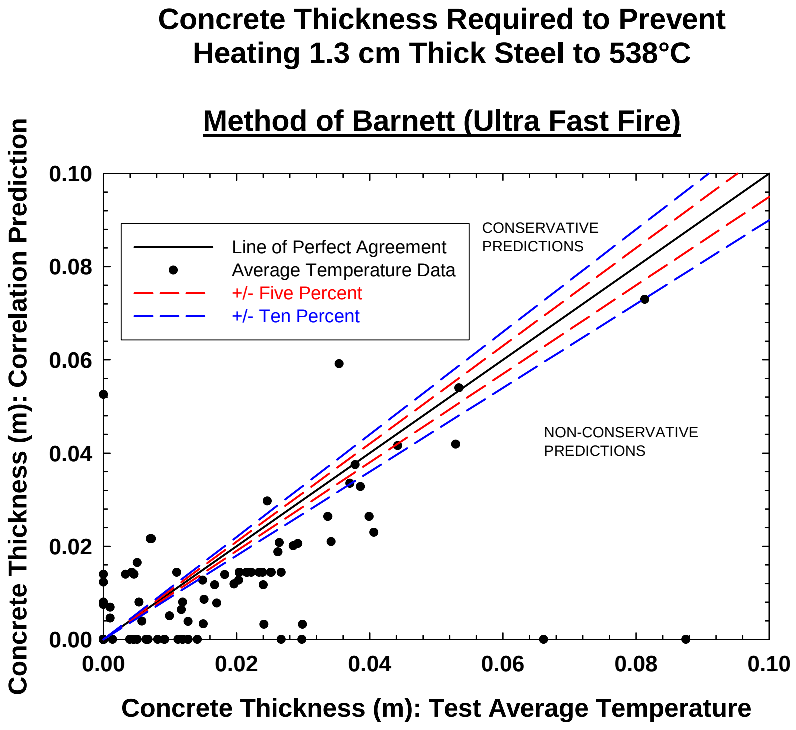


Figure 79 - Concrete-Steel Results – Method of Barnett (Ultra Fast Growth Rate Fire).

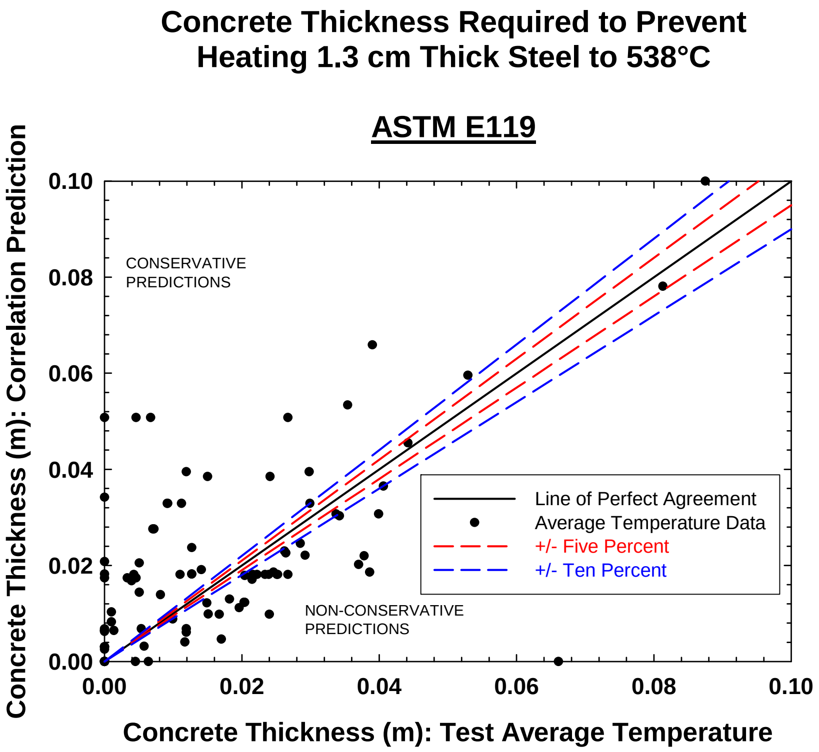


Figure 80 - Concrete-Steel Results – ASTM E119 Fire Exposure.

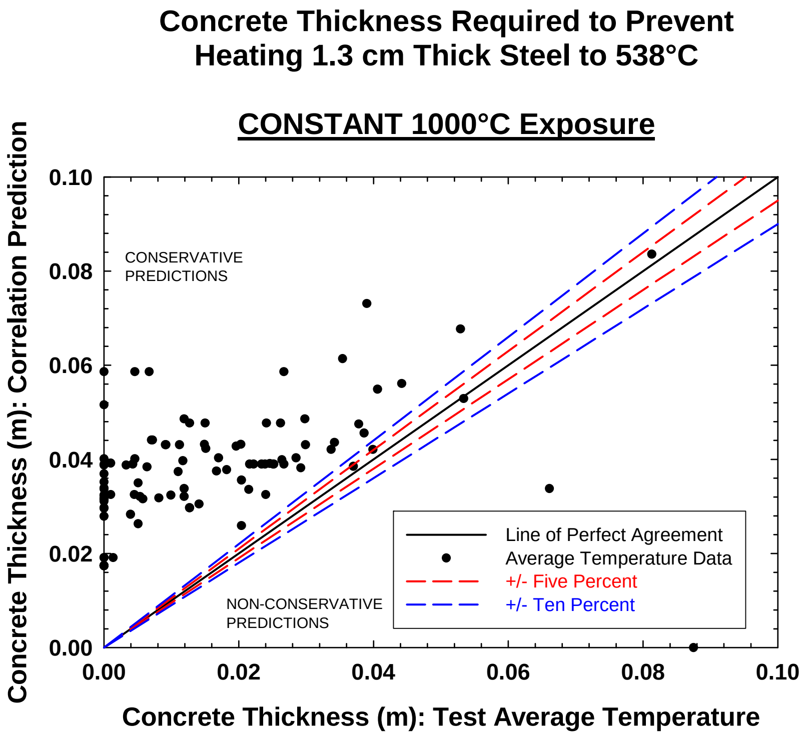


Figure 81 - Concrete-Steel Results – Constant Exposure Temperature (1,000 °C).

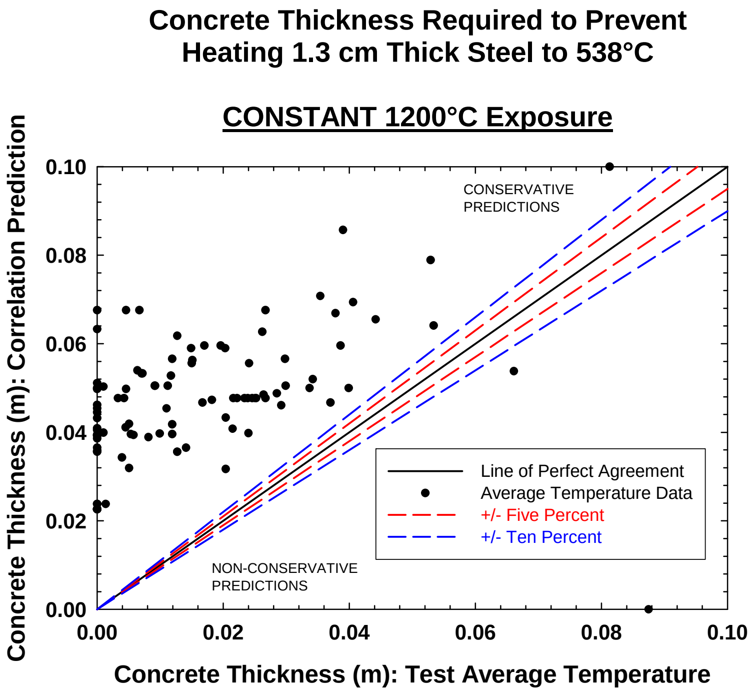


Figure 82 - **Concrete-Steel Results – Constant Exposure Temperature (1,200 °C).**

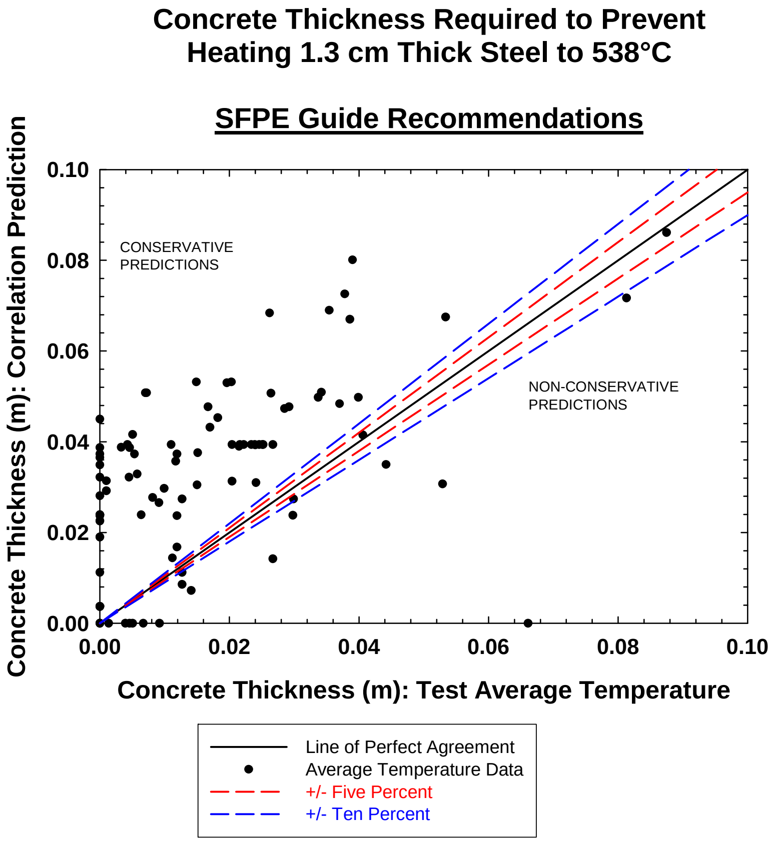


Figure 83 - **Concrete-Steel Results – SFPE Guide Recommendation.**

Based on this comparison, the methods that consistently provided greater predictions of concrete thickness than was calculated using experimental temperature data were the constant temperature exposures and the methods of Barnett, and Tanaka.

The constant 1,200 °C exposure had the fewest points falling below the line of perfect agreement; only one point fell below the line.

5.0 Findings

The results of each comparison were analyzed to determine which predictive method or methods would be the most appropriate for use in a standard on predicting fire exposures for purposes of performance-based design of structural fire resistance. The analysis included several components.

A coefficient of correlation was calculated for each method in each of the four analyses. A value of 1.0 means there is perfect linear relationship between the model predictions and the test data and thus suggests the presence of a correlation.[70] A value of zero indicates that there is no linear relationship between the model predictions and the test data.

Also, the percentage of the data for which the model prediction exceeded the data was determined for each method in each analysis. Four percentages are presented: the percentage of test data that was bounded by model predictions, and the percentage of test data that was bounded by test data within bounds of five, ten and fifteen percent (i.e., the percent of the measure of experimental data that was bounded by the model predictions when the model predictions were multiplied by factors of 1.05, 1.1 and 1.15.)

Tables 3 through 6 summarize the correlation coefficient and the percent data conservatively predicted for the maximum gas temperature, the maximum average gas temperature, and the integrated average temperature as represented by bare steel and insulated steel.

Table 3 - Statistics on Maximum Gas Temperatures

Method	Correlation Coefficient	PERCENT CONSERVATIVE			
		Bounded	Within 5%	Within 10%	Within 15%
Eurocode – Buch.	0.33	62	75	82	87
Eurocode – Frans.	0.63	32	37	44	53
Eurocode – 2002	0.69	27	32	43	51
Lie	0.64	34	42	55	64
Tanaka	0.33	77	82	89	96
Tanaka (Refined)	0.29	92	96	98	98
Magnussen	0.21	48	55	64	69
Babrauskas	0.31	28	31	34	39
CIB	0.08	48	56	60	68
Law	0.61	41	48	55	62
Law (modified)	0.08	70	75	77	81
Barnett (Slow)	0.62	44	49	56	64
Barnett (Med.)	0.62	44	49	56	64
Barnett (U. F.)	0.62	44	49	56	64
ASTM E119-10	0.41	35	40	52	55
1,000 °C	0	71	84	89	96
1,200 °C	0	98	100	100	100
SFPE Guide	0.09	70	73	77	80

Table 4 - Statistics on Bare-Steel Systems.

Method	Correlation Coefficient	PERCENT CONSERVATIVE			
		Bounded	Within 5%	Within 10%	Within 15%
Eurocode – Buch.	0.69	65	67	71	72
Eurocode – Frans.	0.86	44	47	49	49
Eurocode – 2002	0.95	50	52	54	55
Lie	0.66	47	47	49	53
Tanaka	0.71	79	80	83	86
Tanaka (Refined)	0.48	91	91	92	93
Magnussen	0.01	64	66	68	69
Babrauskas	0.14	36	38	40	40
CIB	0.56	75	76	77	78
Law	0.6	64	65	67	68
Law (modified)	0.4	85	86	86	86
Barnett (Slow)	0.53	61	68	69	69
Barnett (Med.)	0.4	66	65	66	66
Barnett (U. F.)	0.51	23	23	25	29
ASTM E119-10	0.35	80	80	82	83
1,000 °C	0.6	93	93	93	93
1,200 °C	0.71	98	98	98	98
SFPE Guide	0.3	80	80	80	81

Table 5 - Statistics on Insulation-Steel Systems.

Method	Correlation Coefficient	**PERCENT CONSERVATIVE**			
		Bounded	Within 5%	Within 10%	Within 15%
Eurocode – Buch.	0.74	54	57	59	60
Eurocode – Frans.	0.84	18	23	26	28
Eurocode – 2002	0.84	28	28	29	29
Lie	0.77	24	28	28	28
Tanaka	0.75	40	52	53	54
Tanaka (Refined)	0.75	62	62	64	66
Magnussen	0.48	41	41	44	45
Babrauskas	0.66	38	38	39	42
CIB	0.53	54	55	57	57
Law	0.59	43	44	44	44
Law (modified)	0.43	75	76	76	76
Barnett (Slow)	0.48	54	55	57	58
Barnett (Med.)	0.51	45	49	50	50
Barnett (U. F.)	0.5	18	21	21	21
ASTM E119-10	0.58	27	28	31	34
1,000 °C	0.61	94	94	100	100
1,200 °C	0.63	100	100	100	100
SFPE Guide	0.46	76	77	77	77

Table 6 - Statistics on Concrete-Steel Systems.

Method	Correlation Coefficient	**PERCENT CONSERVATIVE**			
		Bounded	Within 5%	Within 10%	Within 15%
Eurocode – Buch.	0.66	74	76	78	81
Eurocode – Frans.	0.78	44	47	51	51
Eurocode – 2002	0.8	43	45	50	57
Lie	0.76	34	38	41	43
Tanaka	0.7	64	68	71	76
Tanaka (Refined)	0.67	78	80	82	85
Magnussen	0.42	52	54	54	57
Babrauskas	0.57	39	39	39	42
CIB	0.44	68	69	69	69
Law	0.59	55	57	60	62
Law (modified)	0.44	82	82	83	84
Barnett (Slow)	0.48	62	62	65	67
Barnett (Med.)	0.53	60	60	62	63
Barnett (U. F.)	0.59	19	20	22	24
ASTM E119-10	0.65	47	48	49	56
1,000 °C	0.4	97	98	98	98
1,200 °C	0.41	98	98	98	98
SFPE Guide	0.58	80	81	82	84

Overall, the method that provided the greatest number of predictions that exceeded those derived from the test data was the 1,200 °C constant temperature exposure. Of the correlations that were evaluated, the Tanaka (refined) method provided the greatest number of predictions that were equal to or greater than that derived from the test data.

A constant temperature exposure is also computationally inexpensive and does not give the user a false sense of accuracy. As such, baring modifications or improvements to other approaches, this is the most logical selection for quantifying compartment fire exposures for purposes of performance-based structural fire resistance design.

6.0 Summary

The methods for inclusion in a standard for computing a time-temperature profile in an enclosure were selected from a group of twenty-three different methods or method variations. All methods considered had been documented in published material and did not involve the use of computer simulations. The methods included simplistic approaches such as a constant temperature exposure, correlations of particular data sets, generalized parametric approaches, and correlations of computer generated data.

The selection process involved assessing the performance of all twenty-three methods against a database containing one hundred forty-six fully-developed single compartment fire tests. The database was compiled largely from four decades of published enclosure fire test results. Most of the tests were conducted using full-scale compartments that represented a wide range of parameters that would have some influence on the time-temperature development. Such parameters included the enclosure dimensions, the opening dimensions, the number and location of the openings, the type of boundary materials, the ventilation factor, and the type of fuel burning.

The dominant criterion for selecting a method or methods was the need to produce results that are expected to be equal to or greater than those expected in real-world conditions. Other factors considered included the accuracy, the correlation factor, the prediction trend, the ease of use, the generality, and the method’s technical basis.

To objectively assess the performance of the methods against the data, a set of four metrics were developed that reflected both raw time-temperature predictions and the manner in which the time-temperature predictions would be used. These metrics were as follows:

- The time-temperature profile;

- The thickness of bare steel required to prevent it from reaching 538 °C, an arbitrary threshold temperature for structural design;

- The thickness of a mineral-based insulation required to prevent a steel plate from reaching 538 °C; and

- The thickness of concrete required to prevent a steel plate from reaching 538 °C.

The time-temperature profile comparisons were based directly on the measured test data and the correlation predictions. In contrast, the thickness comparisons were effectively integrated average heat flux comparisons for different types of building materials. The integrated average comparisons involved the use of an iterative heat transfer model to compute a thickness given the measured test data time-temperature exposure profile vs. the predicted time-temperature exposure profile. The integrated average computations used the thermal radiation and convection boundary conditions as recommended in the SFPE Engineering Guide to Fire Exposures to Structural Elements;**Error! Bookmark not defined.** however, because the computations were relative to one another, there was not a great deal of sensitivity to the specific boundary conditions assumed.

A statistical analysis was conducted on the comparison results for each metric to quantify trends, accuracy, and correlation. Both the raw comparison data and the statistical analysis displayed a great deal of scatter, and therefore marked uncertainty in the predictive capability of nearly all methods. Some methods had a high correlation factor, but were not consistently conservative even to within a relatively reasonable percentage; some methods appeared only to perform well for a small subset of data and generated very conservative or very non-conservative results when used on data outside the subset. Still others were generally conservative for all tests but were sometimes overly conservative predictions.

Given these observations, two methods were selected that were nearly always conservative while recognizing that there may be situations where the predictions are substantially over-conservative.

An important aspect of this selection by the user is the recognition that the results are defined with two parameters: the temperature and the time. A raw comparison between the predicted time-temperature and measured time-temperature profiles showed deviations in one or both parameters for any method.

However, there are many paths available to reach a correct result for the integrated average metrics. Because model predictions would ultimately be intended for use as input for defining the boundary conditions that would be used to compute a thermal response, a greater emphasis was placed on the integrated average metrics, which temper the degree of over-conservativeness.

Thus, while the methods suggested in this analysis can have a tendency to over-predict the compartment temperature, the time and temperature taken together tend to produce more reasonable results when used as input for developing the boundary conditions. In short, given the large number of tests considered, there is a reasonable assurance that the methodology suggested will produce a conservative result when used as boundary condition input data but that the predicted temperature-temperature profile may not necessarily be the true time-temperature profile for the assumed fuel load and ventilation conditions.

7.0 References

[1] SFPE, *Engineering Guide - Fire Exposures to Structural Elements*, Society of Fire Protection Engineers, Bethesda, MD, 2004.

[2] Thomas, P. and Heselden, A. "Fully Developed Fires in Single Compartments, A Co-operative Research program of the Conseil International du batiment (CIB Report No. 20)," Fire Research Note No. 923, Fire Research Station, Borehamwood, UK, 1972.

[3] Kirby, B. R., Wainman, D.E., Tomlinson, L. N., Kay, T. R., Peackock, B. N. "Natural Fires in Large-Scale Compartments – A British Steel Technical, Fire Research Station Collaborative Project," British Steel, Rotherdam, UK, June, 1994.

[4] Alam, T. and Beever, P. " Flashover Fires – An Experimental Program," Victoria University Research Report 96-002. CESARE, Victoria, Australia, October, 1996.

[5] ARBED, "Background Document on Parametric Temperature-Time Curves According to Annex A of prEN1991-1-2 (24-08-2001)," Document No. EC-1-1-2 / 72, CEN/TC250/SC1N298A, ARBED Centre de Recherches, France, August 24, 2001.

[6] Arnault, P., Ehm, H., and Kruppa, J., "Rapport Expérimental sur les Essais avec des Feux Naturels Exécutés dans la Petite Installation de Maizières-lès-Metz," CECM 3/73-11-F, Centre technique Industriel de la Construction Métallique, France, June, 1973.

[7] Arnault, P., Ehm, H., and Kruppa, J., "Incendies Naturels avec des Meubles et du Papier exécutés dans la petite installation de Maizières-lès-Metz," Report 2.10.20-3, Centre technique Industriel de la Construction Métallique, France, July, 1974.

[8] Andersson, B., "Model Scale Compartment Fire Tests with Wall Lining Materials," Department of Fire Safety Engineering, Institute of Science and Technology, Lund University, Lund, Sweden, October, 1988.

[9] Babrauskas, V., "Upholstered Furniture Room Fires – Measurements, Comparison with Furniture Calorimeter Data, and Flashover Predictions," *Journal of Fire Sciences*, Volume 2, January/February 1984, pp. 5 – 19.

[10] Blackmore, J., Brescianini, C., Collins, G., Delichatsios, M. A., Everingham, G., Ralph, R., Thomas, I., and Beever, P., "Room and Furnace Tests," Fire Code Reform Center, Project 3, Fire Resistance and Non-Combustibility, New South Wales, Australia, July, 1999.

[11] Bohm, B. and Hadvig, S., "Nonconventional Fully Developed Polyethylene and Wood Compartment Fires," *Combustion and Flame*, Volume 44, 1982, pp. 201-221.

[12] Bruce, D. H. Experimental Dwelling-Room Fires. Report No. 1941. Forest Products Laboratory, U. S. Department of Agriculture, Madison, WI, April, 1959.

[13]Bryner, N. P., Johnsson, E. L., and Pitts, W. M., “Scaling Compartment Fires – Reduced and Full-Scale Enclosure Burns,” *International Conference on Fire Research and Engineering*, September 10 – 15, 1995, Orlando, FL. pp. 9 – 14.

[14]Butcher, E. G., Chitty, T. B., and Ashton, L. A., “The Temperature Attained by Steel in Building Fires,” Fire Research Technical Paper No. 15, Ministry of Technology and Fire Offices’ Committee Joint Fire Research Organization. London, UK, 1966.

[15]Bullen, M. L. and Thomas, P. H., “Compartment Fires with Non-Cellulosic Fuels,” *Seventeenth International Symposium on Combustion*, University of Leeds, UK, August 20 – 25, 1978. pp. 1139 – 1148.

[16]CTICM, “Bâtiment Scolaire à Ossature Métallique Protégé par une Application Igniver,” Report 94-S-247, Centre Technique Industriel de la Construction Métallique, France, June, 1994.

[17]Croce, P., “ A Study of Room Fire Development – the Second Full Scale Bedroom Fire Test of the Home Fire Project,” the Home Fire Project, Factory Mutual Research, Norwood, MA, July 24, 1974.

[18]Durkin, A. F., Williams, F. W., Scheffey, J. L., Toomey, T. A., Hunt, S. P., and Darwin, R. L., “Post-Flashover Fires in Shipboard Compartments Aboard ex-USS Shadwell: Phase IV – Impact of Navy Fire Insulation,” NRL/MR/6183—93-7335, Naval Research Laboratory, Washington, D.C., June 9, 1993.

[19]Fang, J. B. and Breese, J. N., “Fire Development in Residential Basement Rooms,” NBSIR 80-2120l. Center for Fire Research, National Bureau of Standards, Gaithersburg, MD, October, 1980.

[20]Fang, J. B., “Fire Performance of Selected Residential Floor Constructions under Room Burnout Conditions,” NBSIR 80-2134, Center for Fire Research, National Bureau of Standards, Gaithersburg, MD, December, 1980.

[21]Fang, J. B., “Fire Buildup in a Room and the Role of Interior Finish Materials,” NBSTN 879, Center for Fire Research, National Bureau of Standards, Gaithersburg, MD, June, 1975.

[22]Girgis, N., “Full – Scale Compartment Fire Experiments on ‘Upholstered Furniture’,” Master of Engineering Thesis, University of Canterbury, Christchurch, New Zealand, February, 2000.

[23]Gross, D. and Robertson, F., “Experimental Fires in Enclosures,” *Tenth International Symposium on Combustion*, 1978, PA. pp. 931 - 942.

[24]Gross, D., “Field Burnout Tests of Apartment Dwelling Units,” Building Science Series 10, National Bureaus of Standards Report 9527, National Bureau of Standards, Washington, D.C., September 29, 1967.

[25]Hagen, E. and Haksever, A. A., “Contribution for the Investigation of Natural Fires in Large Compartments,” *Fire Safety Science – Proceedings of the First International Symposium*, Hemisphere Publishing Corporation, Bristol, PA, 1986.

[26]Hamins, A., Maranghides, A., McGrattan, K. B., Ohlemiller, T. J., and Anleitner, R. L., "Experiments and Modeling of Multiple Workstations Burning in a Compartment," NIST NCSTAR 1-5E, National Institute of Standards and Technology, Gaithersburg, MD, September, 2005.

[27]Hamins, A., Maranghides, A., McGrattan, K. B., Johnsson, E. L., Ohlemiller, T. J., Donnelly, M. K., Yang, M. K., Mulholland, G. W., Prasad, K. R., Kukuck, S. R., Anleitner, R. L., and McAllister, T. P., "Experiments and Modeling of Structural Steel Elements Exposed to Fire," NIST NCSTAR 1-5B, National Institute of Standards and Technology, Gaithersburg, MD, September, 2005.

[28] Ingberg, S. H., "Tests of the Severity of Building Fires," *Thirty-Second Annual Meeting of the National Fire Protection Association*, Atlantic City, NJ, May 9, 1928.

[29]Kawagoe, K., "Fire Behaviour in Rooms," Report of the Building Research Institute No. 25, the Building Research Institute, Ministry of Construction, Japan, September, 1958.

[30]Kirby, B.R., Wainman, D.E., Tomlinson, L.N., Kay, T.R., and Peacock, B.N., "Natural Fires in Large Scale Compartments," *International Journal on Engineering Performance-Based Fire Codes*, Volume 1, Number 2, 1999. pp. 43-58.

[31]Lee, B. T., "Effect of Wall and Room Surfaces on the Rates of Heat, Smoke, and Carbon Monoxide Production in a Park Lodging Bedroom Fire," NBSIR 85-2998, Center for Fire Research, National Bureau of Standards, Gaithersburg, MD, February, 1985.

[32]Leonard, J. T., Back, G. G., Scheffey, J. L., Willard, R. L., DiNenno, P. J., Steel, G. S., Ouelette, R. L., and Beyler, C., "Internal Ship Conflagration Control Post-Flashover Characterization of Shipboard Compartments," Navy Technology Center for Safety and Survivability Technical Report, Washington, D.C., February 20, 1990.

[33]Lonnermark, A., Blomqvist, P., Mansson, M., and Persson, H., "TOXFIRE – Fire Characteristics and Smoke Gas Analysis in Under-Ventilated Large-Scale Combustion Experiments Tests in the ISO 9705 Room," SP Report 1996:45, Swedish National Testing and Research Institute, Boras, Sweden, 1996.

[34]Lougheed, G. D., McCartney, C., and Kanabus,-Kaminska, M., "Full-Scale Fire Test for Cables in Plenums," National Research Council Canada, Ottawa, Canada, 2004.

[35]McGarry, A. J. and Milke, J., "Full-Scale Room Fire Experiments," NIST-GCR-97-716, National Institute of Standards and Technology, Gaithersburg, MD, June, 1997.

[36]Rodak, S. and Ingberg, S. H., "Full-Scale Residential Occupancy Fire Tests of 1939," National Bureaus of Standards Report 9527, National Bureau of Standards, Washington, D.C., May 15, 1967.

[37]Roy, F., "Essais d' Incendies Naturels avec profilés en acier nus et protégés Etude de ventilation de modèles de développement du feu et de transfert thermique," 92-E-094, Centre technique Industriel de la Construction Métallique, France, October, 1993.

[38]Schaffer, E. L. and Eickner, H. W., "Effect of Wall Linings on Fire Performance within a Partially Ventilated Corridor," U. S. Forest Service Research Paper FPL 49, U. S. Department of Agriculture, Madison, WI, December, 1965.

[39]Shorter, G. W., McGuire, J. H., Hutcheon, N. B., and Legget, R. F. "The St. Lawrence Burns," *Quarterly of the NFPA - April 1963*, National Fire Protection Association, Quincy, MA, 1963.

[40]Su, J. and Taber, B. C., "Full-Scale Fire Study of Spatial Separation," Research Report IRC-RR-195, Institute for Research in Construction, National Research Council Canada, Ottawa, ON, May 19, 2005.

[41]Tewarson, A., "Some Observations on Experimental Fires in Enclosures, Part II – Cellulosic Materials," Combustion and Flame, Volume 19, 1972. pp. 101-111.

[42]Tewarson, A., "Some Observations on Experimental Fires in Enclosures, Part II – Ethyl Alcohol and Paraffin," Combustion and Flame, Volume 19, 1972. pp. 363-371.

[43]CEN, "Eurocode 1 – Basis of design and actions on Structures Part 2.2 Actions on Structures – Actions on Structures Exposed to Fire," ENV 1991-2-2, CEN, 1995.

[44]Buchanan, A., *Structural Design for Fire Safety*, John Wiley and Sons, U.K., 2001.

[45]Franssen, J., "Improvement of the Parametric Fire of Eurocode 1 Based on Experimental Test Results," *Fire Safety Science – Proceedings of the Sixth International Symposium*, International Association for Fire Safety Science, London, 2000.

[46]CEN, "Eurocode 1 – Actions on structures – General actions Densities, self-weight, imposed loads for Buildings, CEN, 2002.

[47] Thomas, I., "Enclosure Fire Temperature-Time Estimation," Section 4-8, *SFPE Handbook of Fire Protection Engineering*, 4th Edition, National Fire Protection Association, Quincy, MA, 2008.

[48]Tanaka, T., et al. "Simple Formula for Ventilation Controlled Fire Temperatures," U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 13th Joint Panel Meeting. Beall, K. A., Editor, Gaithersburg, MD, 1996. MD,

[49]Magnusson, SE, Thelandersson, S, "Temperature-time curves of complete process of fire development", ACTA Polytechnica Scandinavica, Civil Engineering and Building Construction Series No.65, Stockholm, 1970.

[50]Harmathy, T., "A New Look at Compartment Fires, Part I," *Fire Technology*, Volume 8, Number 2, 1972.

[51]Harmathy, T., "A New Look at Compartment Fires, Part II," *Fire Technology*, Volume 8, Number 4, 1972.

[52]Babrauskas, V., "A Closed-Form Approximation for Post-Flashover Compartment Fire Temperatures," *Fire Safety Journal*, Volume 4, 1981, pp. 63 – 73.

[53] Ma, Z. and Mäkeläinen, P., “Parametric Temperature-Time Curves of Medium Compartment Fires for Structural Design,” *Fire Safety Journal*, Volume 34, 2000, pp. 361 – 375.

[54] Thomas, P. and Heselden, A., “Fully Developed Fires in Single Compartments, A Co-operative Research program of the Conseil International du Batiment (CIB Report No. 20),” Fire Research Note No. 923, Fire Research Station, Borehamwood, UK, 1972.

[55] Law, M., “A Basis for the Design of Fire Protection of Building Structures,” *The Structural Engineer*, Volume 61A, Number 5, January, 1983.

[56] Cadorin, J.-F., “Compartment Fire Models for Structural Engineering,” Ph.D. Dissertation, University of Liege, Belgium, 2003.

[57] Barnett, J., “Development of an Analytical Methodology for the Design of Steel Structures Exposed to Fires,” Ph.D. Dissertation, Worcester Polytechnic Institute, Worcester, MA, 1989.

[58] ASTM E119-10, “Standard Test Methods for Fire Tests of Building Construction and Materials,” American Society for Testing and Materials, West Conshohocken, PA, 2009.

[59] Wickstrom, U., “Application of the Standard Fire Curve for Expressing Natural Fires for Design Purposes. Fire Safety: Science and Engineering,” ASTM STP 882, T.Z. Harmathy, Ed., American Society for Testing and materials, Philadelphia, 1985, pp. 145 – 159.

[60] Kawagoe, K, and Sekine, T., “Estimation of Fire Temperature-Time Curve in Rooms,” Occasional Report No.11, Building Research Institute, Tokyo, 1963.

[61] McCaffrey, B., Quintiere, J. and Harkelroad, M., “Estimating Room Fire Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations,” *Fire Technology*, Vol. 17, No. 2, 1981, pp. 98 – 119.

[62] Babrauskas, V., “COMPF: A Program for Calculating Post-flashover Fire Temperatures,” UCB FRG 75-2, Fire Research Group, University of California, Berkeley, CA, 1975.

[63] Babrauskas, V., “Fire Endurance in Buildings,” Ph. D. dissertation, University of California, Berkeley, CA, 1976.

[64] Babrauskas, V., and Williamson, R. B., “Post-Flashover Compartment Fires: Basis of a Theoretical Model,” *Fire and Materials*, Volume 2, 1978, pp. 39 – 53.

[65] Babrauskas, V., and Williamson, R. B., “Post-Flashover Compartment Fires—Application of a Theoretical Model,” *Fire and Materials*, Volume 3, 1979, pp. 1 – 7.

[66] Babrauskas, V., “COMPF2 – A Program for Calculating Post-Flashover Fire Temperatures,” NBS Technical Note 991, National Bureau of Standards, Gaithersburg, MD, 1979.

[67] Abrams, M. “Behavior of Inorganic Materials in Fire,” *Design of Buildings for Fire Safety*, ASTM STP 685, E. E. Smith and T. Z. Harmathy, Eds., American Society of Testing and Materials, Philadelphia, PA, 1979.

[68] Harmathy, T. Z., “Properties of Building Materials at Elevated Temperatures,” DBR Paper No. 1080, Division of Building Research, National Research Council of Canada, Ottawa, March, 1983.

[69] Lie, T. T., *Fire and Buildings*, Applied Science Publishers, LTD, London, 1972.

[70] Alder, H. L. and Roessler, E. B., *Introduction to Probability and Statistics*, W.H. Freeman and Company, San Francisco, CA, 1960.