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Fire safety engineering — Assessment, verification and validation of calculation methods —

Part 2:
Example of a fire zone model

Ingénierie de la sécurité incendie — Évaluation, vérification et validation des méthodes de calcul —

Partie 2: Exemple d'un modèle de zone

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Foreword

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The committee responsible for this document is ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

ISO 16730 consists of the following parts, under the general title *Fire safety engineering — Assessment, verification and validation of calculation methods*:

— *Part 2: Example of a fire zone model* (Technical report)

— *Part 3: Example of a CFD model* (Technical report)

— *Part 4: Example of a structural model* (Technical report)

— *Part 5: Example of an Egress model* (Technical report)

The following parts are under preparation:

— *Part 1: General* (revision of ISO 16730:2008)

Introduction

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose. Nor does such identification imply a finding of fault or negligence by the International Standards Organization.

For the particular case of the example application of ISO 16730-1 described in this document, ISO takes no responsibility for the correctness of the code used or the validity of the verification or the validation statements for this example. By publishing the example, ISO does not endorse the use of the software or the model assumptions described therein and states that there are other calculation methods available.

Fire safety engineering — Assessment, verification and validation of calculation methods —

Part 2: Example of a fire zone model

1 Scope

This part of ISO 16730 shows how ISO 16730-1 is applied to a calculation method for a specific example. It demonstrates how technical and users' aspects of the method are properly described in order to enable the assessment of the method in view of verification and validation.

The example in this part of ISO 16730 describes the application of procedures given in ISO 16730-1 for a fire zone model (CFAST).

The main objective of the specific model treated here is the simulation of a fire in confined compartments with a natural or forced ventilation system.

2 General information on the zone model considered

The name given to the zone model considered in this Technical Report is "CFAST". CFAST is a two-zone fire model capable of predicting the environment in a multi-compartment structure subjected to a fire. It calculates the time-evolving distribution of smoke and fire gases and the temperature throughout a building during a user-prescribed fire. This Technical Report describes the equations which constitute the model, the physical basis for these equations, and an evaluation of the sensitivity and predictive capability of the model.

The modelling equations take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently, the first law of thermodynamics), the ideal gas law, and relations for density and internal energy. These equations predict as functions of time quantities such as pressure, layer height, and temperature given the accumulation of mass and enthalpy in the two layers. The model then consists of a set of ODEs to compute the environment in each compartment and a collection of algorithms to compute the mass and enthalpy source terms required by the ODEs.

3 Methodology used in this Technical Report

For the calculation method considered, checks based on ISO 16730-1 and as outlined in this Technical Report are applied. This Technical Report lists in Annexes A and B the important issues to be checked in the left-hand column of a two-column table. The issues addressed are then described in detail, and it is shown how these were dealt with during the development of the calculation method in the right-hand column of the Annexes A and B cited above, where Annex A covers the description of the calculation method and Annex B covers the complete description of the assessment (verification and validation) of the particular calculation method. Annex C describes a worked example and Annex D adds a user's manual.

Annex A
(informative)

Description of the calculation method

A.1 Purpose	
Definition of problem solved or function performed	The model has been developed for solving practical fire problems in fire protection engineering while at the same time providing a tool to study fundamental fire dynamics and smoke spread. It is intended for system modelling of building and building components. It is not intended for detailed study of flow within a compartment such as is needed for smoke detector siting. Space scales from ~1 m^3 to 1 000 m^3 and time scales from ~1 s to approximately a few hours.
(Qualitative) description of results of the calculation method	The outputs of the model are the sensible variables that are needed for assessing the environment in a building subjected to a fire. These include temperatures of the upper and lower gas layers within each compartment, the ceiling/wall/floor temperatures within each compartment, the visible smoke and gas species concentrations within each layer, target temperatures, and sprinkler activation time.
Justification statements and feasibility studies	The model predicts the environment within compartmented structures resulting from a fire prescribed by the user. It is an example of the class of models called finite element. This particular implementation is called a zone model and, essentially, the space to be modelled is broken down to a few elements. The physics of the compartment fire phenomena is driven by fluid flow, primarily buoyancy. The usual set of elements or zones are the upper and lower gas layers, partitioning of the wall/ceiling/floor to an element each, one or more plumes, and objects such as fires, targets, and detectors. One feature of this implementation of a finite element model is that the interface between the elements (in this case, the upper and lower gas layers) can move, with its position defined by the governing equations. The attached bibliography[1-4] has a compendium of all validation testing which has been done.

A.2 Theory	
Underlying conceptual model (governing phenomena)	The modelling equations take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently, the first law of thermodynamics), and the ideal gas law. These equations predict as functions of time quantities such as pressure, layer height, and temperature given the accumulation of mass and enthalpy in the two layers. The assumption of a zone model is that properties such as temperature can be approximated throughout a control volume by an average value.
Theoretical basis of the phenomena and physical laws on which the calculation method is based	The equations used take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently, the first law of thermodynamics), the ideal gas law, and relations for density and internal energy. These equations predict as functions of time quantities such as pressure, layer height, and temperature given the accumulation of mass and enthalpy in the two layers.

A.3 Implementation of theory	
Governing equations	The modelling equations used take the mathematical form of an initial value problem for a system of ordinary differential equations. These equations are derived using the conservation of mass, the conservation of energy (equivalently, the first law of thermodynamics), and the ideal gas law. These equations predict as functions of time quantities such as pressure, layer height, and temperature given the accumulation of mass and enthalpy in the two layers. The assumption of a zone model is that properties such as temperature can be approximated throughout a control volume by an average value. The formulation uses the definitions of density, internal energy, and the ideal gas law. These rates represent the exchange of mass and enthalpy between zones due to physical phenomena such as plumes, natural and forced ventilation, convective and radiative heat transfer, and so on. For example, a vent exchanges mass and enthalpy between zones in connected rooms, a fire plume typically adds heat to the upper layer and transfers entrained mass and enthalpy from the lower to the upper layer, and convection transfers enthalpy from the gas layers to the surrounding walls.

Mathematical techniques, procedures, and computational algorithms employed, with references to them	The equations used in zone fire modelling are ordinary differential equations (ODEs), which are stiff. The term "stiff" means that large variations in time scales are present in the ODE solution. In our problem, pressures adjust to changing conditions more quickly than other quantities such as layer temperatures or interface heights. Special solvers are required in general to solve zone fire modelling ODEs because of this stiffness, which are used here. There are two assumptions which reduce the computation time. The first is that relatively few zones or elements per compartment are sufficient to model the physical situation. The second assumption is to close the set of equations without using the momentum equation in the compartment interiors. This simplification eliminates acoustic waves. Though this prevents one from calculating gravity waves in compartments (or between compartments), coupled with only a few elements per compartment allows for a prediction in a large and complex space very quickly.
Identification of each assumption embedded in the logic; limitations on the input parameters that are caused by the range of applicability of the calculation method	The model has been developed for solving practical fire problems in fire protection engineering while at the same time providing a tool to study fundamental fire dynamics and smoke spread. It is intended for system modelling of buildings and building components. It is not intended for detailed study of flow within a compartment such as is needed for smoke detector siting. It includes the activation of sprinklers and fire suppression by water droplets. The most extensive use of the model is in fire and smoke spread in complex buildings. The efficiency and computational speed are inherent in the few computation cells needed for a zone model implementation. Most of the use is for reconstruction of timelines for fire and smoke spread in residential, commercial, and industrial fire reconstructions. Some applications of the model have been for design of smoke control systems.

	Compartments: The model is generally limited to situations where the compartment volumes are strongly stratified. However, in order to facilitate the use of the model for preliminary estimates when a more sophisticated calculation is ultimately needed, there are algorithms for corridor flow, smoke detector activation, and detailed heat conduction through solid boundaries. This model does provide for non-rectangular compartments, though the application is intended to be limited to relatively simple spaces such as attics and ship corridors. There is no intent to include complex geometries where a complex flow field is a driving force. For these applications, computational fluid dynamics (CFD) models are appropriate.
	There are also limitations inherent in the assumption of stratification of the gas layers. The zone model concept, by definition, implies a sharp boundary between the upper and lower layers, whereas in reality, the transition is typically over about 10 % of the height of the compartment and can be larger in weakly stratified flow. For example, a burning cigarette in a normal room is not within the purview of a zone model. While it is possible to make predictions within 5 % of the actual temperatures of the gas layers, this is not the optimum use of the model. It is more properly used to make estimates of fire spread (not flame spread), smoke detection and contamination, and life-safety calculations.
	Heat release rate: There are limitations inherent in the assumptions used in the application of the empirical models. As a general guideline, the heat release should not exceed about 1 MW/m^3. This is a limitation on the numerical routines due to the coupling between gas flow and heat transfer through boundaries (conduction, convection, and radiation). The inherent two-layer assumption is likely to break down well before this limit is reached.
	Radiation: Since the model includes a sophisticated radiation model and ventilation algorithms, it has further use for studying building contamination through the ventilation system, as well as the stack effect and the effect of wind on air circulation in buildings.
	Ventilation and leakage: In a single compartment, the ratio of the area of vents connecting one compartment to another to the volume of the compartment should not exceed roughly 2 m^{-1}. This is a limitation on the plug flow assumption for vents. An important limitation arises from the uncertainty in the scenario specification. For example, leakage in buildings is significant, and this affects flow calculations especially when wind is present and for tall buildings. These effects can overwhelm limitations on accuracy of the implementation of the model. The overall accuracy of the model is closely tied to the specificity, care, and completeness with which the data are provided.
	Thermal properties: The accuracy of the model predictions is limited by how well the user can specify the thermophysical properties. For example, the fraction of fuel which ends up as soot has an important effect on the radiation absorption of the gas layer and, therefore, the relative convective versus radiative heating of the layers and walls, which in turn affects the buoyancy and flow. There is a higher level of uncertainty of the predictions if the properties of real materials and real fuels are unknown or difficult to obtain, or the physical processes of combustion, radiation, and heat transfer are more complicated than their mathematical representations in the model.

Discussion of accuracy of the results obtained by important algorithms and, in the case of computer models, any dependence on particular computer capabilities	The predictions generally are accurate within 10 % to 25 % of measurements for a range of scenarios. In general, this is adequate for its intended uses which are life-safety calculations and estimation of the environment to which building elements are subjected in a fire environment. Applied design margins are typically larger than this level of accuracy and may be appropriate to ensure an adequate factor of safety.
Description of results of the sensitivity analyses	Many of the outputs are quite insensitive to uncertainty in the input parameters for a broad range of scenarios. Not surprisingly, heat release rate was consistently seen as the most important variable in a range of simulations. Heat release rate and related variables such as heat of combustion or generation rates of products of combustion provide the driving force for fire-driven flows. All of these are user inputs. Thus, careful selection of these fire-related variables is necessary for accurate predictions. Other variables related to compartment geometry such as compartment height or vent sizes, while deemed important for the model outputs, are typically more easily defined for specific design scenarios than fire-related inputs. For some scenarios, such as typical building performance design, these vents may need to include the effects of leakage to ensure accurate predictions. For other scenarios, such as shipboard use or nuclear power facilities, leakage may be easily defined and may not be an issue in the calculations.

A.4 Input	
Required input	All of the data to run the model are contained in an input data file. Also needed are databases for objects, thermophysical properties of boundaries, and sample prescribed-fire descriptions provided with the model. These files contain information about the building geometry (compartment sizes, materials of construction, and material properties), connections between compartments (horizontal flow openings such as doors, windows, vertical flow openings in floors and ceilings, and mechanical ventilation connections), fire properties (fire size and species production rates as a function of time), and specifications for detectors, sprinklers, and targets (position, size, heat transfer characteristics, and flow characteristics for sprinklers). Materials are defined by their thermal conductivity, specific heat, density, thickness, and burning behaviour (heat release rate, ignition properties, and species yields). The input data file provides the program with parameters to describe the scenario under consideration. The parameters are organized into groups of related variables. Each line of the input data file contains inputs related to a single group and begins with a keyword that identifies the input. For example, compartment geometry is described by a set of lines (keyword: COMPA) that define the width, depth, and height of each compartment. A description of the input parameters can be found in the User's Guide.[2]
Source of the data required	Various sources for data can be used. These data include property data for boundary materials such as specific heat and conductivity, flow coefficients through openings, plume model coefficients, and so on. The data are taken from refereed publications.
For computer models: any auxiliary programs or external data files required	No
Provide information on the source, contents, and use of data libraries for computer models	Examples of data libraries are provided.

Annex B
(informative)

Complete description of the assessment (verification and validation) of the calculation method

(Quantitative) results of any efforts to evaluate the predictive capabilities of the calculation method in accordance with Chapter 5 of ISO 16730-1	Extensive validation of the calculation method was performed (see e.g. Chapter 6 of [1]).
References to reviews, analytical tests, comparison tests, experimental validation, and code checking already performed. If, in case of computer models, the validation of the calculation method is based on beta testing, the documentation should include a profile of those involved in the testing (e.g. were they involved to any degree in the development of the calculation method or were they naive users; were they given any extra instruction that would not be available to the intended users of the final product; etc.)	The calculation method is a publicly available model developed by the National Institute of Standards and Technology (USA). It has been subject to rigorous review, including code checking, verification by numerous researchers, and validation through comparison with many experiments. These include data gathered specifically for this model as well as data developed for other purposes. The full range of comparisons used to validate CFAST is discussed in Chapter 6 of the Technical Reference Guide.[1] In the full validation study, there are comparisons with full-scale tests conducted specifically for the chosen evaluation (13), comparisons with previously published test data (10), comparisons with documented fire experience (5), and comparison with experiments which cover special situations (2 on nuclear facilities, 3 from small scale testing, and 9 on unusual geometry or specific algorithms). The experiments used in the current evaluation of the model, detailed in [4], are: NBS Single Room Tests with Furniture (total compartment volume: 21 m^3, peak fire size: 2,9 MW) VTT Large Hall Tests (total compartment volume: 7 182 m^3, peak fire size: 4 MW) NIST/NRC Tests Series (total compartment volume: 586 m^3, peak fire size: 2,2 MW) FM/SNL Tests Series (total compartment volume: 1 296 m^3, peak fire size: 516 kW) iBMB Compartment Tests (total compartment volume: 74 m^3, peak fire size: 3,6 MW) NBS Multi-Compartment Test Series (total volume: 100 m^3, peak fire size: 500 kW) FM Four Room Including Corridor Test Series (total volume: 200 m^3, peak fire size: 1 MW) NIST Seven-Story Hotel Tests (total building volume: 140 000 m^3, peak fire size: 3 MW) Table B.1 summarizes the validation comparisons for the current version of the model.
The extent to which the calculation method meets this Technical Report.	The V&V process for this particular model meets the requirements of ISO 16730-1.

Table B.1 — Summary of model comparisons[4]

Quantity	Average difference[a] (%)	Median difference[b] (%)	Within experimental uncertainty[c] (%)	90th percentile[d] (%)
HGL temperature	6	14	52	30
HGL depth	3	15	40	28
Plume temperature	17	11	39	29
Ceiling jet temperature	16	5	70	61
Oxygen concentration	−6	18	12	32
Carbon dioxide concentration	−16	16	21	52
Smoke obscuration[e]	272/22	227/18	0/82	499/40
Pressure	43	13	77	206[f]
Target flux (total)	−23	27	42	51
Target temperature	0	18	38	34
Surface flux (total)	5	25	40	61
Surface temperature	24	35	17	76

[a] Average difference includes both the sign and the magnitude of the relative differences in order to show any general trend to over- or under-prediction.

[b] Median difference is based only on the magnitude of the relative differences and ignores the sign of the relative differences so that values with opposing signs do not cancel and make the comparison appear closer than individual magnitudes would indicate.

[c] The percentage of model predictions that are within experimental uncertainty.

[d] 90 % of the model predictions are within the stated percentage of experimental values. For reference, a difference of 100 % is a factor of 2 larger or smaller than experimental values.

[e] The first number is for the closed-door NIST/NRC tests, and the second number is for the open-door NIST/NRC tests.

[f] High magnitude of the 90th percentile value driven in large part by two tests where under-prediction was approximately 2 Pa.

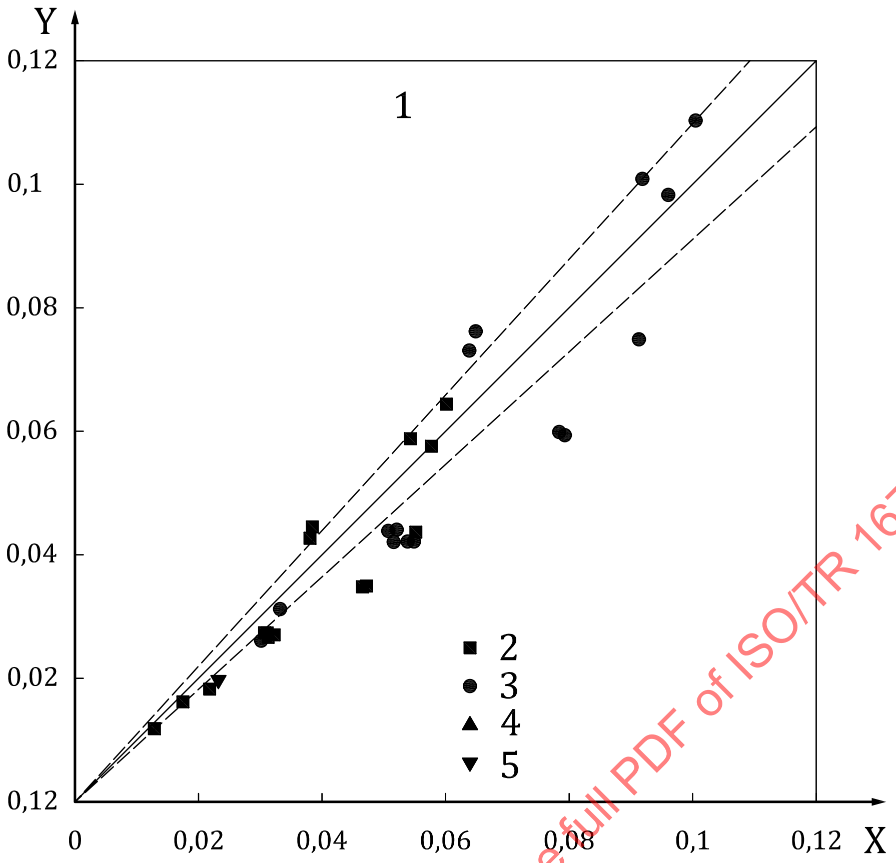
Annex C
(informative)

Worked example

This example calculation is a look at experimental uncertainty, model uncertainty, and a series of full-scale experiments.

A series of fire experiments was performed at NIST for the U.S. Nuclear Regulatory Commission and Electric Power Research Institute.[3] Figure C.1 shows a comparison of the change in volume fraction (concentration) of carbon dioxide and oxygen between CFAST predictions and data for several test layouts from the ICFMP project. Figure C.2 is a similar comparison of the predicted and measured hot gas layer temperature with other data subsets from the same project. Details on the test environment and test conditions are found in the referred literature.[3]

The reference to test series in the ICFMP is contained in [3]. BE n denotes one of the scenarios.



Key

X measured change in volume fraction

Y predicted change in volume fraction

1 CFAST gas species concentrations

2 ICFMP BE #3 upper layer CO_2

3 ICFMP BE #3 upper layer O_2

4 ICFMP BE #5 upper layer CO_2

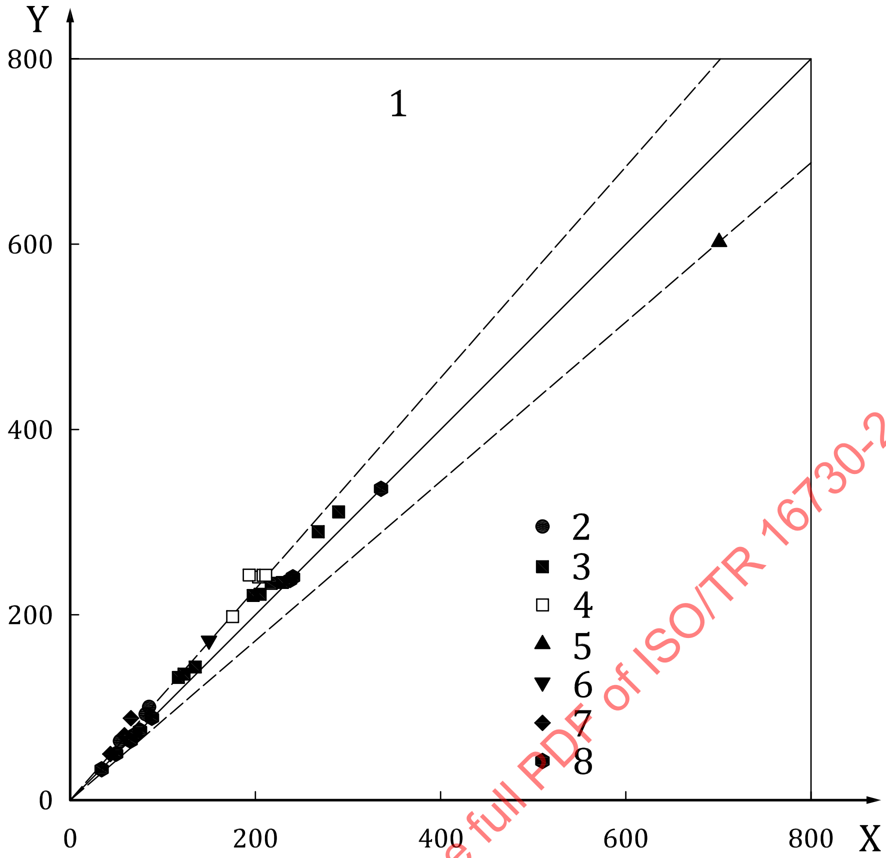
5 ICFMP BE #5 upper layer O_2

— CFAST calculation for the stated scenario

--- (±) combined uncertainty

NOTE ICFMP xx denotes particular test scenarios.

Figure C.1 — Comparison of oxygen concentration and carbon dioxide concentration (see Table C.1)[3]



Key

X measured temperature rise (°C)

Y predicted temperature rise (°C)

1 CFAST hot gas layer temperature rise

2 ICFMP BE #2

3 ICFMP BE #3 (closed-door tests)

4 ICFMP BE #3 (open-door Tests)

5 ICFMP BE #4

6 ICFMP BE #5

7 FM/SNL

8 NBS Multi-Room

— CFAST prediction

--- (±) combined uncertainty

NOTE ICFMP xx denotes particular test scenarios.

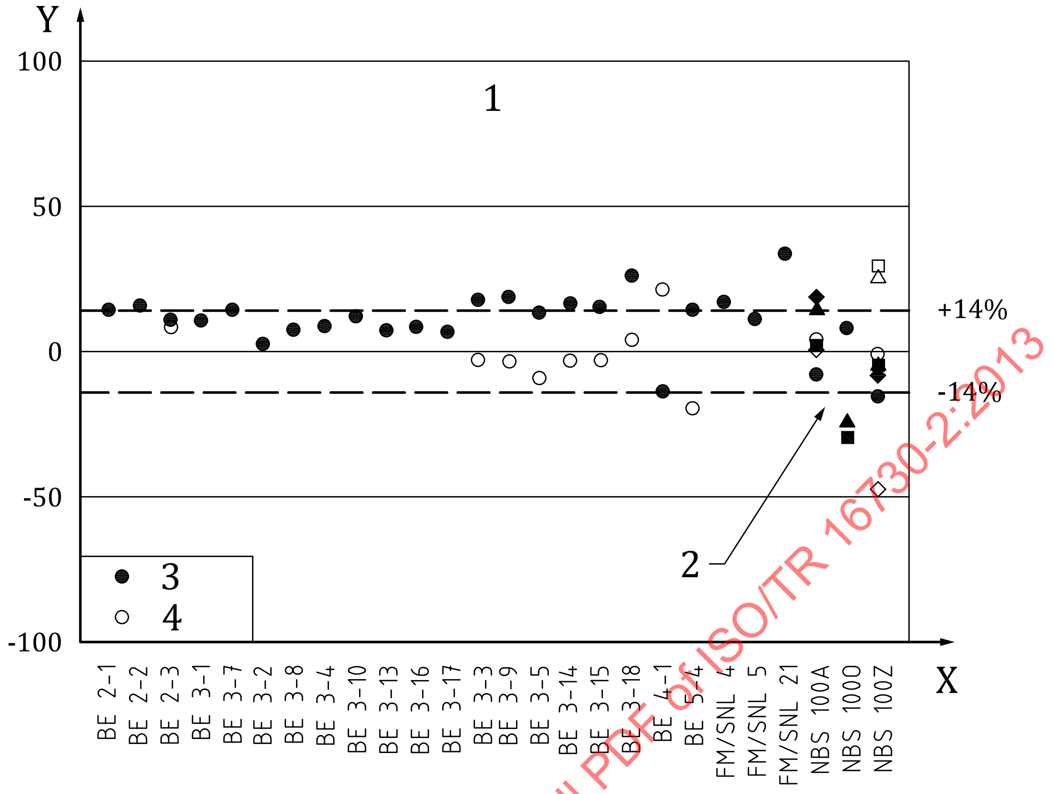
Figure C.2 — Comparison for hot gas layer temperature rise[3]

A comparison for all of the tests (from Reference [3]) gives a sense of uncertainty of the agreement between prediction and measurement, as denoted in Table C.1.

Table C.1 — Combined uncertainty from the ICFMP tests

Quantity	Number of tests	Combined uncertainty (%)
Hot gas layer temperature rise	26	13
Hot gas layer depth	26	9
Ceiling jet temperature	18	16
Plume temperature	6	14
Gas concentration	16	9
Smoke concentration	15	33
Pressure	15	40 (natural)
		80 (forced)
Heat flux	17	20
Target temperature	17	14

It is important to note that there is no statement about which is closer to true values. Another way to view this comparison is a simplistic relative difference (for the same data set), as shown in Figure C.3.



Key

Y relative difference (%)

1 CFAST hot gas layer temperature and depth

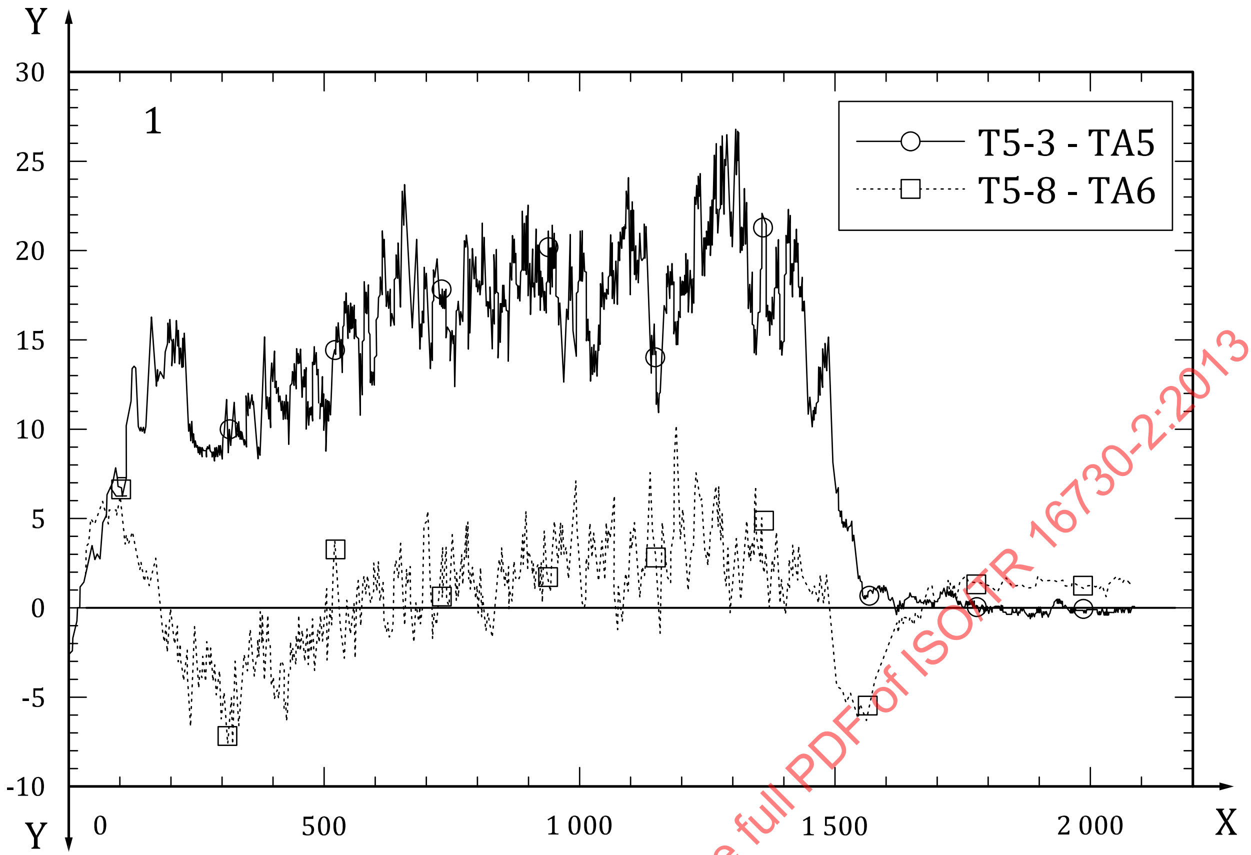
2 points other than circles denote locations remote from the fire room in the NBS Multi-Room series

3 hot gas layer (HGL) temperature

4 hot gas layer (HGL) depth

Figure C.3 — Relative difference of hot gas layer temperature and depth, respectively, to CFAST predictions, for a variety of tests which are denoted on the x-axis and in Reference [3]

Experimental errors can creep into the comparison. Figure C.4 shows, for one of the experiments, a comparison between bare-bead and aspirated thermocouples.



Key

X time (s)

Y temperature (°C)

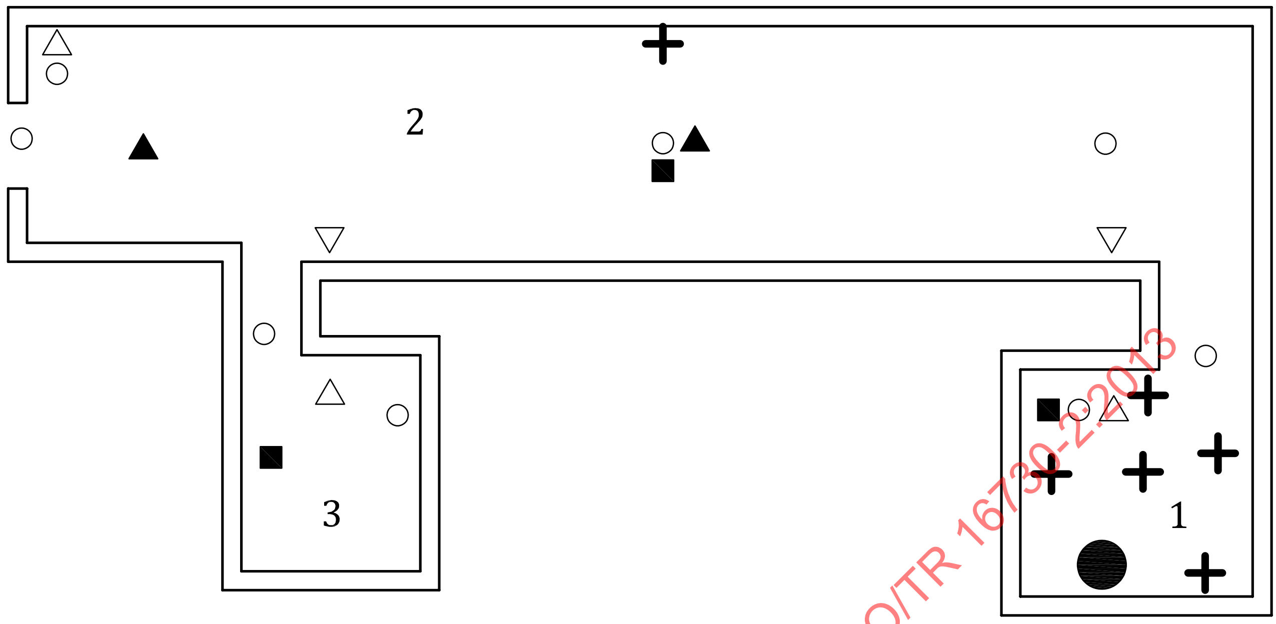
1 test 3

NOTE Circles are for aspirated, and boxes and the lower trace represent the bare thermocouples.

Figure C.4 — Relative temperature change for bare thermocouples as compared to aspirated thermocouples

The upper trace in Figure C.4 is an aspirated thermocouple, whereas the lower trace is a thermocouple without radiation correction. This is often the source of the difference reported when CFAST predictions are presented and the author concludes that the model over-predicts the temperature. There is no simple rule of thumb for this correction since it depends on the temperature and radiation in the environment.

Finally, modelling errors can creep in when the model is not a true representation of the experiment. In a full-scale experiment at NIST, a series of measurements was done in a three-compartment arrangement (see Figure C.5).



Key

1 room 1

2 room 2

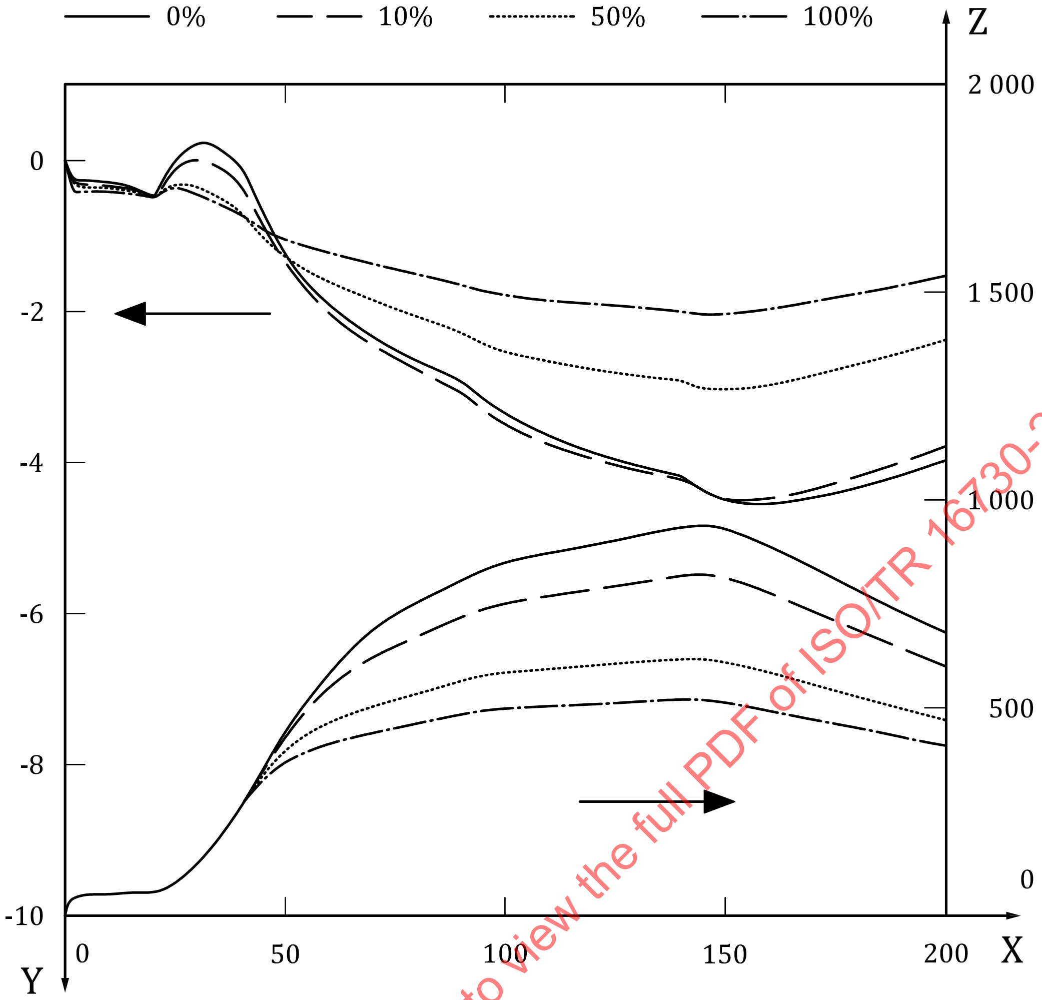
3 room 3

NOTE The symbols denote positions of measurement probes like TCs.

Figure C.5 — Layout of the test arrangement

During the first comparison of measurements with prediction, the difference was startlingly bad. In a following test series, it was found that smoke was leaking out of the top of the front wall of room 2. Consequently, leakage during the fire was considered important and was measured.

The effect of leakage on the upper layer temperature and floor pressure as a fraction of the actual openings is shown in Figure C.6.



Key

X time (s)

Y pressure (Pa)

Z temperature (°C)

Figure C.6 — Effects of leakage as fractions of the actual openings in the layout from Figure C.5 on both pressure and temperature

Doing the correct calculation, that is making a prediction for the experiment as it was rather than what was first imagined to be, is displayed in Figures C.7 and C.8, respectively.