International Collaborative Fire Modeling Project (ICFMP):

Summary of Benchmark Exercises No. 1 to 5

ICFMP Summary Report

Compiled by

M. Röwekamp (GRS),
J. Dreisbach (U.S. NRC),
W. Klein-Heßling (GRS),
K. McGrattan (NIST),
S. Miles (BRE),
M. Plys (Fauske & Ass.),
O. Riese (iBMB)

September 2008

Final Version

GRS - 227

Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) mbH

International Collaborative Fire Modeling Project (ICFMP): Summary of Benchmark Exercises No. 1 to 5

- ICFMP Summary Report -

Compiled by
M. Röwekamp (GRS),
j. Dreisbach (U.S. NRC),
W. Klein-Heßling (GRS),
K. McGrattan (NIST),
S. Miles (BRE),
M. Plys (Fauske & Ass.),
O. Riese (iBMB)

September 2008

Final Version

Vorhaben: SR 2491

Anmerkung:

This report was provided within the frame of the BMU-Project SR 2491. The authors are responsible for the contents of this report.

Dieser Bericht wurde im Rahmen des BMU-Vorhabens SR 2491 erstellt. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren.

GRS - 227

ISBN

Foreword

This document was developed in the frame of the 'International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications' (ICFMP). The objective of this collaborative project is to share the knowledge and resources of various organizations to evaluate and improve the state of the art of fire models for use in nuclear power plant fire safety, fire hazard analysis and fire risk assessement. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current fire models for fire safety analysis in nuclear power plants. The second phase will extend the validation database of those models and implement beneficial improvements to the models that are identified in the first phase of ICFMP. In the first phase, more than 20 expert institutions from six countries were represented in the collaborative project.

This Summary Report gives an overview on the results of the first phase of the international collaborative project. The main objective of the project was to evaluate the capability of fire models to analyze a variety of fire scenarios typical for nuclear power plants (NPP). The evaluation of the capability of fire models to analyze these scenarios was conducted through a series of in total five international Benchmark Exercises. Different types of models were used by the participating expert institutions from five countries. The technical information that will be useful for fire model users, developers and further experts is summarized in this document. More detailed information is provided in the corresponding technical reference documents for the ICFMP Benchmark Exercises No. 1 to 5.

The objective of these exercises was not to compare the capabilities and strengths of specific models, address issues specific to a model, nor to recommend specific models over others.

This document is not intended to provide guidance to users of fire models. Guidance on the use of fire models is currently being developed by several national and international standards organizations, industry groups, and utilities. This document is intended to be a source and reference for technical information and insights gained through the exercises conducted, and provided by the experts participating in this project. This information may be beneficial to users of fire models and developers of guidance documents or standards for the use of fire models in nuclear power plant applications.

Executive Summary

In traditional prescriptive regulation, the design of fire protection means for nuclear power plants is based on codes and standards, tests and engineering judgment derived from operating experience. There is a worldwide movement, however, to introduce risk-informed, performance-based analyses into fire protection engineering, both for general building application as well as specifically to nuclear power plants. Here recourse to computer models and analytical methods may be required to determine the hazards for which fire protection systems must be designed to protect against.

The strengths and weaknesses of different fire modeling methodologies for nuclear power plant applications needs to be systematically evaluated. Furthermore, the validity, limitations and benefits of these methodologies, and the fire models currently in use, needs to be disseminated to all concerned.

In October 1999, the U.S. Nuclear Regulatory Commission (NRC) and the Society of Fire Protection Engineers (SFPE) organized a meeting of international experts and fire modeling practitioners to discuss fire modeling for nuclear power plants. The 'International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications (ICFMP)' was established to share knowledge and resources and to evaluate the predictive capability of fire models for deterministic fire hazard analyses as well as probabilistic fire risk analyses, and to identify areas where fire models needed to be developed further. The ICFMP has complemented related activities such as the ‘Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications’ project conducted by the U.S. NRC and the (U.S.) Electric Power Research Institute (EPRI) or the OECD/NEA PRISME project.

The central theme of Phase I of the ICFMP was a series of five Benchmark Exercises conducted by the participating institutions, using a representative selection of zone, lumped parameter, and CFD fire models. Numerical predictions have been analyzed by comparing the results from different models and, where available, against experimental measurements too. The Benchmark Exercises involved ‘blind’ pre-calculations, where modelers did not have access to experimental measurements or to each others results, and also ‘open’ post-calculations where this information was available. Although a variety of input parameters was defined in the problem specifications, the calculations did involve a non-negligible degree of user judgment.

ICFMP participants were encouraged to undertake simulations using alternate strategies and to examine the sensitivity of the predictions to model input parameters.

Benchmark Exercise No. 1 involved comparative predictions for a representative emergency switchgear room. The objective of Part I of the exercise was to determine the maximum horizontal distance between a specified (trash bag) fire and a cable tray that would result in the ignition of the cable tray. Part II then examined whether a target cable tray would be damaged by a fire in another cable tray separated by a given horizontal distance. The effect of door position (open or closed) and mechanical ventilation were examined. Although there were no experimental measurements, the initial calculations were still conducted in a blind manner, so that participants had no knowledge of each others' work.

Benchmark Exercise No. 2 examined the application of fire models to large enclosures, and complexities introduced by features such as flow of smoke and air between compartments via horizontal openings. Part I was based on a set of full-scale, heptane fire experiments performed under different ventilation conditions inside the VTT Test Hall in Finland. Although for Part II there were no experimental measurements, it extended the scope of the exercise to examine the effect of a 70 MW fire. The building had dimensions akin to those of a turbine hall, and furthermore was separated into a lower and an upper deck, connected by two permanent openings (hatches). Various natural and mechanical ventilation scenarios were included. In addition to calculating the gas temperatures, vent flows etc, participants were asked to estimate the likelihood of damage to cable and beam targets. Most calculations were conducted blind.

Benchmark Exercise No. 3 involved simulations for a series of experiments conducted at NIST, USA, in 2003 and representing a fire inside a switchgear room similar to that studied in Benchmark Exercise No. 1. A heptane spray burner provided the fire source in the experiments selected for the Benchmark Exercise. The heat release rate was determined using both the estimated fuel flow rate and also, in experiments where the door was open, by oxygen consumption calorimetry. Pre-experiment blind calculations were performed by participants, using a specified estimate of fire size. Semi-blind calculations were then conducted using measured fuel supply rates.

The uncertainty in this input parameter was a cause of much discussion in interpreting the fire model predictions, and illustrated the problems that can arise in benchmarking computer models against experiments.

Benchmark Exercise No. 4 was based on experiments for ventilation controlled kerosene pool fire tests conducted in the 'OSKAR' test facility at iBMB in Germany. The main objective of the experiments was to analyze the thermal load on the structures exposed to a fire relatively large compared to the size of the compartment and to investigate how changes in ventilation may influence conditions inside the compartment and the burning of the fuel. Blind calculations were conducted by a small number of participants with no prior knowledge of the kerosene burning rate. Semi-blind calculations were then performed by a larger number of participants, using pyrolysis rates derived from experimental weight loss measurements. The primary quantities to be predicted were gas temperatures at various locations, and the thermal response of target objects inside the compartment.

Benchmark Exercise No. 5 was also based on full-scale fire experiments performed in the 'OSKAR' facility at iBMB. In many respects the most challenging of all the Benchmarks, participants were asked to make predictions for fire induced loss of functionality and for fire spread within vertically orientated cable trays. Only a limited number of calculations were conducted in this Benchmark due to its challenging nature.

The results from the five ICFMP Benchmark Exercises have provided important insights into the performance of the current generation of fire models for a wide range of nuclear power plant applications. This has helped to identify the strengths and weaknesses of these models. Conclusions have been drawn in respect to where fire models can reliably be used, and importantly where they are not yet sufficiently developed. A range of phenomena which all types of fire model can be expected to predict with some reasonable degree of accuracy has been identified. As illustrated in Benchmark Exercise No. 2, if the fire is well ventilated and the geometry not too complex, then once the fire power and boundary heat losses are properly accounted for, all models predict hot gas layer temperature and depth with some confidence. Oxygen consumption was similarly reasonably well predicted by the range of fire models investigated, as was vent flow through vertical openings as illustrated in Benchmark Exercise No. 3.

It was demonstrated in Benchmark Exercise No. 2 that zone models are able to account for irregular ceiling shapes provided the volume of the space is included appropriately and the layer depth interpreted correctly. Although requiring some effort, mechanical ventilation was applied successfully in the application of zone models.

Cases where local three-dimensional effects are important, e.g. the maximum temperature where a fire plume impinges, could be predicted by CFD and, to a lesser extent, lumped-parameter models too. Furthermore, while difficult with two-layer zone models, post-flashover fire conditions could be reasonably modeled by CFD and lumped-parameter models.

The ICFMP has also identified where fire models should be applied with caution or may at present not be appropriate. Of particular relevance to nuclear power plants is the task of predicting the response of cables and cable trays to fire conditions. Benchmark Exercise No. 5 demonstrated that cable heating and pyrolysis models are currently at an elementary stage. Calculating the pyrolysis of 'simpler' fuels such as hydrocarbon pools also proved a challenge, as illustrated in Benchmark Exercise No. 4. The fundamental issues are the same as for cables, i.e. the heat transfer inside the fuel and the incident heat flux are critical phenomena that are difficult to model with sufficient accuracy for pyrolysis and fire spread calculations.

Limitations peculiar to zone models were identified, e.g. predicting flows across horizontal vents as in the turbine hall example in Benchmark Exercise No. 2. Post-flashover fire conditions also posed a problem for the two-zone fire models investigated.

The ICFMP has identified modeling tasks and phenomena requiring further development. Perhaps most important here is the task of predicting the heating and failure of safety critical items such as cables. Ignition, pyrolysis and flame spread are also important tasks for which model development is required. Here the use of empirical measured data may provide a practical near term solution. Other modeling issues for which further research and development is required include natural flows through horizontal (e.g. ceiling) vents, in particular for zone models, the prediction of soot yields and radiation fluxes, and smoke flows between compartments via vents and ducts.

Throughout the ICFMP Benchmark Exercises the definition of the fire source arguably presented the biggest uncertainty. Not only are the fire dimensions and pyrolysis rate difficult to specify, but the physical processes of combustion efficiency, soot and toxic gas yields and radiative fraction also present a challenge to the fire modeler. While it is in theory possible to model these phenomena, in practice they generally require 'engineering judgment'. The value of these terms defines the convective power of the fire, and this in turn strongly influences smoke temperature and entrainment rate. The appropriate setting of the convective power is important in obtaining a good match between prediction and measurement for smoke filling cases, as illustrated in Benchmark Exercise No. 2.

Soot and combustion product concentrations, in combination with gas temperature, have a strong influence on radiation fluxes, for which target heating is particularly sensitive. Modest variations in the gas temperature field can lead to significant differences in the incident radiation flux to a target due to the nonlinear T^4 relationship.

Now that the ICFMP has successfully completed Phase I, attention needs to be directed to Phase II. There clearly remains a useful role for the ICFMP as an independent and open forum for engineers, scientists, model developers, regulators etc. to advance the application of fire models for nuclear power plants. Other activities are currently addressing some areas, e.g. the continuation of the (U.S.) Verification and Validation project and the OECD/NEA PRISME project, to which any future ICFMP work will need to complement. Some of the issues that could be addressed by the ICFMP include:

- A Practical Users Guide providing information on how, where and when to use different types of computer model and on how to model important scenario features such as heat loss, ventilation, smoke spread between compartments, and local effects such as flame impingement,
- Detector response modeling, including an evaluation of existing detector codes and how such models might be applied for nuclear plant applictations,
- A review of specific code input data related to generic phenomena, such as values for flow coefficients,
- Development of heat release rate curves for cable trays,

- A review of cable modeling methods and recommendations for cable dysfunction criteria and
- Updating the Validation Database Report which describes experimental data pertinent to fire model application to nuclear power plants.

Zusammenfassung

Bei einem kerntechnischen Regelwerk, welches starken Verordnungscharakter hat, basiert die Auslegung von Brandschutzeinrichtungen und -maßnahmen in Kernkraftwerken auf Vorschriften und Normen, Experimenten und ingenieurtechnischer Einschätzung, welche sich aus der Betriebserfahrung ableitet. Weltweit besteht eine Bewegung der Methoden zur Brandsicherheit hin zur Einführung schutzzielorientierter Analysen sowohl für Gebäude im Allgemeinen als auch insbesondere für Kernkraftwerke. In diesem Zusammenhang kann es notwendig werden, auf Rechenmodelle und analytische Methoden zurückzugreifen, um jene Gefährdungen zu ermitteln, für deren Beherrschung die Brandschutzmaßnahmen ausgelegt sein müssen.

Die Stärken und Schwächen verschiedener Methoden zur Brandmodellierung für Anwendungen in Kernkraftwerken erfordern eine systematische Bewertung. Weiterhin müssen der Geltungsbereich, die Grenzen und die Vorteile dieser Methoden und der derzeit genutzten Brandsimulationsmodelle allen Anwendern und Entscheidungsträgern zugänglich gemacht werden.

Im Oktober 1999 veranstaltete die amerikanische Genehmigungs- und Aufsichtsbehörde (U.S. Nuclear Regulatory Commission, NRC) zusammen mit der Society of Fire Protection Engineers (SFPE) ein Arbeitstreffen internationaler Experten und Anwender von Brandsimulationscodes zur Diskussion der Brandmodellierung für Kernkraftwerke. Das 'International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications (ICFMP)' wurde als internationales Gemeinschaftsprojekt ins Leben gerufen, um Kenntnisse und Hilfsmittel auszutauschen und die Vorhersagefähigkeit von Brandmodellen für deterministische Brandgefahrenanalysen sowie probabilistische Brandrisikoanalysen zu beurteilen und diejenigen Bereiche identifizieren zu können, wo Brandsimulationscodes noch einer Weiterentwicklung bedürfen. ICFMP ergänzt fachlich verwandte Aktivitäten wie beispielsweise das von der U.S. NRC und EPRI (Electric Power Research Institute) gemeinsam durchgeführte Projekt zur 'Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications' oder das PRISME Projekt der OECD/NEA.

Zentrales Thema der Phase I des ICFMP war eine Serie von fünf Benchmark-Aufgaben, welche von den teilnehmenden Institutionen unter Verwendung einer repräsentativen Auswahl von Zonenmodellen, 'lumped parameter'-Codes und CFD-Brandsimulationsmodellen durchgeführt wurde.

Numerische Vorhersagen wurden dabei anhand von Vergleichen der Ergebnisse verschiedener Modelle und - sofern verfügbar - auch durch Vergleich der Rechenergebnisse mit experimentellen Messdaten untersucht. Die Benchmark-Aufgaben beinhalteten sowohl 'blinde' Vorausrechnungen, bei denen die Modellierer keinen Zugang zu den Versuchsergebnisse oder die jeweiligen Rechenergebnisse der anderen hatten, als auch 'offene' Nachrechnungen, bei denen diese Informationen zur Verfügung standen. Obwohl die meisten Eingabeparameter in den Problemstellungen definiert waren, erforderten die Berechnungen ein höheres Maß an eigener Einschätzung seitens des Anwenders im Vergleich zu den Aktivitäten im Rahmen des U.S.–amerikanischen 'Verification and Validation'-Projektes. Die ICFMP-Teilnehmer wurden ermutigt, Simulationen mit Hilfe wechselnder Strategien durchzuführen und den Einfluss der Eingabeparameter auf die Modellvorhersagen zu untersuchen.

Benchmark-Aufgabe Nr. 1 umfasste vergleichende Vorhersagen für einen repräsentativen Schaltanlagenraum des Notstandssystems. Die Zielsetzung von Teil 1 dieser Aufgabe bestand in der Ermittlung der maximalen horizontalen Entfernung zwischen einem vorgegebenen Brand (Abfallsack) und einer Kabeltrasse, bei welcher es noch zu einer Entzündung von Kabeln dieser Trasse kommen könnte. In Teil II wurde dann untersucht, ob eine Kabeltrasse infolge eines Brandes auf einer anderen Kabeltrasse in einer vorgegebenen horizontalen Entfernung Schaden nehmen könnte. Der Einfluss zum einen einer Türstellung (offen oder geschlossen) und zum anderen einer mechanischen Belüftung wurde untersucht. Wenngleich es keine experimentellen Messungen gab, wurden die ersten Simulationsrechnungen dennoch blind, d.h. ohne Kenntnis der Teilnehmer von den Arbeiten der anderen Teilnehmer, durchgeführt.

Im Rahmen der Benchmark-Aufgabe Nr. 2 wurde die Anwendung von Brandsimulationsmodellen auf große Umschließungen und komplexe Gegebenheiten untersucht, welche durch Merkmale wie Rauchgas- und Luftströmungen zwischen verschiedenen Räumen über horizontale Öffnungen gekennzeichnet sind. Grundlage für Teil I bildete eine Serie realmaßstäblicher Heptan-Lachenbrandversuche unter unterschiedlichen Ventilationsbedingungen in der Versuchshalle des VTT in Finnland.

Wenngleich für Teil II keine experimentellen Messungen vorlagen, wurde der Umfang dieser Aufgabe auf die Untersuchung der Auswirkungen eines 70 MW-Brandes ausgeweitet. Dabei waren die Ausmaße des Gebäudes denen eines Maschinenhauses ähnlich, wobei das Gebäude selbst in eine untere und eine obere Ebene unterteilt war, welche durch zwei ständig vorhandene Öffnungen (Luken) miteinander verbunden waren. Verschiedene Szenarien mit natürlicher und mechanischer Ventilation wurden betrachtet. Die an dieser Benchmark-Aufgabe teilnehmenden Institutionen sollten zusätzlich zur Berechnung der Gastemperaturen, der Strömungen durch die Lüftungskanäle etc. die Wahrscheinlichkeit für Schäden an Kabeln und Zielobjekten (Targets) abschätzen. Die meisten dieser Rechnungen wurden blind durchgeführt.

Benchmark-Aufgabe Nr. 3 beinhaltete Simulationsrechnungen für eine Reihe von Experimenten, die 2003 am NIST in den USA als repräsentativ für einen Brand in einem Schaltanlagenraum mit ähnlichen Eigenschaften wie in der Benchmark-Aufgabe Nr. 1 durchgeführt wurden. Als Brandquelle in den für diese Benchmark-Aufgabe ausgewählten Versuchen diente ein Brenner mit einem Heptan-Spray. Die Wärmefreisetzungsrate wurde zum einen anhand der berechneten Massenstromrate des Brandgutes ermittelt sowie zum anderen, bei Versuchen mit offener Tür, kalorimetrisch anhand der Sauerstoffverbrauchsmethode. Vor dem Versuch wurden von den Teilnehmern blinde Vorausrechnungen unter Verwendung einer vorgegebenen Abbrandrate zur Abschätzung des Brandausmaßes durchgeführt. Im Anschluss daran erfolgten semiblinde Rechnungen unter Verwendung der gemessenen Abbrandraten. Die Unsicherheit bezüglich dieses Eingabeparameters gab Anlass zu erheblichen Diskussionen hinsichtlich der Interpretation von Vorhersagen der Brandsimulationscodes. Diese veranschaulichte die Probleme, die bei einem Vergleich von Rechenmodellen mit Versuchen auftreten können.

Versuche zu ventilationsgesteuerten Kerosin-Lachenbränden, die in der Versuchsanlage 'OSKAR' des iBMB in Deutschland durchgeführt wurden, stellten die Basis für die Benchmark-Aufgabe Nr. 4 dar. Wesentliches Ziel dieser Versuche war die Untersuchung der thermischen Belastung baulicher Strukturen bei einem im Vergleich zur Raumgröße großen Brand. Weiterhin sollte untersucht werden, wie sich Veränderungen in der Ventilation auf die Bedingungen im Brandraum und das Abbrandverhalten auswirken.

Von einer begrenzten Anzahl der Teilnehmer wurden blinde Rechnungen ohne vorherige Kenntnis der Abbrandrate des Kerosins durchgeführt. Im Anschluss daran wurden von einer größeren Anzahl an Teilnehmern semiblinde Rechnungen unter Verwendung von Pyrolyseraten durchgeführt, die aus experimentellen Messungen des Gewichtsverlustes abgeleitet worden waren. Primär sollten dabei Gastemperatur an verschiedenen Orten sowie das thermische Ansprechverhalten von Zielobjekten innerhalb des Brandraums vorgesagt werden.

Benchmark-Aufgabe Nr. 5 wurde ebenfalls auf der Grundlage von realmaßstäblichen Brandversuchen in der Versuchsanlage 'OSKAR' am iBMB durchgeführt. Dabei handelte es sich um die in vielerlei Hinsicht anspruchsvollste Benchmark-Aufgabe. Den Teilnehmern wurde die Aufgabe gestellt, Vorhersagen sowohl zum brandbedingten Funktionsausfall als auch zur Brandausbreitung auf vertikal angeordneten Kabeltrassen zu machen. Da diese Benchmark-Aufgabe eine extreme Herausforderung für die Simulation darstellt, wurde nur eine überaus begrenzte Zahl von Rechnungen durchgeführt.

Die Ergebnisse der fünf ICFMP Benchmark-Aufgaben geben wesentliche Einblicke in die Leistungsfähigkeit der gegenwärtigen Generation von Brandsimulationsmodellen für ein breites Spektrum von Anwendungen in Kernkraftwerken, Damit lassen sich die Stärken und Schwächen solcher Modelle identifizieren. Es wurden Schlussfolgerungen dahingehend gezogen, wo sich Brandsimulationscodes zuverlässig einsetzen lassen und, was besonders wichtig ist, wo diese noch weiterer Entwicklung bedürfen. Eine Reihe von Phänomenen wurde identifiziert, bei denen zu unterstellen ist, dass sie von allen Arten von Brandsimulationsmodellen mit ausreichender Genauigkeit modelliert werden können. Wie in Benchmark-Aufgabe Nr. 2 verdeutlicht, sind alle Modelle in der Lage, bei guter Belüftung des Brandes und nicht allzu komplexer Geometrie Temperatur und Schichtdicke der Heißgasschicht mit einer ausreichenden Aussagegenauigkeit vorauszusagen, sofern die Brandleistung und die Randbedingungen in Bezug auf Wärmeverluste korrekt berücksichtigt worden sind. Der Sauerstoffverbrauch wurde in vergleichbarer Genauigkeit von den eingesetzten Modellen vorhergesagt, ebenso wie die Luftströmung durch die vertikalen Öffnungen, wie in Benchmark-Aufgabe Nr. 3 gezeigt.

In Benchmark-Aufgabe Nr. 2 wurde gezeigt, dass Zonenmodelle in der Lage sind, unregelmäßige Deckenformen zu berücksichtigen, sofern das Volumen des Raums in angemessener Weise berücksichtigt und die Schichtdicke korrekt interpretiert wird. Obwohl dies einige Bemühungen erforderte, wurde bei der Anwendung von Zonenmodellen die mechanische Ventilation erfolgreich umgesetzt.

Szenarien, bei welchen lokale dreidimensionale Effekte von Bedeutung sind (z. B. maximale Temperatur dort, wo ein Plume auftrifft), ließen sich mittels CFD-Codes und in geringerem Umfang auch mit 'lumped parameter'-Codes modellieren.

Außerdem war eine sinnvolle Simulation der Vollbrandphase mit Hilfe von CFD- und 'lumped parameter'-Codes möglich, was mit nur zweischichtigen Zonenmodellen schwierig ist.

Mittels ICFMP konnte identifiziert werden, wo Brandmodelle nur mit Vorsicht angewendet werden sollten oder gar ungeeignet sind. Die anspruchsvolle Aufgabe der Modellierung des Verhaltens von Kabeln und Kabeltrassen unter Brandbedingungen ist von besonderer Bedeutung bei der Sicherheitsbewertung von Kernkraftwerken. Benchmark-Aufgabe Nr. 5 hat deutlich aufgezeigt, dass dies jenseits der Prognosefähigkeiten von Brandsimulationsmodellen liegt. Auch die Modellierung der Pyrolyse 'einfacherer' Brandgüter, wie beispielsweise Kohlenwasserstoff-Lachen, erwies sich ebenso als eine Herausforderung, wie sich in Benchmark-Aufgabe Nr. 4 herausstellte. Die wesentlichen Fragestellungen sind die gleichen wie bei Kabeln, d.h. der Wärmeübergang im Brandgut und der einfallende Wärmestrom sind kritische Phänomene, die nur schwerlich mit ausreichender Genauigkeit in Bezug auf die Ermittlung der Pyrolyse und der Brandausbreitung zu modellieren sind.

Insbesondere für die Zonenmodelle wurden Grenzen identifiziert, z. B. bei der Simulation von Strömungen durch horizontale Lüftungsöffnungen, wie beispielsweise im Maschinenhaus in Benchmark-Aufgabe Nr. 2. Die Randbedingungen eines Vollbrandes stellten ebenfalls ein Problem für die beteiligten Zweizonen-Brandsimulationscodes dar.

Mittels des ICFMP konnten Aufgaben und Phänomene identifiziert werden, bei deren Modellierung noch erheblicher Weiterentwicklungsbedarf besteht.

Die wahrscheinlich bedeutsamste Aufgabe besteht in der Vorhersagbarkeit der Aufheizung und des brandbedingten Versagens von sicherheitstechnisch relevanten Einrichtungen, wie Kabeln.

Die Modellierung von Entzündung, Pyrolyse und Flammenausbreitung bedarf ebenfalls noch einer erheblichen Weiterentwicklung.

Hier kann eine Verwendung empirischer Messdaten kurzfristig eine praktikable Lösung darstellen. Weitere Themen der Brandsimulation, die noch weiterer Forschung und Entwicklung bedürfen, sind natürliche Strömungen durch horizontale Öffnungen (z. B. im Deckenbereich) sowie insbesondere bei den Zonenmodellen die Vorhersage des Rußaufkommens, der Strahlung sowie der Rauchgasströmungen zwischen einzelnen Brandräumen über Lüftungsöffnungen und -kanäle.

Während der gesamten ICFMP Benchmark-Aufgaben erwies sich die Definition des Brandherdes als die wohl größte Unsicherheit. Nicht nur die Dimensionen des Feuers und die Pyrolyserate sind schwer zu spezifizieren, auch die physikalischen Prozesse der Verbrennungseffektivität, die Freisetzung, zum einen von Ruß und giftigen Gasen wie zum anderen von radioaktiven Partikeln, stellen eine Herausforderung für die Brandmodellierer dar. Während es in der Theorie möglich ist, diese Phänomene zu modellieren, erfordern sie in der Praxis grundsätzlich eine ingenieurtechnische Einschätzung. Diese Größe bestimmt die konvektive Leistung des Brandes, was wiederum die Rauchtemperatur und Luftzufuhr erheblich beeinflusst. Wie in Benchmark-Aufgabe Nr. 2 gezeigt, ist für die konvektive Leistung ein geeigneter Wert anzunehmen, um in Fällen mit starker Rauchentwicklung eine gute Übereinstimmung von rechnerischer Vorhersage und Messung zu erzielen.

Konzentrationen von Rauch und Verbrennungsprodukten haben in Kombination mit der Gastemperatur einen erheblichen Einfluss auf die Strahlungsintensität, wobei die Erwärmung solcher Zielobjekte von großer Bedeutung ist, die überaus sensitiv auf Erwärmung reagieren. In den verschiedenen Benchmark-Rechnungen wurden in Bezug auf die Eingangsstrahlungsintensität Unterschiede von bis zu zwei Größenordnungen infolge von Änderungen der Gastemperatur beobachtet.

Nach dem erfolgreichen Abschluss der Phase I des ICFMP muss sich die Aufmerksamkeit der Phase II widmen. Die wichtige Rolle des ICFMP als ein unabhängiges und offenes Forum für Ingenieure, Wissenschaftler, Programmentwickler, Behördenvertreter, etc. zur Beschleunigung der Anwendung von Brandsimulationscodes für Kernkraftwerke hat offensichtlich auch weiterhin Bestand.

Andere Aktivitäten konzentrieren sich derzeit auf andere Bereiche, wie beispielsweise die Fortsetzung des amerikanischen Verifikations- und Validierungsprojektes oder das PRISME-Projekt der OECD/NEA, zu dem auch zukünftige Arbeiten des ICFMP beitragen werden. Themen, welche vom ICFMP behandelt werden könnten, beinhalten unter anderem:

- einen praktischen Leitfaden für Nutzer mit Informationen darüber, wie, wo und wann verschiedene Arten von Computermodellen anzuwenden sind und wie wichtige Merkmale von Brandszenarien, wie Wärmeverlust, Ventilation, Rauchausbreitung zwischen verschiedenen Räumen und lokale Auswirkungen, wie das Auftreffen von Flammen, abgebildet werden können,

- die Modellierung des Ansprechens von Detektoren, einschließlich einer Einschätzung vorhandener Detektormodelle und deren möglicher Anwendung in Kernkraftwerken,

- eine Überprüfung bestimmter Programm-Eingabedaten bezogen auf generische Phänomene, wie z. B. Werte für die Strömungskoeffizienten,

- die Modellierung der Verläufe der Wärmefreisetzung bei Bränden auf Kabeltrassen,

- eine Überprüfung der Methoden zur Simulation von Kabeln sowie Empfehlungen für Kriterien in Bezug auf Kabelfunktionsstörungen und

- die Aktualisierung des 'Validation Database Reports', in welchem experimentelle Daten beschrieben werden, die für die Anwendung von Brandmodellen in Kernkraftwerken hilfreich sind.

Table of Contents

1 Introduction

Risk-informed and performance-based approaches to fire regulation in nuclear power plants (NPP) require the use of computer models and analytical methods to predict a wide range of fire conditions. In traditional prescriptive regulations, fire protection system configurations are specified based on engineering judgment derived from operating experience, tests, and codes and standards. In a risk-informed, performance-based regulatory system, computer models and analytical methods are relied on to determine the hazards for which the fire protection systems must be designed to protect against.

The foremost need is to develop and define guidance on the validity and limitations of fire models for specific applications. Simple, usable, and acceptable (to the regulatory authorities) models for specific applications need to be made available.

The strengths and weaknesses of fire models have not been systematically evaluated, and currently there is a lack of technology transfer from the fire modeling research community to model users. The validity, limitations, and conservatism of the current state of the art fire models, including the benefits that can be derived from them, need to be defined. The applications should be related to the design and assessment of fire protection programs.

In October 1999, the U.S. Nuclear Regulatory Commission (NRC) and the Society of Fire Protection Engineers (SFPE) organized a planning meeting with international experts and practitioners of fire models to discuss the evaluation of numerical fire models for nuclear power plant applications /INT 00/. This resulted in the establishment of a so-called International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications (ICFMP).

1.1 General Goals and Objectives

The main objective of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications is to share the knowledge and resources of international experts and practitioners of fire models from various organizations to evaluate the predictive capabilities of state of the art fire models and improve fire models for use in nuclear power plant safety analysis, covering e.g. deterministic fire hazard analysis (FHA) as well as probabilistic fire risk analysis (Fire PSA).

The evaluation is focused toward determining the suitability of the various models for different applications, specifying the appropriate input parameters and assumptions, and describing model limitations and uncertainties.

1.2 Process for Developing Scenarios

The first step in the process of developing scenarios was to establish the reasons fire models are used for nuclear power applications. The problems being addressed were clearly defined prior to developing precise applications, scenarios and experiments. This is an essential and critical step since the requirements of fire models will vary with their application. Fire models that provide conservative bounding results may suffice for comparing fire safety features, and for determining weaknesses in designs; whereas, best estimate models may be required to support safety decisions that are based on the contribution of fire risk to total risk from all other threats to plant safety. Once the applications were established, fire scenarios and experiments were then developed for those applications. A review of previous work on the issue being investigated was conducted as part of the evaluation.

The second step was to determine how current fire models can be used to support specific applications and safety decisions. This assessment highlighted a number of technical issues that needed further investigation. Some of these issues involved determining the validity and limitations of the fire models to support decision making drawing from work already done by participants, and also entailing new work.

1.3 Process for Set-up of Benchmark Exercises

The predictions from the various fire models were compared with the experimental data from the Benchmark Exercises (BE) in three ways: blind, semi-blind, and open. Participants were invited to submit calculations for some of the planned experiments to a non-participating third party prior to the conduct of the experiments. These are referred to as 'blind' calculations. For the blind calculations, the modelers predicted the fire development in addition to the environment created by the fire. The non-participating third party reviewer served to certify that the model results were not based on the results of the experiments.

Participants also conducted semi-blind calculations. In semi-blind calculations, modelers were given the experimentally derived fire size in the form of a mass or heat release rate (HRR) curve, but were not provided with any information about the compartment temperature, heat fluxes, or other experimental data.

Finally, participants also submitted open calculations. For the open calculations, the modelers had all experimental data available to compare with their model results. The comparisons between experimental data and all three types of calculations were generally qualitatively evaluated by the modelers who performed the calculations. Summaries of these evaluations are included in the individual Benchmark Reports. These Benchmark Reports did not compare models against other models in a quantitative way.

In this context, it is important to realise that the above definitions of blind, semi-blind and open calculations do not necessarily concur with the definitions used by other bodies and standards, such as ASTM E1355–05a 'Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models' /AST 05/ or ISO/TR 13387-3 'Fire Safety Engineering - Part 3: Assessment and Verification of Mathematical Fire Models' /ISO 99/ providing a formal framework to quantitatively assess the predictive capabilities of fire models, including accuracy, uncertainty, and sensitivity. These standards suggest detailed techniques for quantitative evaluations of fire models, while the evaluations within the ICFMP were performed more qualitatively. The terminology used in the standard guidance documents also differs from the terminology used in this report.

For example, ASTM E1355–05a /AST 05/ defines 'blind calculations' where the model users are provided with only a basic description of the scenario to be modeled. They are then responsible for developing appropriate model inputs, specifiying material properties, defining gemoetry details, etc. as necessary. The user is left to make more judgements than for the blind calculations conducted in the ICFMP. ASTM E1355–05a /AST 05/ goes on to descibe 'specified calculations' where the model user is given a complete description of the model inputs, geometry, etc., in a manner more akin to the blind calculations conducted in the ICFMP. 'Open calculations' are defined in much the same way as for the ICFMP.

Such differences in definitions should be kept in mind when comparing the conclusions drawn in the ICFMP Benchmark Exercises with those from other activities such as the U.S. NRC Verification and Validation work /NRC 07/.

2 Overview on Benchmark Exercises No. 1 to 5

A series of five Benchmark Exercises was conducted, which have been used for evaluating and validating current fire models from around the world. As part of this project, participants have compared predictions from a range of numerical fire models against experimental measurements taken during the Benchmark experiments.

2.1 Benchmark Exercise No. 1

2.1.1 Specific Objectives

The objective of Benchmark Exercise No. 1 was to evaluate the capability of various fire models of different types to analyze cable tray fires of redundant safety systems in nuclear power plants. The exercise consisted of several hypothetical scenarios with enough fire-related phenomena to allow evaluation of the physics in the fire models. The goal of the exercise was to assure that each model had the appropriate input parameters, physical assumptions, and output quantities to embark on the validation exercises to come. The exercise was conducted from 2000 to 2002.

The objective of the exercise was not to compare the capabilities and strengths of specific models, address issues specific to a model, nor to recommend specific models over others.

The models evaluated in this exercise are listed in Tab. 2-1 below.

Tab. 2-1 Models applied in Benchmark Exercise No. 1

Model Type	Code	Code Version	Modeler (Institution)	Part I	Part II
Zone	CFAST	3.1.6	S. Miles (BRE)	bc, 1 – 5	bc, 1 - 13
		4.0.1	J. Will (iBMB)	bc, 1 – 3	bc, 1 - 13
		3.1.6	M. Dey (NRC/NIST)	bc, 1 – 5	bc, sc
	FLAMME_S	2.2	E. Bouton, B. Tourniaire (IPSN; now IRSN)	bc, 1 – 5	bc, 1 - 13
	MAGIC	3.4.1	D. Joyeux, O. Lecoq-Jammes (CTICM)	bc, 1 – 5	bc, 1 - 13
		3.4.7	B. Gautier, H. Ernandorena, M. Kaercher (EdF)	bc, 1 – 5	bc, 1 - 13
Lumped Parameter	COCOSYS	1.2	W. Klein-Heßling (GRS)	bc, 1 - 5	bc, 1, 2, 5, 10 - 13
CFD	CFX	4.3	M. Heitsch (GRS)	bc, 1, 5	bc, 6, 10
	FDS	2.0	M. Dey (NRC/NIST)	bc, 4, 5	bc, sc
	JASMINE	3.1	S. Miles (BRE)	bc, 1, 4	1, 2, 9 - 13

2.1.2 Problem Specification

Three zone models, three computational fluid dynamics (CFD) codes, and one lumped parameter model were used by, in total, eight institutions. A representative emergency switchgear room for a pressurized water reactor (PWR) was selected for the Benchmark Exercise No. 1 (BE 1, see Fig. 2-1). The exercise simulated a basic scenario defined in sufficient detail to allow the evaluation of the physics modeled in the fire computer codes.

There were two parts to the exercise. The objective of Part I was to determine the maximum horizontal distance between a specified transient (trash bag) fire and a cable tray that would result in the ignition of the cable tray.

Part II examined whether a target cable tray would be damaged by a fire in another cable tray stack separated by a given horizontal distance. The effects of a fire door position (open and closed) and of the mechanical ventilation system were examined in both parts of the Benchmark Exercise.

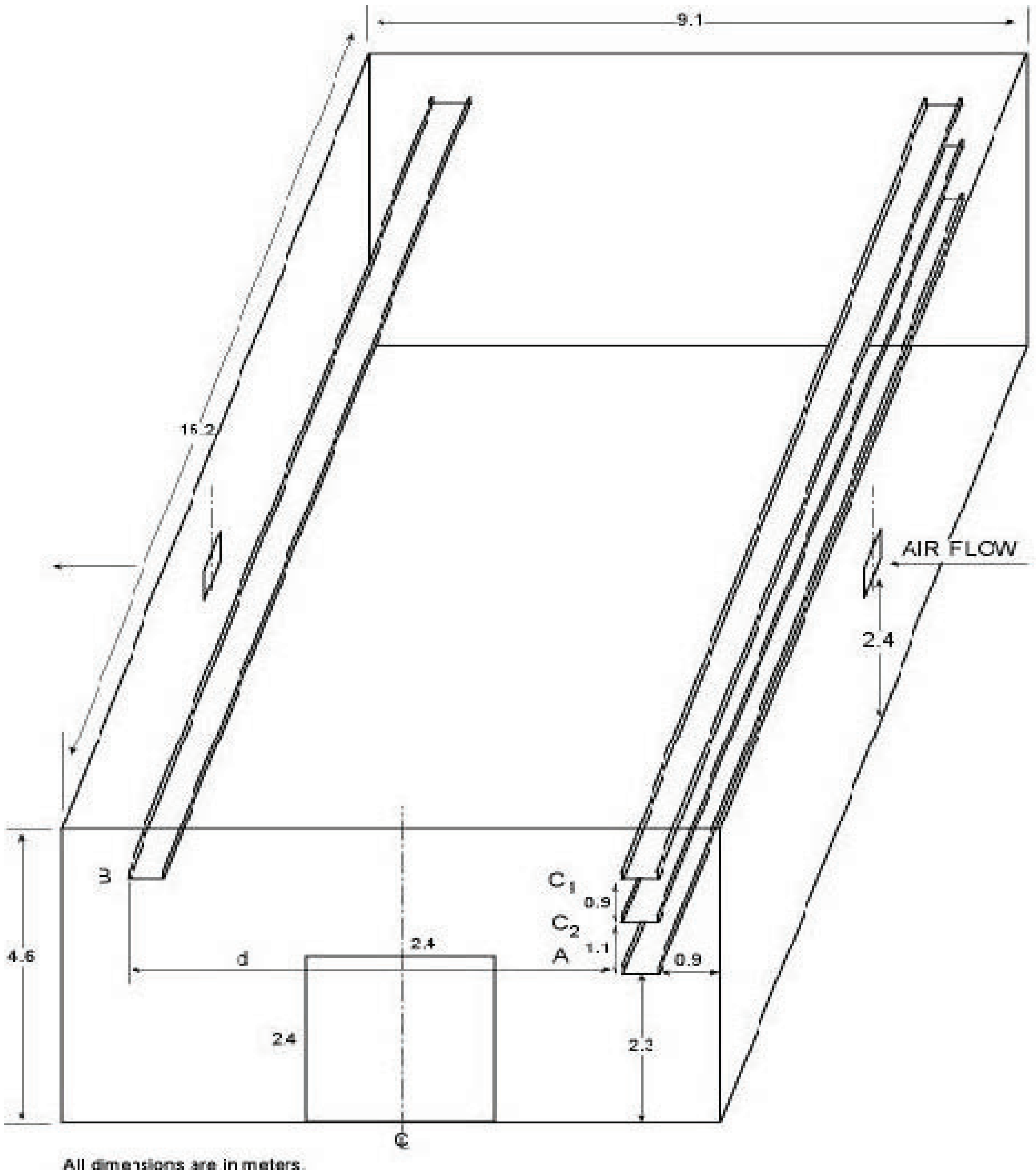


Fig. 2-1 Benchmark Exercise No. 1 configuration

2.1.3 Results

The specific results were published in /DEY 02/. For Part I, none of the analyses conducted did predict the ignition of the target cable (specified at 370 °C) by the postulated trash bag fire for varying ventilation conditions in the room. The predicted temperature rise for all the cases in Part I was similar (see Fig. 2-2). Given the dimensions of the room and the heat release rate of the trash bag, the maximum surface temperature of the target outside the fire plume region for all the cases analyzed was less than 80 °C (see Fig. 2-3). This temperature is much less than that which was specified for target damage. The target cable in this exercise could only have ignited had it been located within the plume region of the fire.

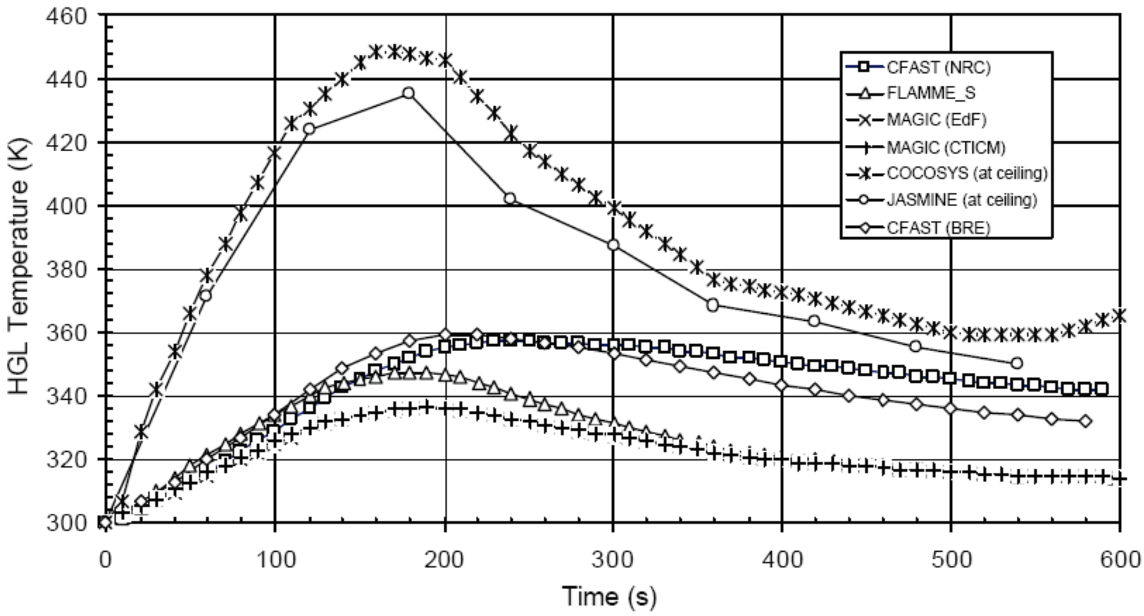


Fig. 2-2 Hot gas layer temperature calculated for Benchmark Exercise No. 1, Part I, Base Case

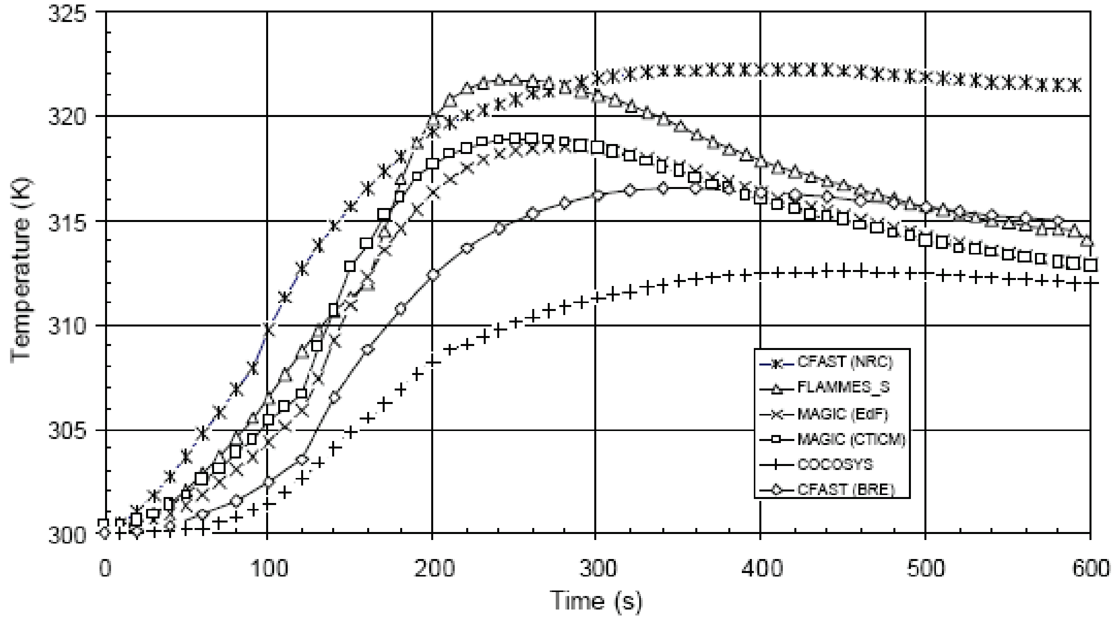


Fig. 2-3 Target surface temperature calculated for Benchmark Exercise No. 1, Part I, Base Case

The predicted maximum temperatures of the target cable, using a lower oxygen limit (LOL) of 12 %, were below 130 °C for all the cases analyzed in Part II (see Fig. 2-4 and Fig. 2-5). The cable tray fire was weakened after about 10 minutes by the depletion of oxygen near the cable tray. Given the elevation of the fire source and the predicted extinction of the fire, cable damage was judged unlikely for the scenarios examined.

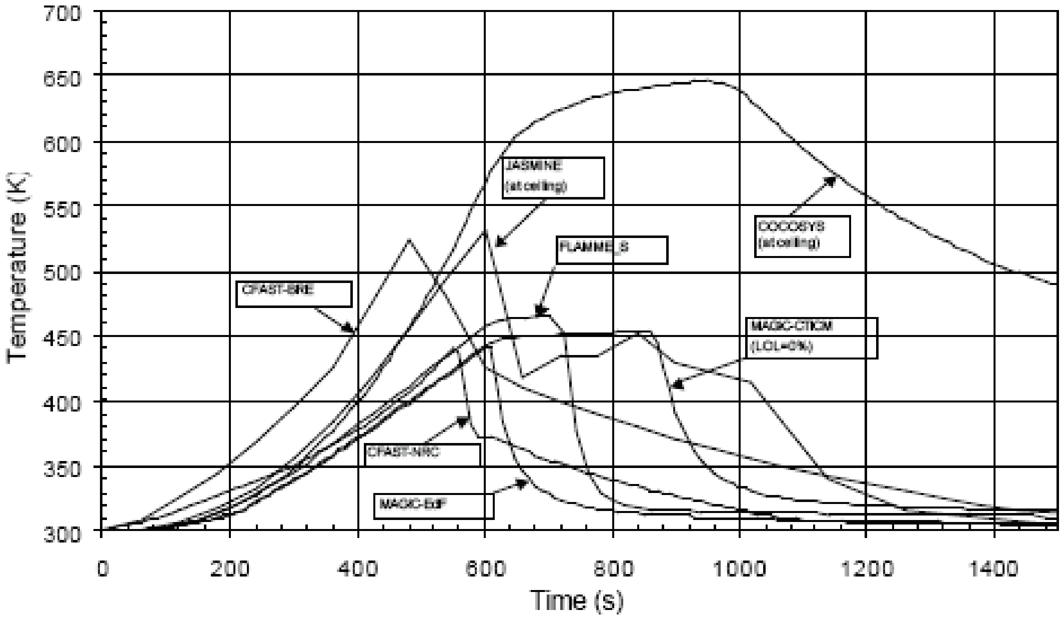


Fig. 2-4 Hot gas layer temperature calculated for Benchmark Exercise No. 1, Part II, Base Case

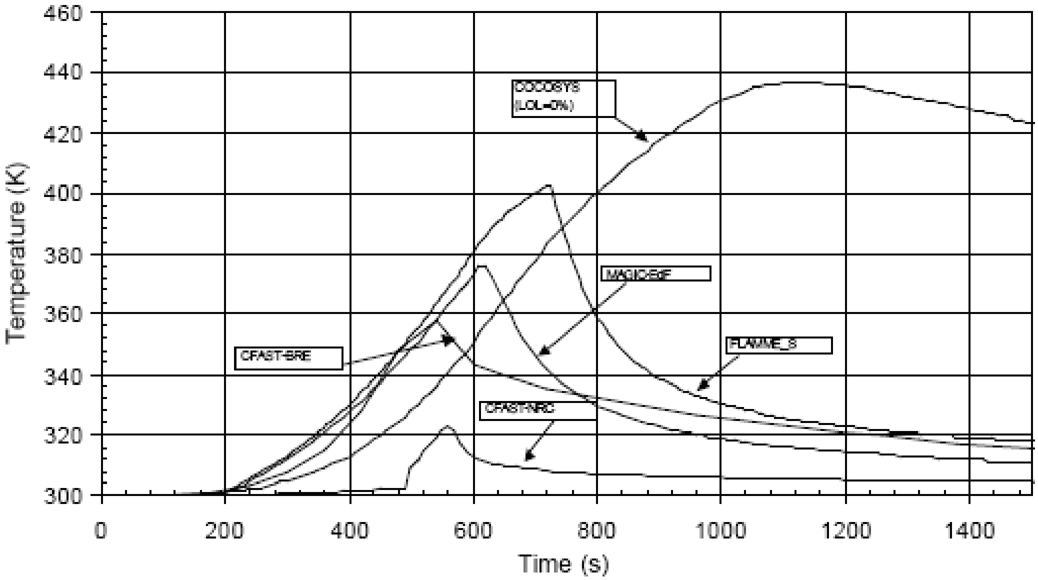


Fig. 2-5 Target surface temperature calculated for Benchmark Exercise No. 1, Part II, Base Case

2.1.4 Discussion

The participants in ICFMP Benchmark Exercise No. 1 cited three issues as most important for this type of fire scenario:

(1) Specification of the fire source,

(2) Modeling of the target and

(3) Value for the lower oxygen limit (LOL).

The overall uncertainty in the parameters associated with these sub-models is often referred to as ‘user effects’. Characterizing the relative magnitude of the errors associated with ’user effects’ has been a large part of the ICFMP Benchmark Exercises.

There were no experiments performed as part of Benchmark Exercise No. 1, thus it is not considered a *validation* exercise. Exercising the models to check that expected trends are captured is part of the *verification* process. Verification is essentially a check that the mathematical model has been properly implemented. It does not necessarily indicate that the mathematical model is appropriate for the given fire scenario.

The results of the verification analyses indicated that the trends predicted by the models were reasonable for the specified scenarios. The conservation equations for mass and energy qualitatively predicted the hot gas layer (HGL) development and temperatures in the compartment. The fire models were shown to balance mass and energy, in particular the concentration of oxygen and the net heat loss from the compartment. Mass flows that resulted from the pressurization of the compartment, or natural and mechanical ventilation, were captured qualitatively by the zone, CFD, and lumped-parameter models. Convective and radiative heat fluxes to the boundaries and target were accounted for in the models but utilized different approaches. Most participants identified the thermal response of the cables as an area that could use improvement.

The analyses of the scenarios also demonstrated the complexity in modeling an elevated fire source which can be affected by a limited oxygen environment. The extinction sub-models are approximations of the complex combustion processes within a limited oxygen environment.

The assumption for the LOL affects the predicted peak target temperature. Conservative assumptions are often made due to the uncertainty in the extinction models.

The inclusion of emission/absorption due to soot, water vapor, and carbon dioxide may play a significant role both in the radiation heat transfer to the target cable and also in the general thermodynamics inside the compartment. The latter will influence heat loss to the compartment boundaries and the mass flow rates through the opening(s). Radiation from the flaming region will be important in determining damage to cables close to the fire source.

Consideration of appropriate input parameters and assumptions, and the interpretation of the results to evaluate the adequacy of the physical sub-models established useful technical information regarding the capabilities and limitations of the fire models.

Detailed results of ICFMP Benchmark Exercise No. 1 can be found in /DEY 02/.

2.1.5 Conclusions

The participants of Benchmark Exercise No. 1 concluded that current zone models, CFD codes, and lumped parameter fire models addressed most of the physical phenomena of interest in the scenarios analyzed. The results indicated that the trends predicted by the sub-models were reasonable for the intended use of the models. The participants recommended further validation, in particular for target response, larger compartments (like the turbine building) with large pool fires, multi-compartment geometries with horizontal and vertical vent connections, and control room configurations.

2.2 Benchmark Exercise No. 2

2.2.1 Specific Objectives

Benchmark Exercise No. 2 was designed to challenge fire models in respect to their application to large enclosures and large fires, and to address complexities introduced by features such as flow of smoke and air between compartments via horizontal openings. As far as possible the intention was to compare model predictions against experimental measurements.

Although most input parameters were defined in the problem specification, the Benchmark did involve a greater degree of user judgment compared to Benchmark Exercise No. 1, e.g. selection of sub-model parameters and how to the treat a sloping roof (with zone models).

2.2.2 Problem Specification

The exercise was divided into two stages, *Part I* and *Part II*, each consisting of three scenario cases. A summary of the main aspects of the exercise is given below. A full specification is presented in the Panel Report for the ICFMP Benchmark Exercise No. 2 (BE 2) /MIL 04/.

Part I

Part I was based on a series of full scale experiments performed inside the VTT (Valtion Teknillinen Tutkimuskeskus) test hall in Finland in the late 1990 s /HOS 01/. The building has dimensions 19 m high by 27 m long by 14 m wide and an apex roof, as shown in Fig. 2-6. The locations of the ceiling exhaust duct used in one of the scenarios, and of two large obstructions, are shown also. Although the height of the test hall is akin to that of a turbine hall, the floor area is significantly less. However, the test hall was one of the largest enclosures for which experimental fire data was available.

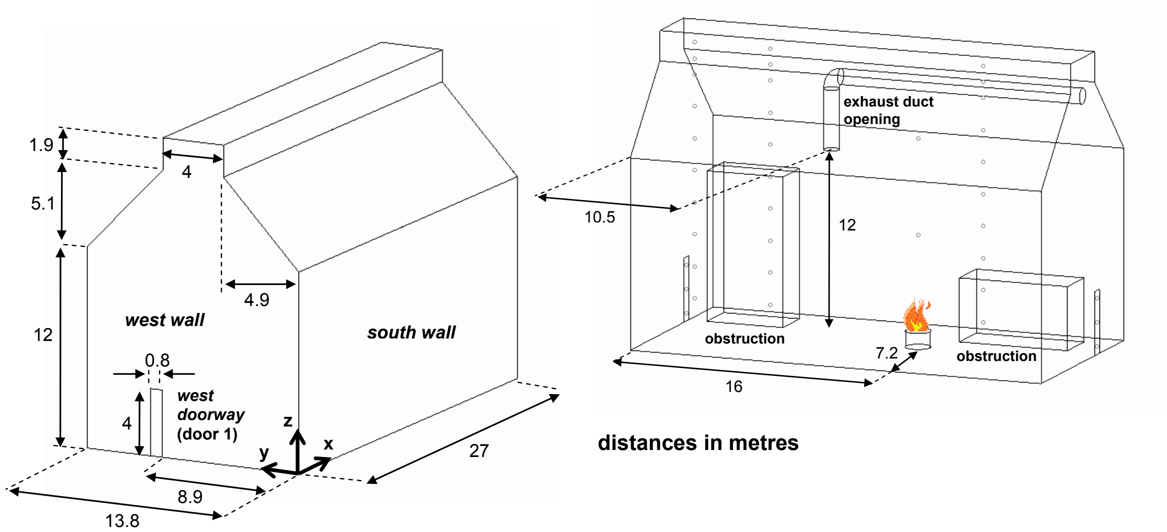


Fig. 2-6 Main geometry for Benchmark Exercise No. 2, Part I

Participants were left to decide for themselves how to incorporate the roof geometry (potentially a challenge for zone models in particular), and were encouraged to undertake a series of simulations using alternate strategies, and to comment on the findings. The walls and ceiling comprised 1 mm sheet metal on top of 50 mm of mineral wool, and the floor was constructed from concrete.

Each scenario involved a single heptane pool fire burning on top of water in a circular, steel tray, located 1 m above the floor and lasting for approximately five minutes. The trays were placed on load cells, and the mass release rate [dm_f/dt] shown in **Tab. 2-2** was calculated from the time derivative of the readings. The values quoted are the average from the repeated (two or three) tests for each scenario. While the choice of combustion mechanism was left to each participant, it was suggested in the Benchmark specification that the heat release rate [dQ_f/dt] be modeled as,

$$\frac{dQ_f}{dt} = \chi_{eff} \frac{dm_f}{dt} \Delta H_c$$

Here the heat of combustion (ΔH_c) was defined as 44.6 x 10^6 J kg^{-1}. While the Benchmark specification suggested the combustion efficiency (χ_{eff}) take a value 0.8, the final choice of value was left to participants. Values for χ_{eff} reported in the literature vary from as low as 0.7 to close to unity, reflecting the fact that combustion efficiency is a complicated function of fire size, compartment geometry and other effects.

Radiative fraction (χ_{rad}) is another uncertainty directly related to the fire source. As for combustion efficiency, the value of χ_{rad} depends on fire size, and will be influenced by the surrounding enclosure. While in principle it can be calculated, it is often an input parameter. Here the choice of χ_{rad} was left to the participants. Together, combustion efficiency and radiative fraction arguably account for the biggest uncertainty in fire modeling, and user judgment can have a significant influence on the gas temperatures and other calculated quantities.

Tab. 2-2 Specified fuel release rates for Benchmark Exercise No. 2, Part I

Scenario 1 (1.17 m *Φ* pan)		***Scenario 2*** (1.6 m *Φ* pan)		***Scenario 3*** (1.6 m *Φ* pan)	
t [min]	dm_f/dt [kg s^{-1}]	t [min]	dm_f/dt [kg s^{-1}]	t [min]	dm_f/dt [kg s^{-1}]
0	0	0	0	0	0
0.22	0.033	0.23	0.057	0.22	0.064
1.5	0.045	0.5	0.067	1.05	0.084
4.8	0.049	1.52	0.081	2.77	0.095
5.45	0.047	3.22	0.086	4.27	0.096
6.82	0.036	4.7	0.083	4.87	0.091
7.3	0	5.67	0.072	5.5	0.07
		6.2		5.75	0.06
		6.58			0

The three scenarios were characterized by the combination of fire size and ventilation conditions, the latter summarized in Table 2-3.

For *Scenarios 1* and *2* the hall was nominally sealed, with the presence only of 'infiltration ventilation'. Exact information on air infiltration during these tests was not available. However, following discussions with the experimentalists involved, it was recommended that it be modeled by including four small openings, each having an area 0.5 m^2. For the Benchmark it was suggested that two openings be located in the east wall, one at floor level and one 12 m above the floor, and two in the opposite west wall.

For *Scenario 3*, there was mechanical exhaust ventilation at a constant volume flow rate of 11 m^3s^{-1}, with replacement air provided by two 'doorway' openings, each with dimensions 0.8 m by 4 m and located in the east and west walls. Note that air infiltration was ignored in *Scenario 3*.

Tab. 2-3 Ventilation conditions for Benchmark Exercise No. 2, Part I

Scenario 1	Scenario 2	Scenario 3
doors closed	Doors closed	2 doors open (each 0.8 m x 4 m)
no mechanical exhaust	no mechanical exhaust	mechanical exhaust ($11\ m^3s^{-1}$)
natural infiltration	Natural infiltration	natural infiltration ignored

Experimental measurements for gas temperatures at three thermocouple columns (trees) and above the fire source were available as shown in Fig. 2-7. While there were data for the air velocity at the doorway openings, comparison against predictions was not formally conducted due to uncertainly in the data.

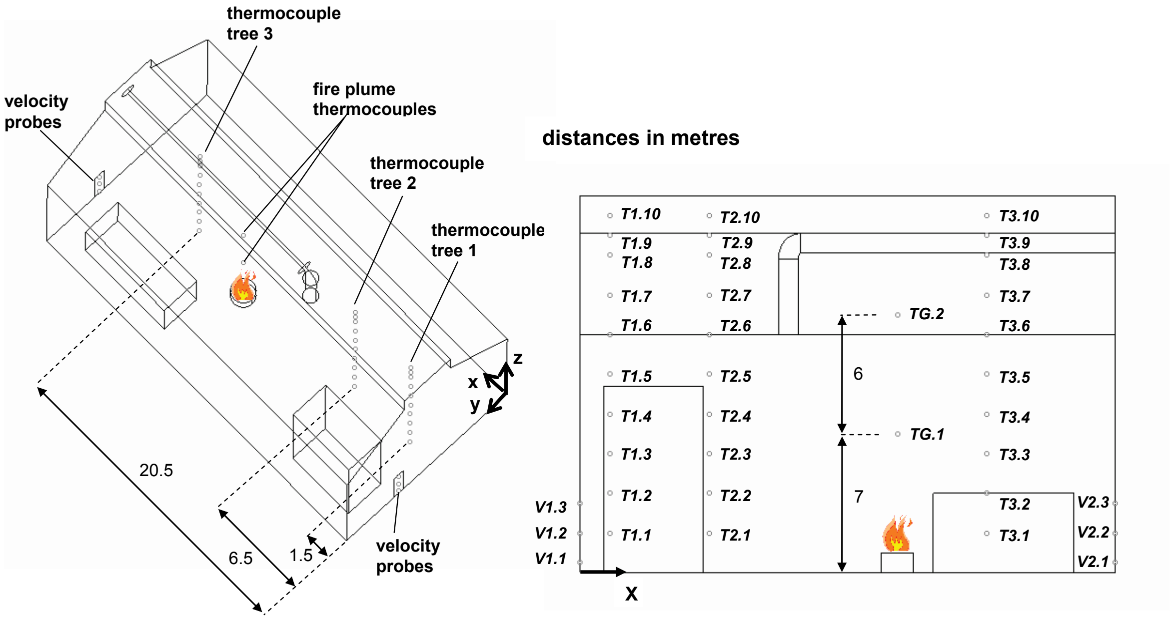
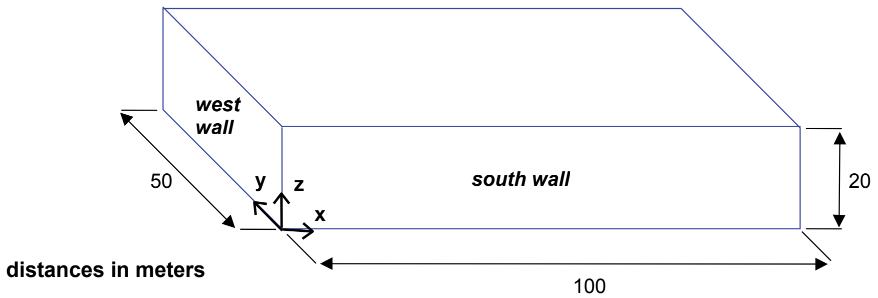


Fig. 2-7 Location of thermocouples and velocity probes for Benchmark Exercise No. 2, Part I

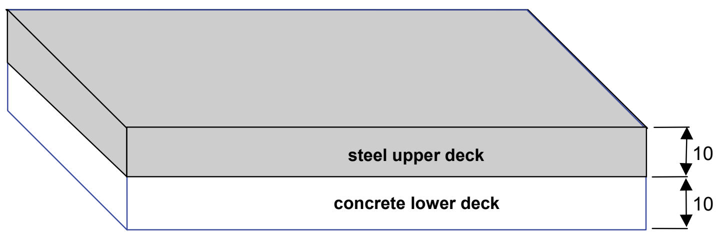
While lumped parameter and CFD models could provide predictions for gas temperature at each thermocouple location, for zone models another approach was required. Assuming a two-layer description as valid for the three scenarios, zone model predictions for upper layer gas temperature and layer height were compared against the measured data. This required the measured data to be numerically processed to yield estimates for these two parameters. For the Benchmark, comparisons were made against upper layer temperatures and interface heights generated by a data reduction method proposed by the experimentalists.

Part II

Although for Part II there were no experimental measurements, it extended the scope of the Benchmark to examine the effect of a bigger fire, growing to approximately 70 MW. As shown in Fig. 2-8 (i), the building had dimensions representative of a turbine hall, and furthermore was separated into a lower and an upper deck. The two decks shown in Fig. 2-8 (ii) were connected by two permanent openings (hatches), each with dimensions 10 m by 5 m, as shown in Fig. 2-9. Although turbine halls may indeed be larger than this, it was decided for the purpose of this Benchmark Exercise it was sufficient without being overly demanding for numerical modeling.



(i) External dimensions



(ii) Separation into two decks

Fig. 2-8 Building geometry for Benchmark Exercise No. 2, Part II

The lower deck and the internal ceiling (separating the two decks) were constructed from concrete with a thickness of 0.15 m, and the upper deck from steel with a thickness of 0.002 m. An emissivity of 0.95 and a convective heat transfer coefficient of 10 W m^{-2} K^{-1} were assumed throughout.

The fire size was chosen to produce temperatures potentially capable of damaging equipment or cables. For all three scenarios, the fire source was a pool of lube oil burning in a tray with dimensions 7 m by 7 m, located at the centre of the lower deck and 1 m above the floor. The mass release rate [dm_f/dt] grew from zero to a steady value 1.66 kg s^{-1} at ten minutes as follows,

$$\frac{dm_f}{dt} = \alpha t^2$$

Here α is a constant with a value 4.611 x 10^{-6} kg s^{-3}, equivalent to a growth rate similar to an NFPA (National Fire Protection Association) ultra-fast t-squared fire. The period of steady fuel release lasted for a further ten minutes in each scenario. The heat of combustion for lube oil was specified as 4.235 x 10^7 J kg^{-1} and the suggested value for the radiative fraction of heat generated in the fire plume was 0.51. Furthermore, while it was proposed that the lower oxygen limit takes a value of 12 % both this and the radiative fraction were parameters that individual participants were free to specify themselves.

Scenarios 1, *2*, and *3* were characterized by different ventilation conditions, involving 'near-sealed' conditions, natural ventilation conditions and a combination of natural and mechanical ventilation as summarized in Tab. 2-4.

Tab. 2-4 Ventilation conditions for Benchmark Exercise No. 2, Part II

Senario 1	Scenario 2	Scenario 3
nearly-sealed	natural ventilation	mechanical (extract) and natural ventilation
two infiltration openings	36 roof vents	194.4 m^3 s^{-1} mechanical exhaust ventilation (divided evenly between 36 roof vents)
	24 replacement air wall vents	24 replacement air wall vents

For *Scenario 1* the two 'infiltration' openings were located at floor level on the lower deck, one was in the west wall and the other was in the opposite east wall.

For *Scenario 2*, each of the 36 (smoke exhaust) roof vents had an area 4.5 m^2, and each of the 24 replacement air wall vents an area 4 m^2 (12 at floor level on the lower deck and 12 at floor level on the upper deck). For *Scenario 3* the roof vents were replaced by mechanical exhaust vents, which in total provided (corresponding to 7 air changes per hour) a fixed exhaust capacity of 194.4 $m^3 s^{-1}$.

Targets were added to Part II to allow the onset of such damage to be studied. These included three power cable targets (50 mm diameter PVC (Polyvinylcloride)) and two simplified steel beam targets (150 mm by 6 mm in cross section), located as shown in Fig. **2-9**. Tab. 2-5 presents the thermal properties for the two types of target.

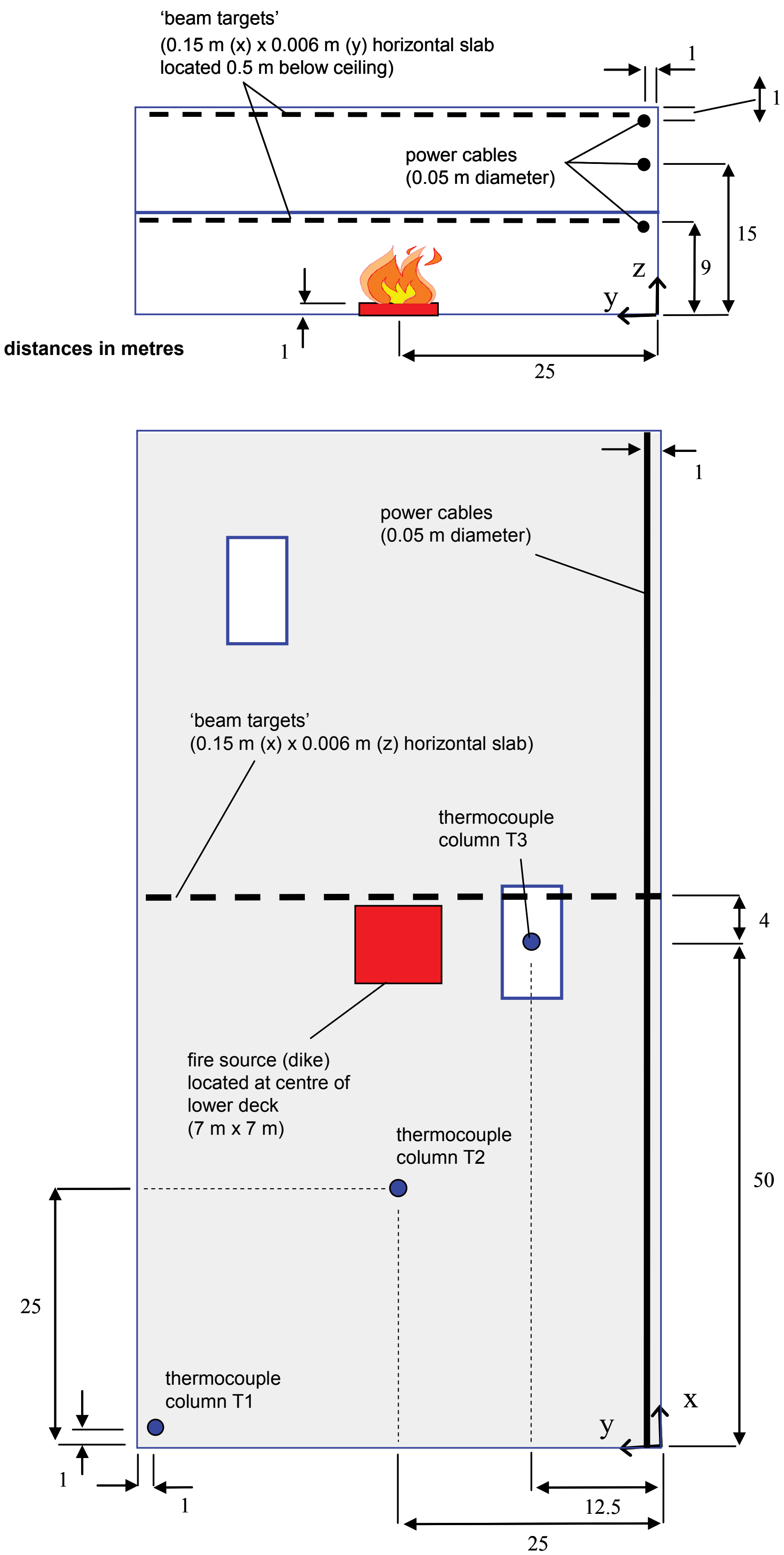


Fig. 2-9 Location of fire source, hatches and targets for Benchmark Exercise No. 2, Part II

Tab. 2-5 Thermal properties of targets for Benchmark Exercise No. 2, Part II

Target material	Conductivity [$Wm^{-2}K^{-1}$]	Density [$kg\ m^{-3}$]	Specific heat [$J\ kg^{-1}K^{-1}$]
PVC (power cable)	0.092	1710	1040
Steel (beam)	54	7833	465

The surface emissivity was 0.8 for both materials, and a fixed convective heat transfer coefficient of 10 $W^1m^{-2}K^{-1}$ was also specified.

Onset of cable damage was defined as when the center-line temperature reached 200 ºC, and for the steel beams a surface temperature of 538 ºC was the damage criterion. Additionally, there was a 'human target', located 1.5 m above floor level (the internal ceiling) at the centre of the upper deck.

While the Benchmark specification included an extensive list of variables to be calculated, as a core requirement participants were asked to report gas layer temperatures for zone models and discrete location gas temperatures for CFD and lumped-parameter models. Where zone models treated the hall as two compartments, participants were to report layer temperatures, heights etc. individually for each deck.

CFD models were to report gas temperatures and oxygen concentrations at 1 m intervals at three 'virtual thermocouple' columns, shown in Fig. **2-9** as T1, T2 and T3. For the cable and beam targets the maximum temperature at the center-line or surface respectively was requested.

2.2.3 Results

Part I

Part I was conducted as an open exercise with the measured temperature data available to participants prior to the simulations. Ten organizations participated in *Part I*, collectively making calculations with three zone models, two lumped parameter models and four CFD models as summarized in Tab. **2-6**.

Tab. 2-6 Participation for Benchmark Exercise No. 2, Part I

Model Type	Code	Code Version	Modeler (Institution)	BE 2, Part I Scenarios investigated
Zone	CFAST	3.1.6	S. Miles (BRE)	1, 2, 3
		3.1.6	A. Martin, A. Coutts (WSMS)	1, 2, 3
		3.1.6	WPI class exercise	1, 2, 3
	FLAMME_S	2.2	D. Robineau (IRSN)	1, 2, 3
	MAGIC	3.4.1	D. Joyeux, O. Lecoq-Jammes (CTICM)	1, 2, 3
		3.4.7	L. Gay, B. Gautier (EdF)	1, 2, 3
Lumped Parameter	COCOSYS	2.0	W. Klein-Heßling (GRS)	1, 2, 3
	HADCRT	1.4	B. Malinovic, M. Plys (Fauske)	1, 2, 3
CFD	CFX	4.4	M. Heitsch (GRS)	1, 2, 3
	FDS	2.0	K. McGrattan (NIST)	1, 2, 3
		2.0	WPI class exercise	1
	JASMINE	3.2.1	S. Miles (BRE)	1, 2, 3
		3.1	WPI class exercise	1
	KOBRA-3D	4.7.1	J. Will (HHP)	1, 2, 3

Generally, participants were able to reproduce the upper layer temperatures measured in the tests once the radiative fraction and boundary heat losses had been treated appropriately. Fig. 2-10 illustrates the CFD (FDS) predictions for *Scenario 2* at the T2 thermocouple locations, showing good agreement in the upper region and reasonable agreement nearer the floor.

Fig**. 2-11** illustrates the influence of the choice of radiative fraction on the predicted upper layer temperature (DT) with CFAST for *Scenario 2*. Also illustrated in Fig. **2-11** is that the predictions were not sensitive to the details of how the infiltration area was specified (for *Scenarios 1* and *2*).

Further discussion of the calculations is given in the next section. Full results and more detailed analysis are presented in the panel report /MIL 04/, as well as technical descriptions of the codes themselves.

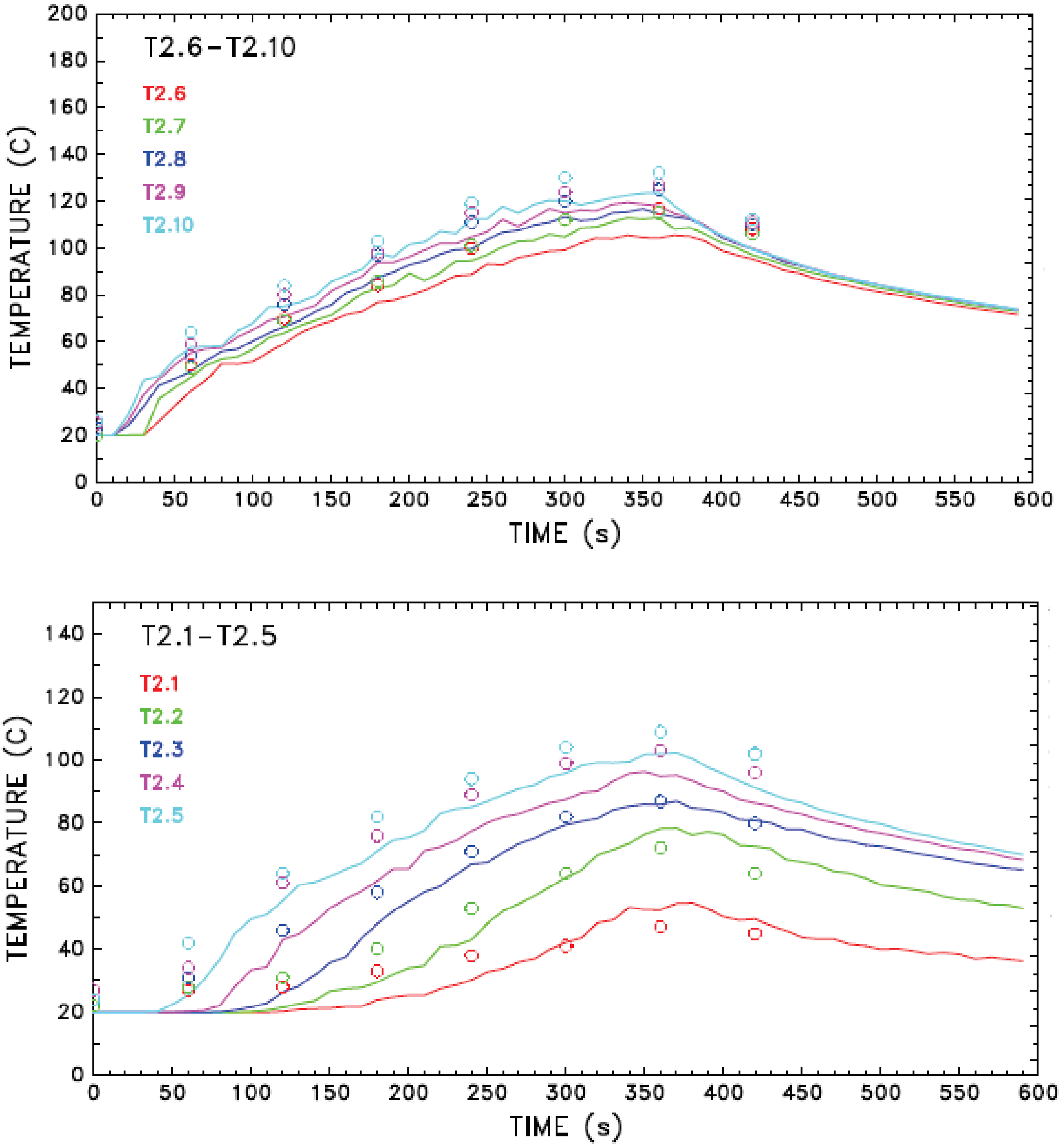
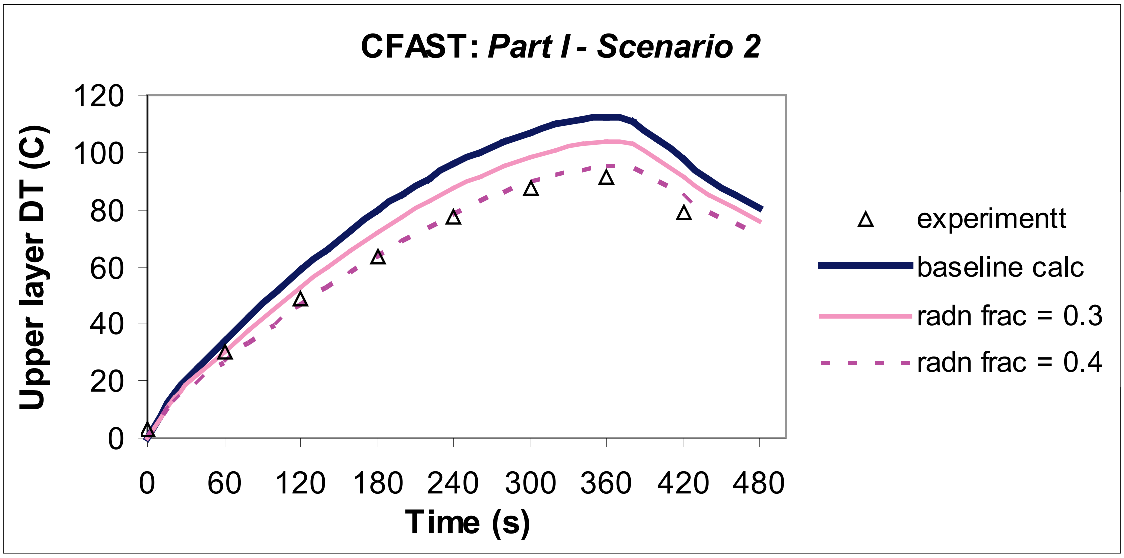


Fig. 2-10 FDS (solid lines) calculated and measured temperatures for Benchmark Exercise No. 2, Part I, Scenario 2 (NIST)



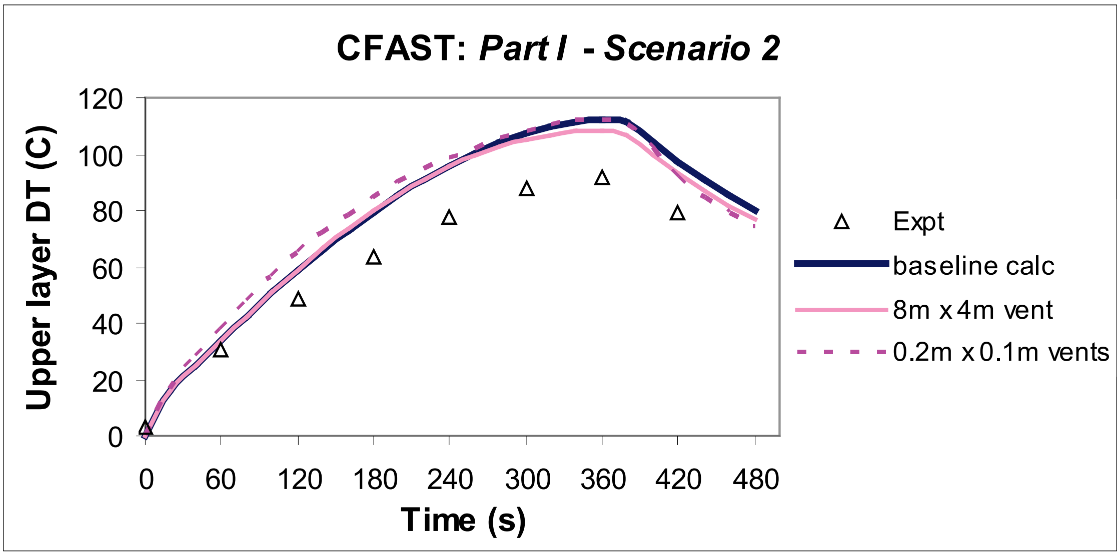


Fig. 2-11 CFAST (solid line) calculated and measured temperatures for Benchmark Exercise No. 2, Part I, Scenario 2 (BRE)

Part II

For *Part II*, there were nine participating organizations, making simulations with three zone, one lumped parameter and four CFD models as summarized in Table 2-7. Independent simulations were undertaken by eight organizations prior to the 6th meeting of the international collaborative project in October 2002, without knowledge of the predictions being made by fellow participants, and referred to here as 'blind' calculations.

This was followed by further optional open simulations, conducted with knowledge of other participants´ predictions.

In contrary to *Part I*, the predictions from different numerical models varied to a greater extent. While the size of the building was a challenge to CFD models, it was the fluid dynamics associated with two vertical compartments connected by two hatches that provided the greatest test to all models. This was true, in particular, with *Scenario 1* where the upper deck was completely sealed.

Tab. 2-7 Participation for Benchmark Exercise No. 2, Part II

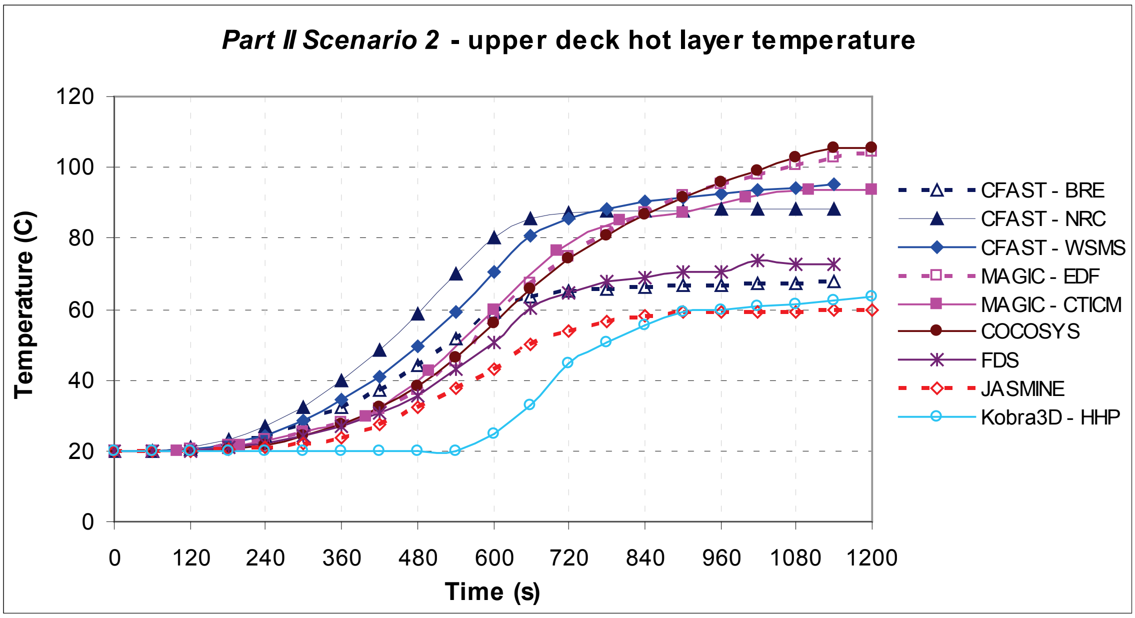
Model Type	Code	Code Version	Modeler (Institution)	BE 2, Part II Scenarios investigated
Zone	CFAST	3.1.6	S. Miles (BRE)	1, 2, 3
		3.1.6	A. Martin, A. Coutts (WSMS)	2, 3
		3.1.6	M. Dey (NRC)	1, 2, 3
	FLAMME_S	2.2	D. Robineau (IRSN)	1, 2 *
	MAGIC	3.4.8	D. Joyeux, O. Lecoq-Jammes (CTICM)	1, 2, 3
		3.4.8	L. Gay, B. Gautier (EdF)	1, 2, 3
Lumped Parameter	COCOSYS	2.0	W. Klein-Heßling (GRS)	1, 2, 3
CFD	CFX	4.4	M. Heitsch (GRS)	1
	FDS	2.0	M. Dey (NRC)	1, 2, 3
	JASMINE	3.2.2	S. Miles (BRE)	1, 2, 3
	KOBRA-3D	4.7.1	J. Will (HHP)	1, 2, 3

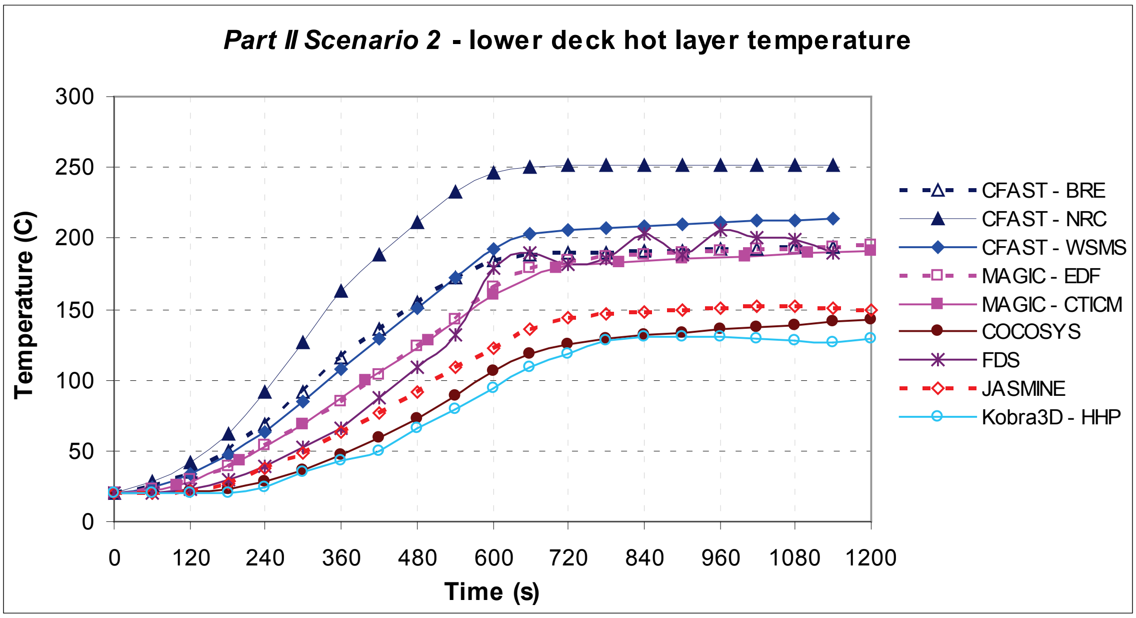
* A simplified form of the geometry was investigated, approximating the turbine hall by just the lower deck (*Scenario 1*) and a single compartment with no internal partition (*Scenario 2*).

While all models indicated that damage to the cable and beam targets was unlikely, there were still notable variations in the predicted local gas and target temperatures, as well as the incident thermal fluxes.

Fig. 2-12 illustrates inter-code predictions for upper and lower deck temperature conditions for *Scenario 2* (natural ventilation). Here, for the zone models the upper gas layer temperature is plotted, and for the CFD and lumped parameter models the average gas temperatures 1 m below the ceiling at thermocouple tree locations T1 and T2 are given. The rationale for selecting these measurement locations is that they are representative of locations where a fire model might be employed to predict the thermal hazard to a target such as a cable, and furthermore provide a 'measure' comparable to the hot gas layer temperature in a zone model. While the results show that the different fire models capture the same qualitative behavior, the 'hot layer temperature rise' [ºC] does vary by up a factor of about two in both decks.

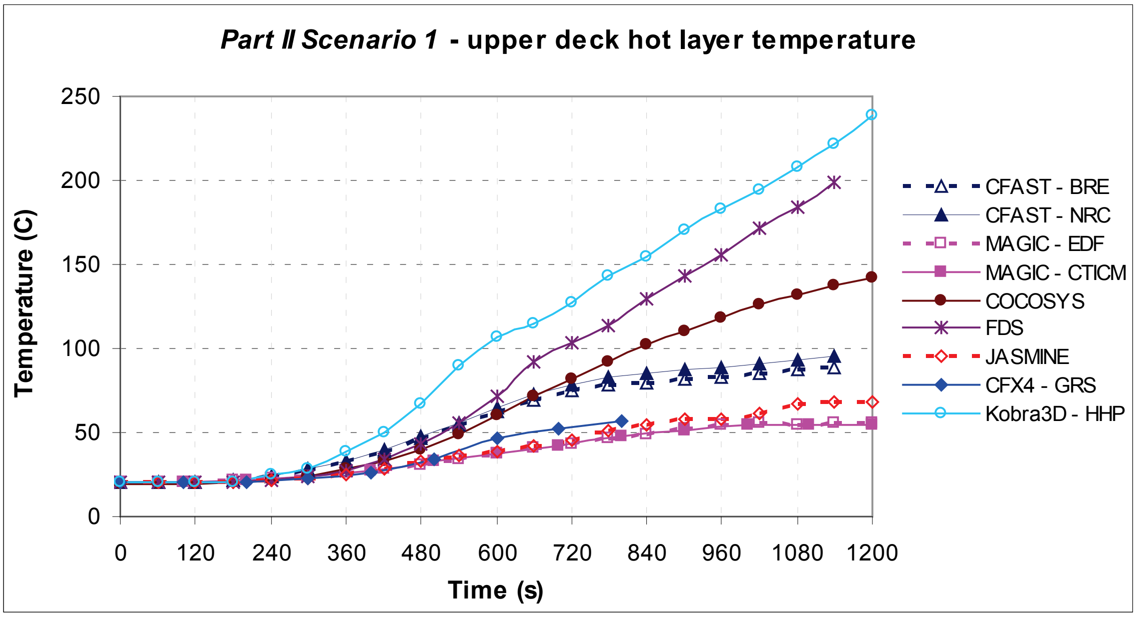
Fig. 2-13, however, illustrates that while there is broad agreement for the 'hot layer temperature rise' in the lower deck for *Scenario 1*, there is a notable spread of values for the upper deck where the predicted gas temperature rise varies by a factor of about 5 for the different fire models.

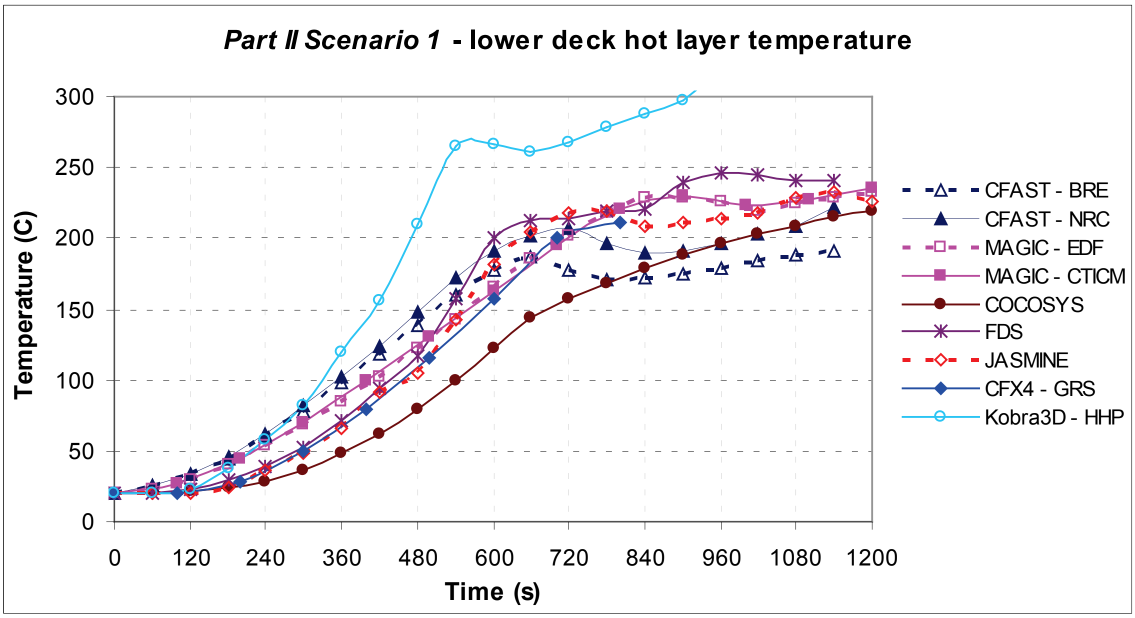




Note: Zone models (CFAST and MAGIC) - upper layer temperature plotted; lumped parameter and CFD models (COCOSYS, FDS, JASMINE and KOBRA-3D) - average of 'ceiling level' thermocouple tree locations at T1 and T2 plotted

Fig. 2-12 Inter-code comparison of 'hot layer' temperatures for Benchmark Exercise No. 2, Part II, Scenario 2





Note: Zone models (CFAST and MAGIC) - upper layer temperature plotted; lumped parameter and CFD models (COCOSYS, FDS, JASMINE and KOBRA-3D) - average of 'ceiling level' thermocouple tree locations at T1 and T2 plotted

Fig. 2-13 Inter-code comparison of 'hot layer' temperatures for Benchmark Exercise No. 2, Part II, Scenario 1

2.2.4 Discussion

Part I

The results for *Part I* were judged encouraging, with the general, qualitative, nature of the experiments being captured in the simulations by zone, lumped parameter and CFD models. Comparison between predictions and measurements was restricted to gas temperatures at three thermocouple trees and two locations directly above the fire source. However, this was sufficient to allow the above issues to be addressed with some degree of confidence.

The main findings are now summarized:

- Despite the 'complexity' of the roof structure the various types of model were able to predict the smoke layer formation process with reasonable reliability. Of particular note here was the ability of zone models to make an assumption of a flat ceiling such that the volume of the hall was conserved.
- Zone models generally predicted lower layer heights than those derived from the experimental measurements using the suggested data reduction formula. This might possibly be attributed to the flat ceiling approximation. An alternative explanation may lie in the data reduction formula, where closer examination of the numerical reduction method suggests that the layer height could be interpreted as being lower than the method suggests, especially later in the fire as illustrated in Fig. 2-14.
- For *Scenario 1* and *2* the precise specification of the 'infiltration' ventilation was not important in respect to the predicted temperatures inside the test hall. This provides some encouragement in modeling such scenarios.
- When using the original Benchmark specification there was, in most cases, a tendency to predict higher smoke layer temperatures than those measured. Two principle mechanisms were identified, to which modifications were possible to reduce the temperature of the smoke layer.

The first of these was the proportion of heat attributed to the convective power of the fire plume, the value being dependent on the choice of heat of combustion, combustion efficiency and radiative fraction. It seems that the choice of 80% for the combined effect of combustion efficiency and radiative fraction was not ideal, resulting in too much heat being convected into the upper layer. This may have contributed to the predicted temperatures being higher than those measured. The second was the boundary heat loss, which was shown to play an important role in a number of studies.

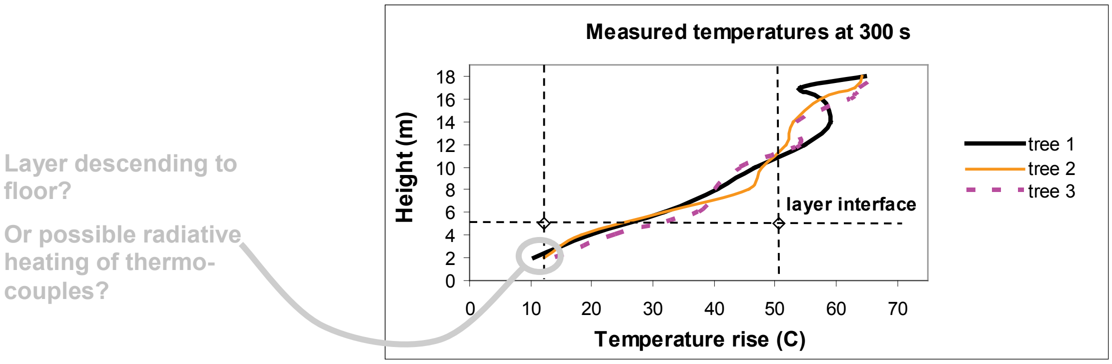


Fig. 2-14 Measured temperature profiles and numerically reduced two-layer interface for Benchmark Exercise No. 2, Part I, Scenario 1

Part II

A detailed, comparative analysis of the range of predicted maximum hazard levels presented inside the two decks, and also to the individual targets, was performed and is presented in the Benchmark Exercise No. 2 Panel Report /MIL 04/. The main aspects of this are reported below.

Tab. **2-8** compares the predicted maximum (and minimum) values of various key variables for the three scenarios with a view to allowing a broad comparison of the general hazard level predicted by the various participants. In particular, maximum lower and upper deck temperature provides a rough estimate of the thermal hazard that ceiling level targets (cables etc.) would be exposed to.

For lumped parameter and CFD models the maximum temperature at each of the three thermocouple trees T1 to T3 is shown, which provides an indication of the lateral distribution of the thermal hazard, not available from a zone model. (Note that the FLAMME_S calculations were performed for an approximate geometry with a view to obtaining bounds for the target temperatures, and are not appropriate for comparing the bulk gas phase parameters reported in Tab. 2-8. Some general findings are:

- For *Scenarios 2* and *3* the maximum lower and upper deck temperatures are, from an 'engineering perspective', broadly similar for the different models. To some extent the differences between the predicted temperatures can be attributed to different assumptions for the convective power of the fire source. For example, the FDS simulations have taken a greater convective power than the JASMINE ones, and the variation in the CFAST predictions seems to be due primarily to this also. It can be seen that the two CFD models, and to a lesser extent the lumped parameter model, have identified three-dimensional effects not within the scope of a zone model. For example, in the upper deck the local heating at T3 due to hatch 1 is clear. And the increased temperature at T2 in the lower deck due to the proximity of the fire plume is quite pronounced.
- For *Scenario 1* the variation between models is more marked, particularly in respect to the upper deck temperature. The main cause of this discrepancy seems to be the treatment of the hatch flows. While it is understood that this is a complex phenomenon for the zone models, there is discrepancy between the CFD models too. In the case of FDS there is upward flow through hatch 1 and downward flow through hatch 2 throughout the simulation, whereas for JASMINE and CFX there is flow reversal.

- There is some discrepancy between models in terms of the relative level of thermal hazard predicted for the different cases. For example, the MAGIC simulations indicate that the smoke layer in *Scenario 2* and *3* is markably hotter compared to *Scenario 1*, whereas for FDS the reverse is true.
- The CFD models have predicted higher maximum plume temperatures than the lumped parameter and zone models. This is most likely a consequence, in part at least, of the fact that the CFD models have resolved the plume structure, and will hence have identified the 'hot region'.
- In terms of the pressure and oxygen consumption predictions, the difference between the results is judged to be not that significant. Here is should be noted that a small variation in 'leakage ventilation' rates can give rise to large differences in compartment pressures, thus the difference between, approximately 500 and 1000 Pa may be not significant.

Tab. 2-8 Comparison of gas phase predictions for Benchmark Exercise No. 2, Part II

Scenario	Property	Zone Models		CFD and Lumped Parameter Models			
1	Maximum gas temperature in lower deck (outside plume) [°C]		T		T1	T2	T3
		CFAST (BRE)	192	JASMINE (BRE)	216	249	217
		CFAST (NRC)	229	FDS (NRC)	230	278	371
		MAGIC (EDF)	233	CFX-4 (GRS) [5]		238	
		MAGIC (CTICM)	233	COCOSYS (GRS)	194	244	234
				KOBRA-3D (HHP)	390	385	354
1	Maximum gas temperature in upper deck [°C]		T		T1	T2	T3
		CFAST (BRE)	90	JASMINE (BRE)	61	77	262
		CFAST (NRC)	98	FDS (NRC)	191	230	346
		MAGIC (EDF)	56	CFX-4 (GRS)		64	134
		MAGIC (CTICM)	56	COCOSYS (GRS)	130	160	177
				Kobra-3D (HHP)	240	243	342
1	Maximum plume temperature [°C][6]		T		T		
		MAGIC (EDF)	461	JASMINE (BRE)	963		
		MAGIC (CTICM)	460	FDS (NRC)	887		
				COCOSYS (GRS)	463		
1	Maximum (net) heat convected through hatches [MW]		T		T		
		MAGIC(EDF)	5	JASMINE (BRE)	9		
				FDS (NRC)	9		
				COCOSYS (GRS)	16		
1	Maximum heat lost to solid boundaries [MW]		T		T		
				JASMINE (BRE)	40		
				COCOSYS (GRS)	37		
1	Maximum relative static pressure [Pa]		T		T		
		CFAST (BRE)	599	JASMINE (BRE)	475		
		CFAST (NRC)	698	FDS (NRC)	1367		
		MAGIC (EDF)	1280	CFX-4 (GRS) [5]	1051		
		MAGIC (CTICM)	1278	COCOSYS (GRS)	1580		
1	Minimum O_2 concentration [%]		T		T		
		CFAST (BRE)	15.9[1]	JASMINE (BRE)	13.6[2]		
		CFAST (NRC)	13.6[1]	FDS (NRC)	11.8[1]		
		MAGIC (EDF)	12.1[1]	CFX-4 (GRS) [5]	15.0[1]		
		MAGIC (CTICM)	12.2[1]	COCOSYS (GRS)	16.2[1]		
2	Maximum gas temperature in lower deck (outside plume) [°C]		T		T1	T2	T3
		CFAST (BRE)	194	JASMINE (BRE)	148	157	104
		CFAST (NRC)	252	FDS (NRC)	191	236	167
		CFAST (WSMS)	215[3]/243[4]	COCOSYS (GRS)	129	157	152
		MAGIC (EDF)	195	Kobra-3D (HHP)	132	130	64
		MAGIC (CTICM)	193				
2	Maximum gas temperature in upper deck [°C]		T		T1	T2	T3
		CFAST (BRE)	68	JASMINE (BRE)	58	61	120
		CFAST (NRC)	88	FDS (NRC)	72	80	163

Scenario	Property	Zone Models		CFD and Lumped Parameter Models			
		CFAST (WSMS) MAGIC (EDF) MAGIC (CTICM)	96[3]/122[4] 105 95	COCOSYS (GRS) Kobra-3D (HHP)	99 65	120 64	128 90
2	Maximum plume temperature [°C][6]		T		T1	T2	T3
		MAGIC (EDF) MAGIC (CTICM)	244 238	JASMINE (BRE) FDS (NRC) COCOSYS (GRS)	947 791 279		
2	Maximum (net) heat convected through hatches [MW]		T		T1	T2	T3
		MAGIC(EDF)	15	JASMINE (BRE) FDS (NRC) COCOSYS (GRS)	37 46 37		
2	Maximum heat lost to solid boundaries [MW]		T		T1	T2	T3
				JASMINE (BRE) COCOSYS (GRS)	18 22		
3	Maximum gas temperature in lower deck (outside plume) [°C]		T		T1	T2	T3
		CFAST (BRE) CFAST (NRC) CFAST (W'SMS) MAGIC (EDF) MAGIC (CTICM)	196 266 216[3]/238[4] 195 195	JASMINE (BRE) FDS (NRC) COCOSYS (GRS) Kobra-3D (HHP)	147 197 128 329	164 241 155 315	113 172 150 219
3	Maximum gas temperature in upper deck [°C]		T		T1	T2	T3
		CFAST (BRE) CFAST (NRC) CFAST (WSMS) MAGIC (EDF) MAGIC (CTICM)	94 139 98[3]/132[4] 100 98	JASMINE (BRE) FDS (NRC) COCOSYS (GRS) Kobra-3D (HHP)	82 105 101	91 120 119	137 175 128
3	Maximum plume tem-perature [°C][6]		T		T1	T2	T3
		MAGIC(EDF) MAGIC(CTICM)	245 248	JASMINE (BRE) FDS (NRC) COCOSYS (GRS)	986 820 277		
3	Maximum heat convected through hatches [MW]		T		T1	T2	T3
		MAGIC(EDF)	14	JASMINE (BRE) FDS (NRC) COCOSYS (GRS	31 44 37		
3	Maximum heat lost to solid boundaries [MW]		T		T1	T2	T3
				JASMINE (BRE) COCOSYS (GRS)	27 22		

[1] volume % [2] mass % [3] rad fraction = 0.51

[4] rad fraction = 0.2 [5] first 864 s [6] 8 m above fire for CFD

The Benchmark Exercise No. 2 Panel Report /MIL 04/ includes detailed comparisons for the peak hazard conditions at the targets. In the case of zone models, the maximum gas temperature at the targets corresponds to the temperature in the layer in which the target is located.

While the general consensus was that cable and beam target damage would not have occurred, the level of thermal hazard posed was quite varied between the different models. This was a consequence of the variation in gas phase conditions, and also the modeling of the incident flux. The flux predictions, in particular, were in some instances quite varied, which will have directly influenced the predicted surface and centre-line target temperatures.

The JASMINE simulations indicated fairly severe conditions for beam 1 due to its proximity to the fire source, with high local gas temperature and incident flux levels, and provided conditions closest to those indicating damage. For the models that provided surface and center-line temperature predictions the agreement was in some instances quite close, and in others more varied. Of particular note was the variation in some of the target temperatures predicted in the two MAGIC contributions. The variation in predicted conditions at the human target was quite significant too. In the case of zone models this can be explained, in part, by whether the human target was located in the upper or lower layer.

Overall, it seems clear that further 'validation' of existing fire models is required for the type of scenario represented by *Part II*. Comparison against measurements would be useful here. Issues identified for further work are included in the Conclusions section below.

2.2.5 Conclusions

Benchmark Exercise No. 2 provided some valuable insights into the performance of fire models, extending the findings from the first Benchmark Exercise in a number of important respects. These included the modeling of large spaces, complex geometries and in comparing predictions against experimental measurement data. Confidence in the application of zone, lumped parameter and CFD models has been provided in the simulations of the test hall experiments in *Part I*, where reasonable agreement was obtained once the important, controlling mechanisms were accounted for.

However, the simulations of the hypothetical turbine hall in *Part II* identified a number of current weaknesses, and illustrated that quite varied predictions could be obtained with different models, including with those of the same type, e.g. zone or CFD models.

Despite the 'complexity' of the roof structure in *Part I* the various models were able to predict the smoke layer formation process with reasonable reliability. Of particular note here was the justification in assuming a flat ceiling with the zone models, with the height set such that the volume of the hall was conserved. The fact that zone models generally predicted lower layer heights than those derived from the experimental measurements might be attributed, in part at least, to the data reduction method used in calculating the layer height from the experimental temperature measurements.

When using the original Benchmark specification, there was a tendency in *Part I* to predict higher smoke layer temperatures than those measured. Two principle mechanisms were identified, to which modifications were able to reduce the temperature of the smoke layer. The first of these was the proportion of heat attributed to the convective power of the fire plume, the value being dependent on the choice of heat of combustion, combustion efficiency and radiative fraction. The second was the boundary heat loss, which was shown to play an important role in a number of studies.

In contrary to *Part I*, the predictions form different numerical models for *Part II* varied to a greater extent. This is perhaps not surprising given the complexity of the fluid dynamics and the fact that measurements were not available against which to compare simulations. While the size of the building was a challenge to CFD models, it was the fluid dynamics associated with two vertical compartments connected by two hatches that provided the greatest test to all models. This was true, in particular, to *Scenario 1* where the upper deck was completely sealed.

For *Scenarios 2* and *3*, the maximum lower and upper deck temperatures were, from an 'engineering perspective', broadly similar for the different models. To some extent the differences between the predicted temperatures could be attributed to the different assumptions for the convective power of the fire source. It was apparent that the CFD models, and to a lesser extent the lumped parameter model, identified three-dimensional effects not within the scope of a zone model.

For *Scenario 1* the variation between models was more marked, in particular in respect to the upper deck temperature. The main cause of this discrepancy seems to be the treatment of the hatch flows. This is known to be a complex phenomenon for the zone models, both for single vent and multiple vent scenarios. However, there were discrepancies between the CFD models, too, with differences in the predicted hatch flow mechanisms. Further development and validation in respect to the ability of all types of fire models to predict flows through horizontal hatch type openings seems to be required. By contrast, in terms of the pressure and oxygen consumption predictions, the difference between the various models was judged not to be significant.

While the general consensus was that cable and beam target damage would not have occurred, the predicted level of thermal hazard varied quite significantly between different models. This was a consequence of differences in gas phase conditions and also the modeling of the incident flux. The flux predictions, in particular, were in some instances quite varied, which will have directly influenced the surface and centre-line target temperatures for those models including these calculations.

As in the first Benchmark Exercise, the treatment of the radiative fraction and effective heat of combustion had a big influence on the results. The difference in the predicted temperatures for the various models in *Part II*, and discrepancies with measurements in *Part I*, seems to have been due, in part at least, to assumptions made here.

Further development of suitable sub-models for predicting the thermal damage to target elements, in particular cables, cable bundles and cable trays, seems to be required. The calculation of incident fluxes is particularly important in predicting cable damage, and highlights the need to address the radiative heat transfer, both from the flaming region and the smoke layer, more carefully.

The usefulness in applying a combination of simpler (e.g. zone) and more complex (e.g. CFD) models to practical problems akin to those represented by the Benchmark Exercise was apparent. In particular, the zone model approach, while obviously more limited in its geometrical and scientific capabilities, provides a very useful tool for an initial scoping study. CFD can then be used for selected scenarios as required in a particular safety study. This may be particularly important for large geometries such as a turbine hall where CFD calculations are likely to be expensive.

2.3 Benchmark Exercise No. 3

2.3.1 Specific Objectives

The design of Benchmark Exercise No. 3 incorporated several lessons learned from previous NRC-sponsored large scale fire tests. Most importantly, a considerable emphasis was placed on obtaining material properties (cables, in particular), ventilation flow rates, leakage rates, and enough measurements to estimate the integrated heat losses through the walls and compartment opening. This information is vital for a model validation exercise.

2.3.2 Problem Specification

The experiments for Benchmark Exercise No. 3 were designed by staff members from the U.S. NRC and NIST. A draft specification of the experiments was issued to participants on September 6, 2002, to solicit comments, further ideas, and suggestions. Written comments on the draft specification were received from participants.

Benchmark Exercise No. 3 consisted of 15 large scale experiments performed at NIST in June 2003. Numerous measurements (350 per test) were made including gas and surface temperatures, heat fluxes and gas velocities. The experiments are documented in /HAM 06/. Only a brief description of the experiments is included here.

The test compartment dimensions were 21.7 m x 7.1 m x 3.8 m high. The walls and ceiling were lined with two layers of marinate boards; the floor was covered with one layer of gypsum board on top of one layer of plywood. Thermo-physical properties of the marinite and other materials were provided to the participants. The compartment had one 2 m by 2 m door and a mechanical air injection and extraction system. Some of the tests were conducted with the door closed and no mechanical ventilation, and in those tests the measured compartment leakage was an important consideration. /HAM 06/ reports leakage areas based on measurements performed prior to five of the fifteen tests.

Ventilation conditions, the fire size, and fire location were the key parameters varied in the test series. The fire pan was located at floor level in the center of the compartment for most of the tests. In three tests, the fire was positioned near the wall.

The fuel pan was 2 m long, 1 m wide and 0.1 m deep. The fuel used in 14 of the tests was heptane, while toluene was used for one test. The heat release rate was determined using both the estimated fuel flow rate and oxygen consumption calorimetry. The uncertainty in the HRR measurement is described in /HAM 06/. The recommended uncertainty values were 17 % for all of the tests.

The photograph presented in Fig. 2-15 shows a typical benchamerk Exercise No. 3 experiment. A heptane spray fire can be observed through the open doorway, which was instrumented to measure the temperature and velocity fields.

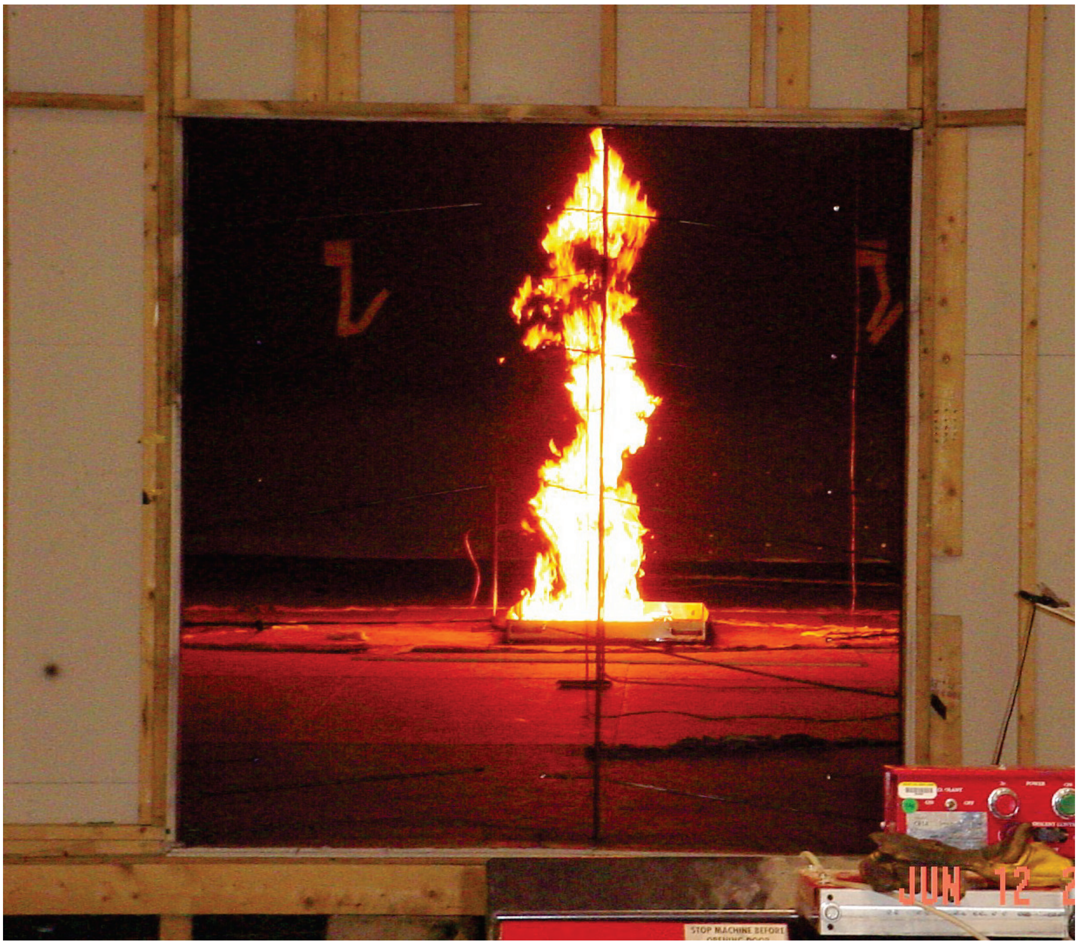


Fig. 2-15 Photograph of a Benchmark Exercise No. 3 experiment conducted in a large compartment at NIST

2.3.3 Results

It is difficult to summarize in a simple way the accuracy of the models assessed in Benchmark Exercise No. 3, as each participant chose different quantities and different tests to analyze, see Tab. 2-9. Some performed calculations before the test data was released (blind calculations), some after (open calculations). Some used the recommended values of the input parameters; others chose to vary the parameters to assess sensitivity. All of the participants agreed that the approximate forms of the conservation equations for mass, momentum and energy in the various fire models evaluated provide a ‘reasonable’ prediction of the hot gas layer temperature, depth and product concentration. Other issues were discussed on a case by case basis. Tab. 2-10 presents a sample of the qualitative assessments. All of the participants considered the influence of the HRR, leakage rate, ventilation rate, door opening and material properties, but in a very qualitative way. For example, a higher specified radiative fraction leads to lower upper layer temperatures. Splitting the ventilation duct between the upper and lower layers of a zone model influenced the layer height.

Tab. 2-9 Models used for Benchmark Exercise No. 3

Model Type	Code	Code Version	Modeler (Institution)	Blind (b), Semi-blind (s) or Open (o) Calculation
Zone	CFAST	3.1.6	S. Miles (BRE)	b, s
		3.1.7	M. Dey (Deytec)	s, o
	FATE	2.0	T. Elicson, S.J. Lee, M. Plys (Fauske)	o
	FLAMME_S	2.3.2	L. Rigollet (IRSN)	s
	MAGIC	3.4.8	L. Gay, B. Gautier (EdF)	b, s
Lumped Parameter	COCOSYS	2.0	W. Klein-Heßling (GRS)	b, s, o
CFD	CFX	5.7	M. Heitsch (GRS)	s
	FDS	4.0	K. McGrattan (NIST)	s
		4.0.5	M. Dey (Deytec)	s, o
	JASMINE	3.2.3	S. Miles (BRE)	b, s

Tab. 2-10 Individual Assessments of Model Accuracy, Benchmark Exercise No. 3

	CFAST S. Miles (BRE)	**FATE M. Plys (Fauske)**	**FLAMMME_S L. Rigollet (IRSN)**	**MAGIC L Gay (EdF)**	**COCOSYS W. Klein-Heßling (GRS)**	**CFX M. Heitsch (GRS)**	**FDS K. McGrattan (NIST)**	**JASMINE S. Miles (BRE)**
HGL tempera-ture	“good agreement”		“simulated ade-quately”	"good, less than 12 %”	“quite good”; open “better” than blind	case by case	“10 % with exceptions”	“accurately captured”
HGL depth	“good”	“flow-splitting” important	good agreement”	“quite good, less than 20 %”		case by case	not assessed	“approx-imately … correct”
Gases	“reasonable”		“good results”	case by case	case by case	case by case	“10 % in most cases”	“reasonable”
Pressure	sensitive to leakage	leakage im-portant	“good agreement”	case by case	case by case		“within exp. uncertainty”	sensitive to leakage
Heat flux	“quite varia-ble”	“validated”	“well predicted”	case by case	case by case			“tending to over-predict”
Target tempera-tures	“reasonable”	“effective cable model”	sensitive to door opening	case by case	case by case		10 % to 20 % “reasonable”	“reasonable”
Door flows			“good agreement”				over-predicted near sill	“captured accurately”
Overall	“encourag-ing”			“encouraging”	“quite good”	“worse” than other Bench-mark Exercis-es	“sufficiently accurate”	“encourag-ing”

2.3.4 Discussion

Benchmark Exercise No. 3 consisted of 15 experiments, each of which consisted of 350 point measurements. With little or no guidelines for analysis, the participants chose to assess their models as they saw fit. The individual reports consist of dozens of observations, but little quantification of model accuracy. Most fire modeling analyses published over the past 30 years have a similar character.

However, some regulatory authorities like the U.S. NRC, and standards bodies in the U.S. like the National Fire Protection Association (NFPA), are meanwhile demanding a more quantitative assessment of fire model accuracy. Given the adoption of NFPA 805 /NFP 01/, the U.S. NRC now requires that all fire models used for NPP safety assessment be verified and validated (V&V). Towards this end, the U.S. NRC has more recently published a seven-volume report, 'Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications' /NRC 07/ being available to the public on the NRC's Web site[1]. Five of the seven volumes contain individual evaluations of fire models having also been applied in the frame of ICFMP Benchmark ExerciseNo. 3 such as CFAST, MAGIC, FDS. Fifteen of the 26 experiments used for the NRC V&V study /NRC 07/ are from Benchmark Exercise No. 3. Results from Benchmark Exercises No. 2, 4 and 5 were also used, as were two sets of experiments performed at the National Bureau of Standards (now NIST) and Factory Mutual (under sponsorship of the NRC).

A key component of /NRC 07/ is the quantification of experimental uncertainty. In fact, the final assessments for all the models considered were made in light of the experimental uncertainty for the quantities that were being compared. An example of the process to determine experimental uncertainty is as follows; suppose that the uncertainty in the measurement of the heat release rate of a fire was determined to be 15 %. According to the well known McCaffrey, Quintiere, Harkleroad (MQH) correlation, the upper layer gas temperature rise in a compartment fire is proportional to the two-thirds power of the heat release rate. This means that the 15 % uncertainty in the measured heat release rate that is input into the fire models leads to a 10 % uncertainty in the prediction of the upper layer temperature.

---

[1] www.nrc.gov/reading-rm/doc-collections/nuregs/staff/

Combining this with the uncertainty associated with the thermocouple temperature measurement leads to a combined uncertainty in the reported temperature of about 12 %.

This type of analysis is particularly important for Benchmark Exercise No. 3. The originally specified heat release rate (HRR) for most of the Benchmark Exercise No. 3 experiments was 1 MW. This was the HRR used in the blind exercise. However, after the experiments were completed, the HRR was reported to be on the order of 1.15 MW, 15 % higher than the original estimate. To put this into perspective, consider the set of graphs shown in Fig. 2-16, Tests 2, 3 and 4 (the original blind simulation cases) were re-run with the CFD model FDS using different HRR values of 1000 kW, 1150 kW, and 1190 kW.

Notice that the heat release rate has little effect on the hot gas layer height predictions, but it does have a noticeable effect on the hot gas layer temperature predictions. The difference between the 1150 kW and 1190 kW simulations is fairly small, and well within the uncertainty bounds of the HRR measurement itself. However, the 1000 kW simulations noticeably under-predict the HGL temperature. This is not surprising, because the HGL temperature rise is proportional to the two-thirds power of the HRR, according to the well-established MQH correlation. Thus, a 15 % change in the input heat release rate will yield a 10 % change in the hot gas layer temperature rise.

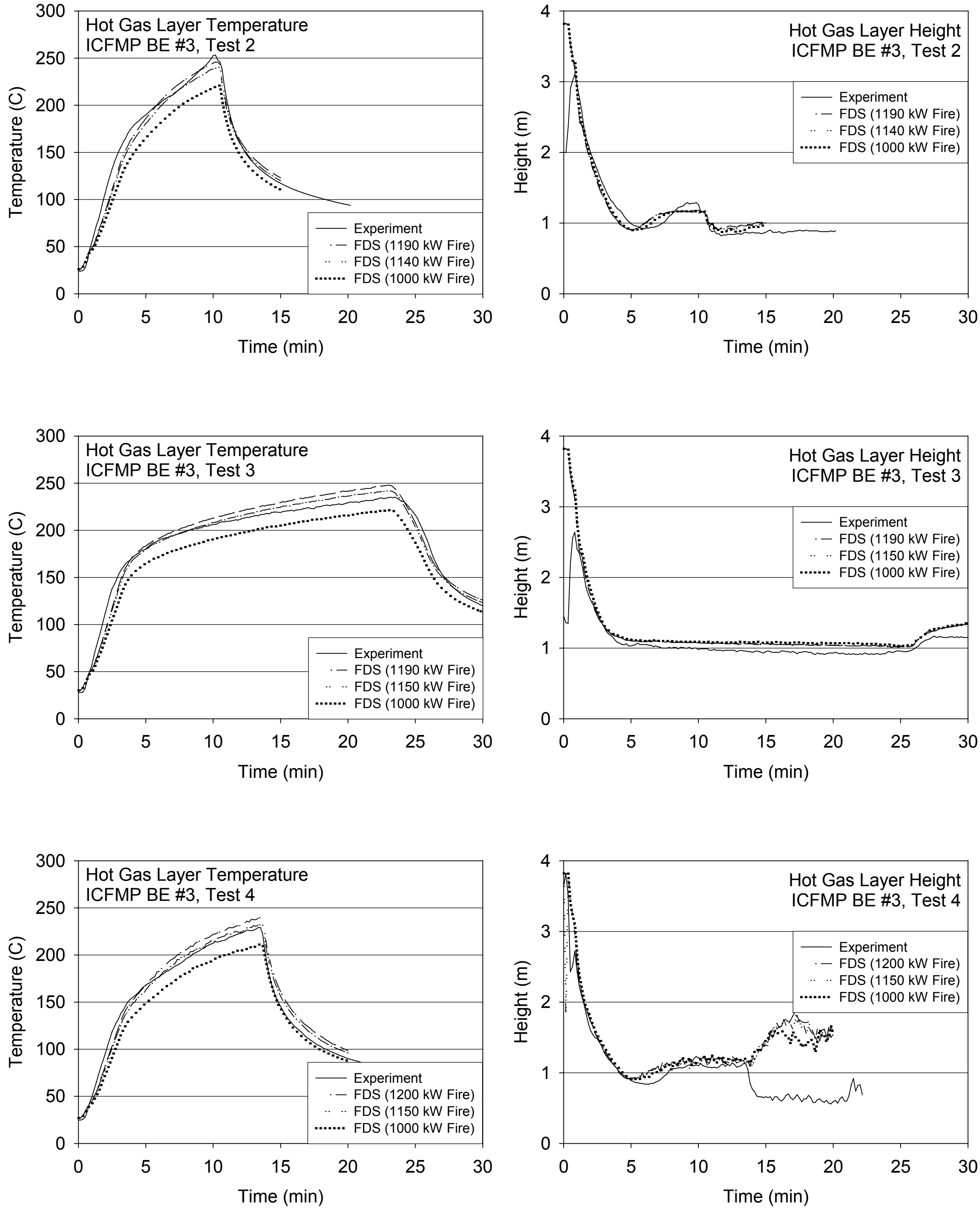


Fig. 2-16 Measured and predicted hot gas layer temperature and height for Benchmark Exercise No. 3, Tests 2, 3 and 4

A similar analysis was performed for the other quantities of interest. In Volume 2 of /NRC 07/, Hamins quantifies the experimental uncertainty of Benchmark Exercise No. 3 (see Tab. 2-11). Experimental uncertainty is due to both uncertainty in the measurements of the model input parameters (such as the heat release rate), and also the measurement of the model output quantities (such as the gas temperature). By quantifying the experimental uncertainty, especially the consequence of uncertainty in model inputs, it becomes much easier to re-assess the qualitative conclusions drawn by the participants of Benchmark Exercise No. 3.

All the participants noted how sensitive their results were to leakage and ventilation rates. Some went so far as to say that their models were performing badly based on the apparent discrepancy between their predicted pressures and the measured pressures. However, consider that the uncertainty in the specified leakage and ventilation rates can lead to as much as an 80 % combined uncertainty in the reported measurements. In other words, any model within 80 % of the measured pressure could claim to be within experimental uncertainty, and no further assessment can be made, based on this set of experimental data.

The real value of Hamins' uncertainty analysis is that it quantifies what has been referred to as 'User Effects' by the ICFMP participants. All the participants pointed to the HRR, leakage rate, and ventilation rate as key parameters, and now we see why. The compartment pressure, for example, goes like the square of each. However, the hot gas layer depth was well-predicted by all because it is not sensitive to input parameters that have a high degree of uncertainty. For any fire scenario, there are dozens of input parameters that a modeler must specify. A simple uncertainty analysis like the one described here will focus attention on those inputs that really matter.

The above discussion quantifies the sensitivity of model results to model inputs. But it does not tell us how accurate the models are. To assess accuracy, there first must be a standard metric to quantify the difference between the measurement and the model prediction. For Benchmark Exercise No. 3, there was no single metric that the participants used to quantify the accuracy of each point to point comparison. However, in /NRC 07/, a relative difference was defined as the difference between the peak value of the prediction and the peak value of the measurement, divided by the peak value of the measurement. This definition was specified by the regulatory authority because peak values are seen as a good measure of the severity of the fire.

Tab. 2-11 Sensitivity of model outputs from /NRC 07/

Quantity	Important Input Parameters	Power Dependence	Combined Uncertainty [%]
HGL temperature	HRR	**Fehler! Textmarke nicht definiert.**2/3	12
HGL depth	door height TC spacing	1 1	63
Gas concentrations	HRR	1/2	9
Smoke concentration	HRR soot yield	1 1	33
Pressure	HRR leakage rate vent rate	2 2 2	40 (unventilated) 80 (ventilated)
Heat flux	HRR	4/3	20
Surface/Target temperature	HRR	2/3	14

Once all of the relative differences for all of the chosen quantities had been calculated, the results were assembled into simple scatter plots. These scatter plots provided a very effective way to compare models, and types of models. Consider, for example, the predicted average hot gas layer temperature rise (determined using a simple two layer reduction method) from all the models compared to the experimental measurements as shown in Fig. 2-17.

The data shown there are from Benchmark Exercises No. 2, 3, 4 and 5, plus several other NRC and NIST sponsored experiments. The combined experimental uncertainty of 13 % is an average for all the data sets. For Benchmark Exercise No. 3 alone, the uncertainty was estimated at 12 %. The hand calculation methods show the greatest deviation and scatter when compared to the measurements. Both the zone and CFD models show less scatter and very similar accuracy for the experiments under consideration.

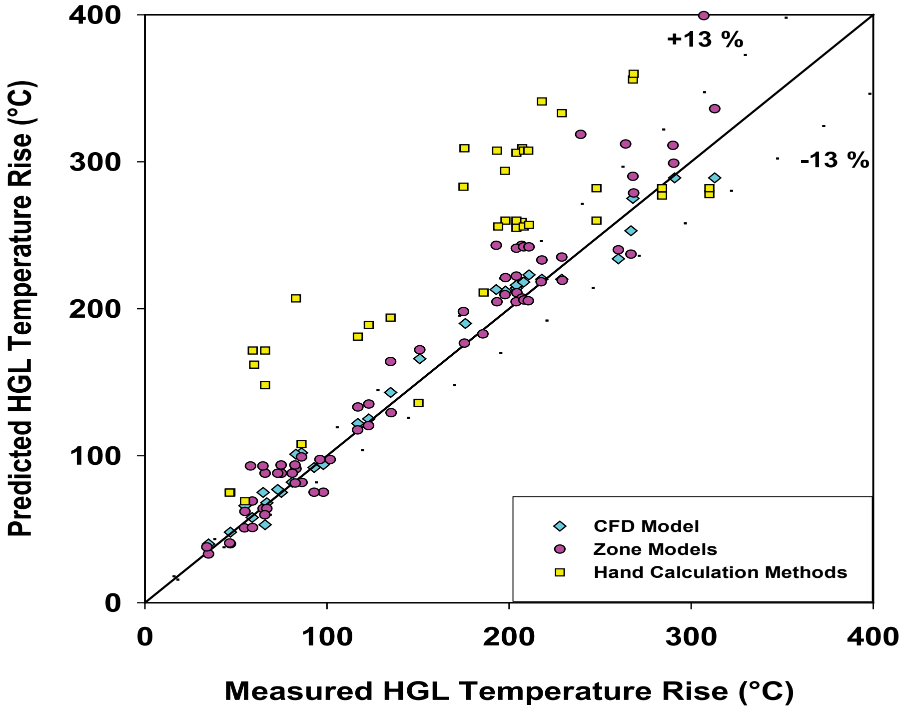


Fig. 2-17 Measured versus predicted hot gas layer temperature rise from different ICFMP Benchmark Exercises and other experiments (from /NRC 07/)

Next, consider the predicted heat fluxes onto various horizontally and vertically oriented targets in Fig. 2-18.

The CFD model, overall, is more accurate for this parameter, even though the zone and CFD models are of comparable accuracy in predicting the gas temperature. Why is the CFD model more accurate in predicting heat flux? The heat flux at a target is dependent on the thermal environment of the surroundings, the details of which the CFD model is inherently better able to predict. Hand calculations and zone models predict average temperatures over the entire compartment, and thus are less accurate in predicting a heat flux to a single point.

Whereas the CFD model was more accurate in predicting heat fluxes and surface temperatures, the simpler models performed equally well, sometimes better, for plume and ceiling jet temperatures and flame heights. The reason is that hand calculations as well as simple zone models with only a hot gas and a cold gas layer (two zones) use well-established correlations for these fire phenomena.

A CFD model solves the basic transport equations, making it truly predictive of these quantities, but not necessarily more accurate. And the increased cost of a CFD calculation is substantial. The spreadsheet and two-zone models produce results in seconds to minutes, versus a CFD model which takes hours to days. If hand calculations and zone model results are obtained faster and are equal to (or better than) CFD results, why should an engineer use a CFD model. Real fire scenarios can be more complex than the experiments used in this study and may not conform to the assumptions inherent in the hand calculations and zone models. Fire plumes may not be free and clear of obstacles, because fires sometimes occur in cabinets or near walls. Ceilings might not be flat and unobstructed, because duct work, structural steel, and cable trays are often present. Although hand calculations and zone models can be applied in these instances, the results require more extensive explanation and justification. Since CFD models can make predictions on a more local level with fewer assumptions, the results are likely to be more applicable in these more complex situations.

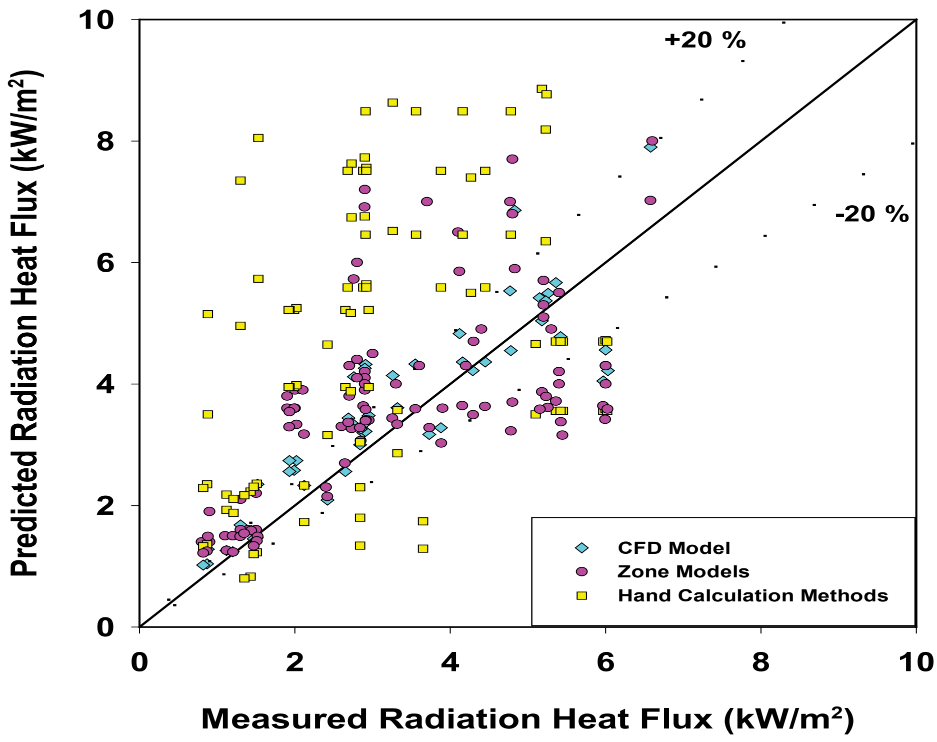


Fig. 2-18 Measured versus predicted radiation heat flux onto various horizontally and vertically oriented targets in Benchmark Exercise No. 3 (from /NRC 07/)

2.3.5 Conclusions

Benchmark Exercise No. 3 provided a tremendous amount of experimental data with which to assess fire models. The participants in this exercise used these data in various ways, but without a common framework for analysis. Thus it was difficult to assess the relative accuracies of the different models. However, the further analysis of the ICFMP Benchmark Exercise No. 3 data that is included in /NRC 07/ should allow the Benchmark Exercise No. 3 participants to re-evaluate their models in light of the quantifying metrics developed. Although only five models were assessed in the above mentioned NRC/EPRI study /NRC 07/, the process provides a means to evaluate any fire model in a consistent manner against a common database of experiments. The study highlights the use of experimental uncertainty as a means to assess the level of agreement between models and measurements. It also provides a way of quantifying 'User Effects'.

Much remains to be done in improving fire models beyond the basic transport capabilities that were assessed in Benchmark Exercise No. 3. But before any improvements can be made, the accuracy of the commonly used models has to be quantified rigorously, so that resources can be spent on the parts of the models that need the most improvement. At this stage, the basic transport algorithms within the zone and CFD models were shown to be robust and nearly comparable to the uncertainty of the measurements against which they were compared. Heat flux and surface temperature predictions are more challenging and could benefit from continued development. Hand calculations are typically less accurate than zone or CFD models, but are easy to use and predictably conservative.

2.4 Benchmark Exercise No. 4

At iBMB (Institut für Baustoffe, Massivbau und Brandschutz) University of Braunschweig - Institute of Technology in Germany, a set of nine real scale fuel pool fire experiments has been performed. The objective of these experiments was to systematically vary the major influencing parameters on the burning behavior to derive standard fire curves (time dependence of temperatures and heat flow densities at different distances from the fire source, burning rates, energy release rates and temperature loads) and to examine the dependence on the pool surface area, the fuel filling level and the ventilation conditions. Test 1 and Test 3 have been used for the Benchmark Exercise No. 4. Details of the specification and results are published in /KLE 06/.

2.4.1 Specific Objectives

The main objective of the experiments for Benchmark Exercise No. 4 was to analyze the thermal load on the structures surrounding a fire relatively large compared to the floor area and volume of the fire compartment. In several experiments the natural and forced ventilation has been varied to investigate the influence of oxygen depleted conditions on the fire. However, the thermal loads and the oxygen depleted conditions are somewhat difficult aspects to calculate, and therefore these experiments can contribute to the further improvement of fire codes. Additionally, the results give some insight concerning the uncertainties of simulations of pool fires in an enclosure under the given boundary conditions.

2.4.2 Problem Specification

The fire compartment ‘OSKAR’ of iBMB, an enclosure with a compartment floor size of 3.6 m x 3.6 m = 12.96 m^2 and a height of 5.7 m, was used for the pool fire test series (see Fig. **2-19**). The opening in the front (with different sizes in the Tests 1 and 3) was open only for the natural ventilation of the fire compartment. Above the front door a hood was placed to measure the gas composition of the smoke.

Inside the fire compartment the gas temperatures, wall surface temperatures, wall heat fluxes and surface as well as the inner temperatures at the material probes (3 plates of different materials and one barrel container, see Fig. 2-20), gas concentration and the gas velocity at the front opening have been measured.

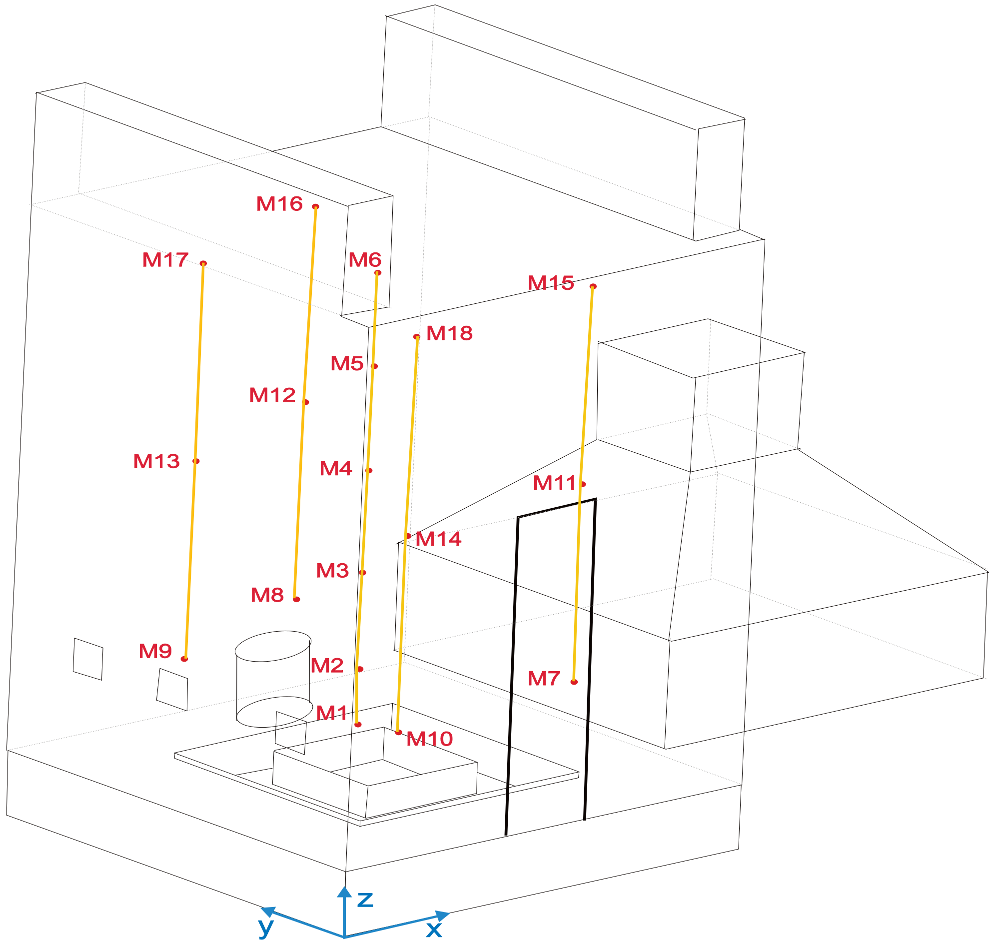


Fig. 2-19 3D view of the OSKAR fire compartment used for Benchmark Exercise No. 4

Fig. 2-20 View of the three material probes implemented in the Benchmark Exercise No. 4 test compartment

At the beginning of the experiments the pan was filled with fuel, with the chemical summary formula $C_{11.64}H_{25.29}$. In all experiments the fuel level was 0.1 m. To ignite the fuel pool, a cleaning rag soaked with liquid fuel was put at the corner of the pan. Then the outer end was ignited, leading to ignition of the whole pool. The duration of this process was approx. 30 to 60 s. The experiments ran until the fuel was consumed.

In those tests considered for Benchmark Exercise No. 4 the fan system was running. Although the valves on the top of the fire compartment should have been closed, some velocity was measured. Due to these measurements, some leakages from the ceiling of the fire compartment have to be assumed.

2.4.3 Results

In the following, the experimental results, and some main results of the fire simulations performed will be discussed. The list of performed calculations is given in Tab. 2-12.

The FATE calculation is not presented, because no calculated data values are available. In cases where a participant has delivered several calculations then one of these has been selected.

To obtain an overview of the calculated results a FFT (Fast Fourier Transformation) based method (FFTBM) /LEO 94/ has been used to compare these results to the experimental data.

The differences based on the continuously varying error function $\Delta F(t) = F_c(t) - F_{\exp}(t)$, continuously varying, should be condensed to give a limited number of values that could be taken as indexes for quantifying accuracy. Integral approaches satisfy this requirement, since they produce a single value on the basis of the instantaneous trend of a given time function. On the other hand, care should be taken in expressing all the information through a single value to avoid the loss of significant details. A fundamental property of the Fourier transformation is that the differences can be analyzed from a different viewpoint without any lack of information with respect to the original one. The accuracy quantification of a code calculation is based on the amplitude of the FFT of the experimental signal and of the difference between experimental signal and the calculated trend. In particular, the method characterizes each calculation through two values. Using the error function $\Delta F(t) = F_c(t) - F_{exp}(t)$ and the discrete Fourier transformations $\Delta\tilde{F}$ and $\tilde{F}_{exp}$ via FFT a dimensionless average amplitude

$$AA = \frac{\sum_{n=0}^{2^m} \left| \Delta\tilde{F}(f_n) \right|}{\sum_{n=0}^{2^m} \left| \tilde{F}_{exp}(f_n) \right|}$$

and a weighted frequency

$$WF = \frac{\sum_{n=0}^{2^m} \left| \Delta\tilde{F}(f_n) \right| \cdot f_n}{\sum_{n=0}^{2^m} \left| \tilde{F}_{exp}(f_n) \right|}$$

is defined.

The most significant information is given by the average amplitude AA, which represents the relative magnitude of the discrepancy derived from the comparison between two curves. (AA = 1 means a calculation affected by a 100 % of error.) The weighted frequency (WF) factor characterizes the kind of error, because its value emphasizes whether the error has more relevance at low or high frequencies. A larger value of 1/WF (inverse of WF) indicates larger deviations for low frequencies. Depending on the transient, high frequency errors can be more acceptable than low frequency ones. Depending on the transient, high frequency errors can be more acceptable than low frequency ones. For receiving meaningful results it can be compared qualitatively. Such a qualitative comparison is therefore needed before.

The above described FFTBM has been used within several ISP (International Standard Problem) projects. Based on the experience gained /LEO 94/ (roughly 200 code calculations analyzed from about ten experiments), an upper limit of AA_{tot} = 0.4 has been chosen as reference threshold value identifying good accuracy of a code calculation. AA_{tot} is a weighted average value over all relevant data for the corresponding experiment.

For this kind of comparison a few variables have been selected. These are the plume temperature M3, the atmospheric gas temperatures at the second level at 3.35 m M11 to M14, the upper layer temperature T_{up}, the surface temperatures of the three material probes M29, M33 and M34 and the oxygen concentration at position GA1. Only the time period from 0 s to 800 s is considered for both tests, during which time the measurement of the fuel weight loss is reliable.

Tab. 2-12 List of calculations performed for Benchmark Exercise No. 4

Model Type	Code	Code Version		Modeler (Institution)	Part I	Part II
Zone	CFAST	3.1.6	CFABRs	S. Miles (BRE)	semi-blind [1]	semi-blind [2]
		3.1.7	CFANRs	M. Dey (NRC/NIST)	semi-blind	semi-blind
	FLAMME_S	2.3.2	FLAIRo	L. Rigollet (IRSN)	open [3]	open [3]
	FATE	2.0	(not presented)	T. Elicson (Fauske)	open	open
	MAGIC	4.1.1b	MAGEDo	B. Gautier (EdF)	open	open
Lumped Parameter	COCOSYS	2.2dev	COCGRo	B. Schramm (GRS)	open	open
CFD	CFX	5	CFXGRo	M. Heitsch (GRS)	open	open
	FDS	3.1.5	FDSNRs	M. Dey (NRC/NIST)	semi-blind	semi-blind
		3	FDSGRo	W. Brücher (GRS)		open[4]
		4	FDSNIb	K. McGrattan (NIST)	blind	blind
		4	FDSNIs	K. McGrattan (NIST)	semi-blind	semi-blind
	JASMINE	3.2.3	JASBRb	S. Miles (BRE)	blind [5]	blind [5]
		3.2.3	JASBRs	S. Miles (BRE)	semi-blind	semi-blind [6]
		3.2.3	JASBRo	S. Miles (BRE)		open [7]
	VULCAN		VULSAo	V. Nicolette (SNL)		open

1 CFAST 3.1.6 semi-blind calculation: run 1 with measured pyrolysis rate (see Table B1 in Appendix B of /KLE 06/)
2 CFAST 3.1.6 semi-blind calculation: run 3 with limited measured pyrolysis rate (see Table B1 in Appendix B of /KLE 06/)
3 FLAMME_S open calculation with measured pyrolysis rate (see Appendix E of /KLE 06/)
4 FDS 3 calculation using the coarse grid resolution (see Appendix G of /KLE 06/)
5 JASMINE 3.2.3 blind calculation: run1 with constant pyrolysis rate of 0.039 kg s^{-1} (see Table B2 in Appendix B of /KLE 06/)
6 JASMINE 3.2.3 semi-blind calculation: run1 with measured pyrolysis rate (see Table B3 in Appendix B of /KLE 06/)
7 JASMINE 3.2.3 open calculation: run4 with 0.75 x measured pyrolysis rate (see Table B4 in Appendix B of /KLE 06/)

Atmospheric Temperatures Inside the Fire Compartment

Fig. 2-21 and Fig. 2-22 present the FFT results for the atmospheric temperatures M3 (plume) and M11 to M14 (Level 2) for Test 1 and Test 3, respectively. The following conclusions can be drawn:

- The simulation of the upper layer temperature in Test 1 is much worse than Test 3 for CFD calculations. It has to be kept in mind, that only three levels of temperature measurements are available. Therefore the calculation of the experimental upper layer temperature is somewhat critical. Also the deviations of the calculated upper layer temperature of some FDS simulations are greater compared to the temperatures M3 and M11 to M14.
- The AA value of most of the calculations is between 0.1 and 0.6. The semi-blind and open calculations are better compared to the blind ones (see arrows inside above pictures for FDS and JASMINE calculation).
- The frequency value (1/WF) is higher for Test 3 compared to Test 1. Therefore, the deviation in the time characteristics of the results is higher. This is valid especially for the temperature M12 close to the backside of the fire compartment.
- FDS and CFAST have been used by several participants for semi-blind calculations. The quality of the FDS calculations is quite similar (about 0.2 for Test 1 and between 0.3 and 0.4 for Test 3). Compared to this the errors for CFAST are much higher (about factor of 2 for Test 3).

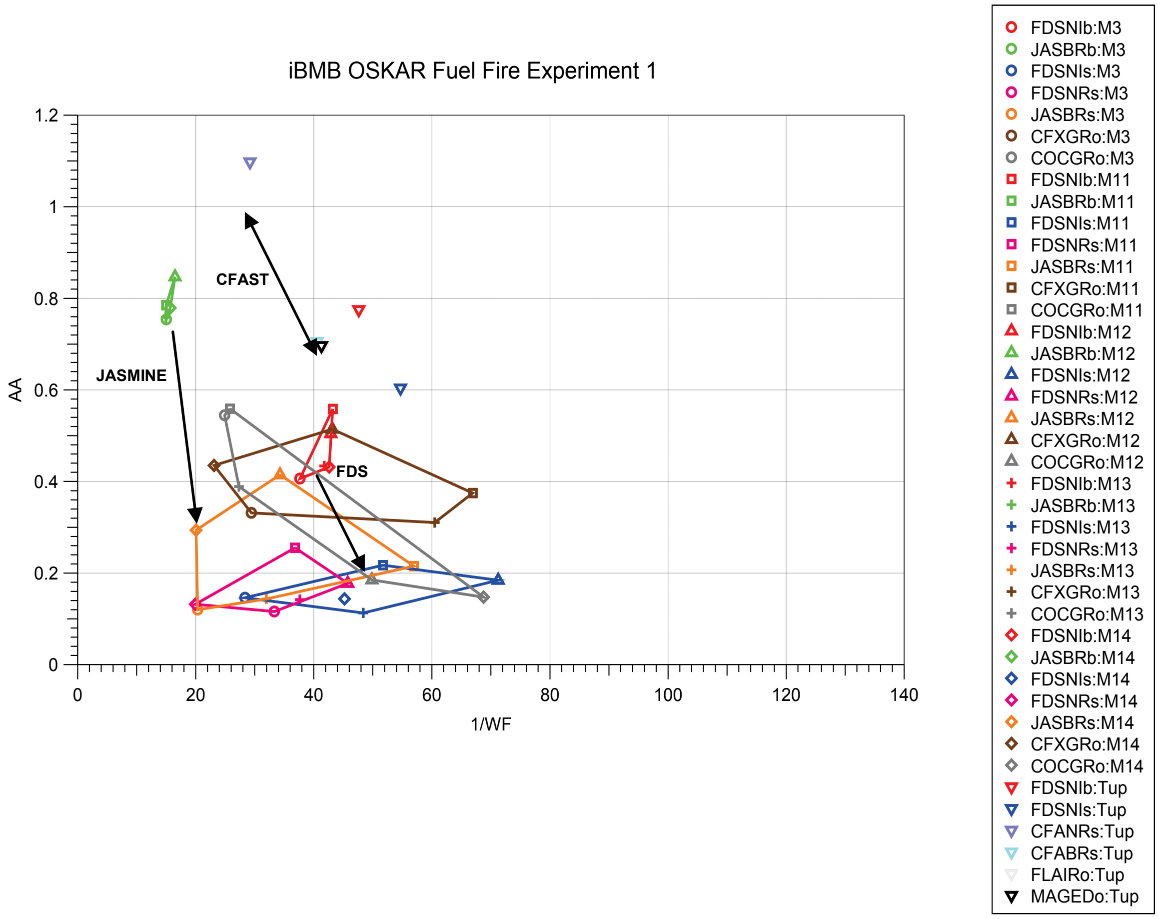


Fig. 2-21 Evaluation of atmospheric temperatures (M3, M11 to M14) for Benchmark Exercise No. 4, Test 1

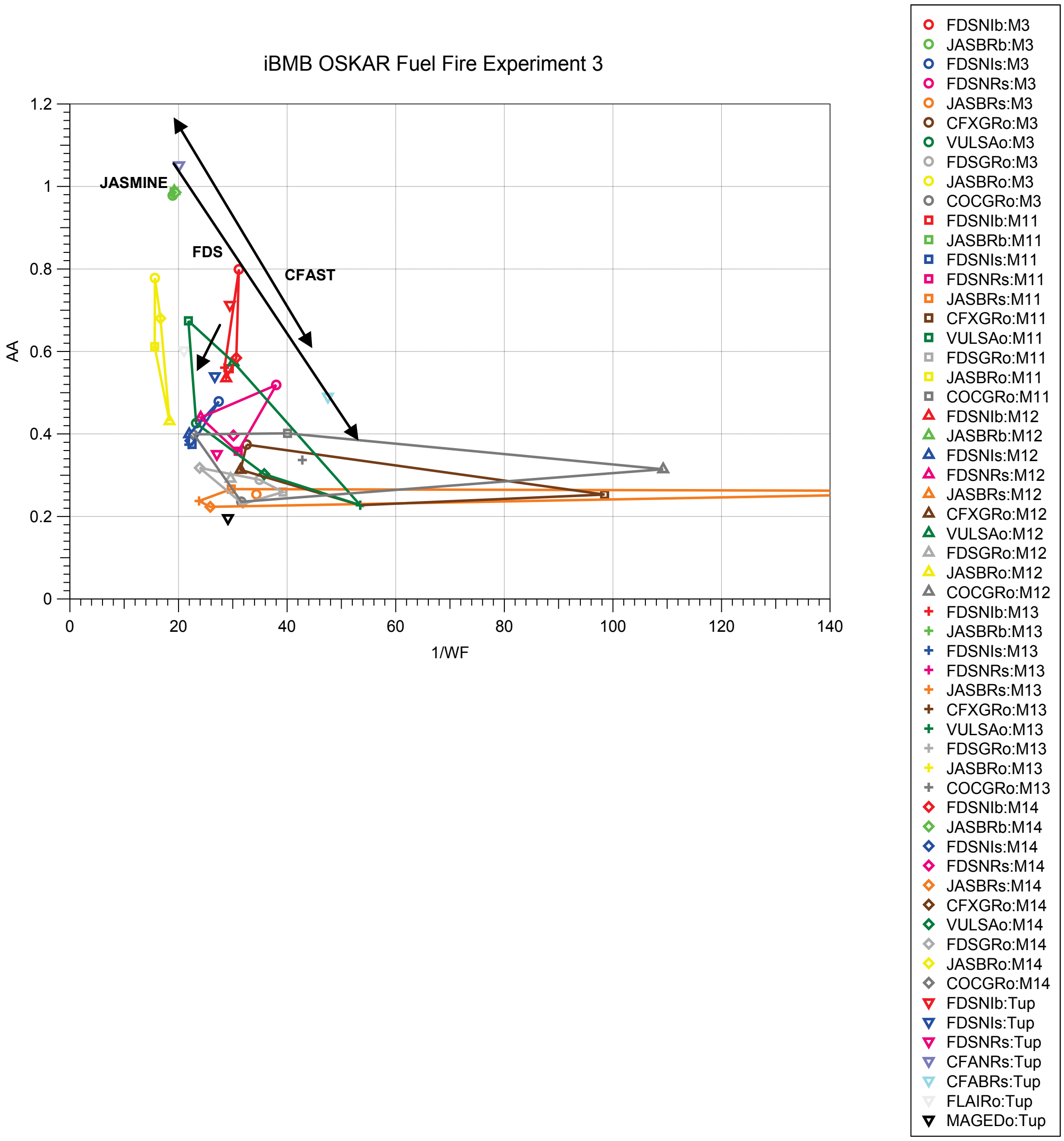
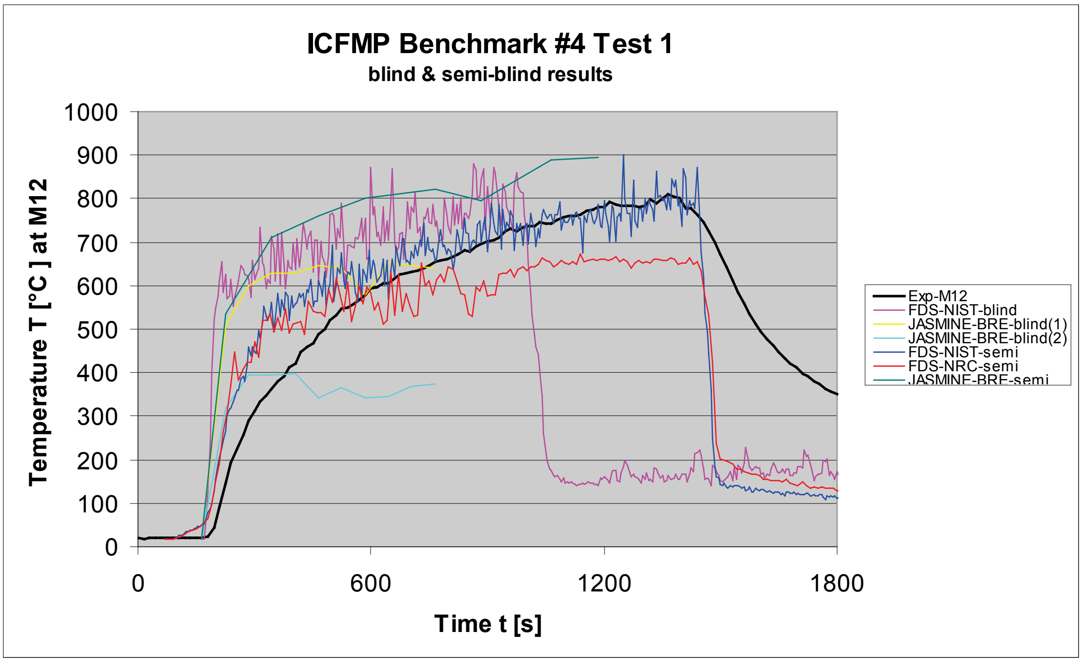


Fig. 2-22 Evaluation of atmospheric temperatures (M3, M11 to M14) for Benchmark Exercise No. 4, Test 3

For comparison the results for measurement M12 of the blind and semi-blind calculations for both tests are presented in Fig. 2-23. This figure gives an impression between the AA values and the corresponding differences in time and particularly in the time characteristic. Details can be found in /KLE 06/.



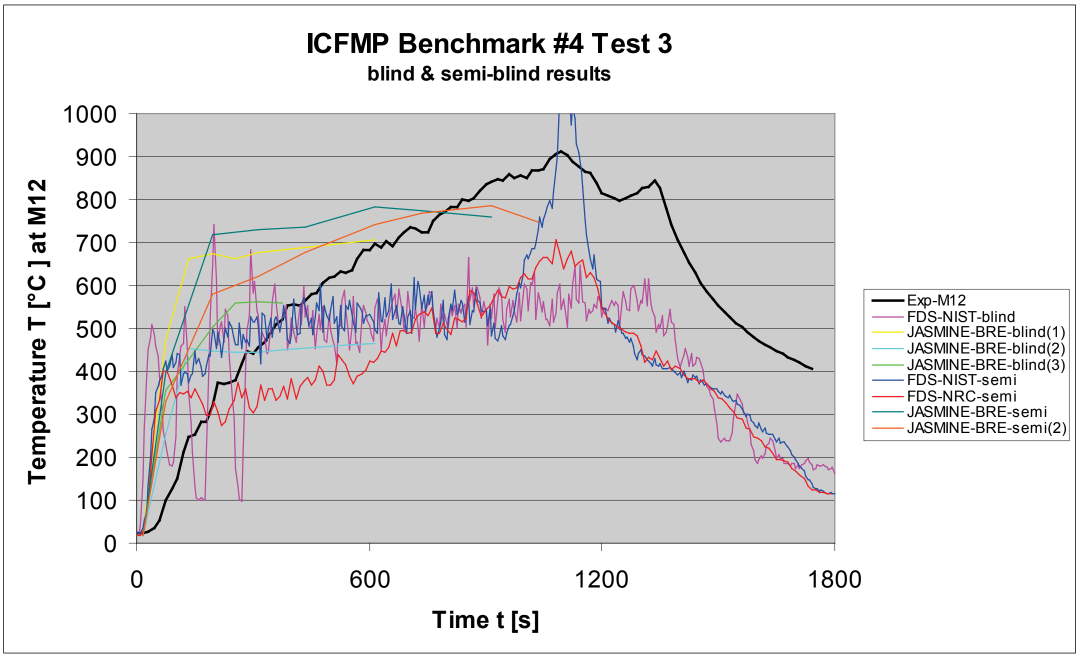


Fig. 2-23 Comparison of Benchmark Exercise No. 4 temperature measurement M12 to blind and semi-blind calculations

Surface Temperatures

One of the main tasks of a fire simulation is the estimation of thermal loads to different types of targets. Therefore, the temperature measurements M29, M33 and M34 have been selected for comparison with the FFT method. The results are presented in Fig. 2-24 and Fig. 2-25.

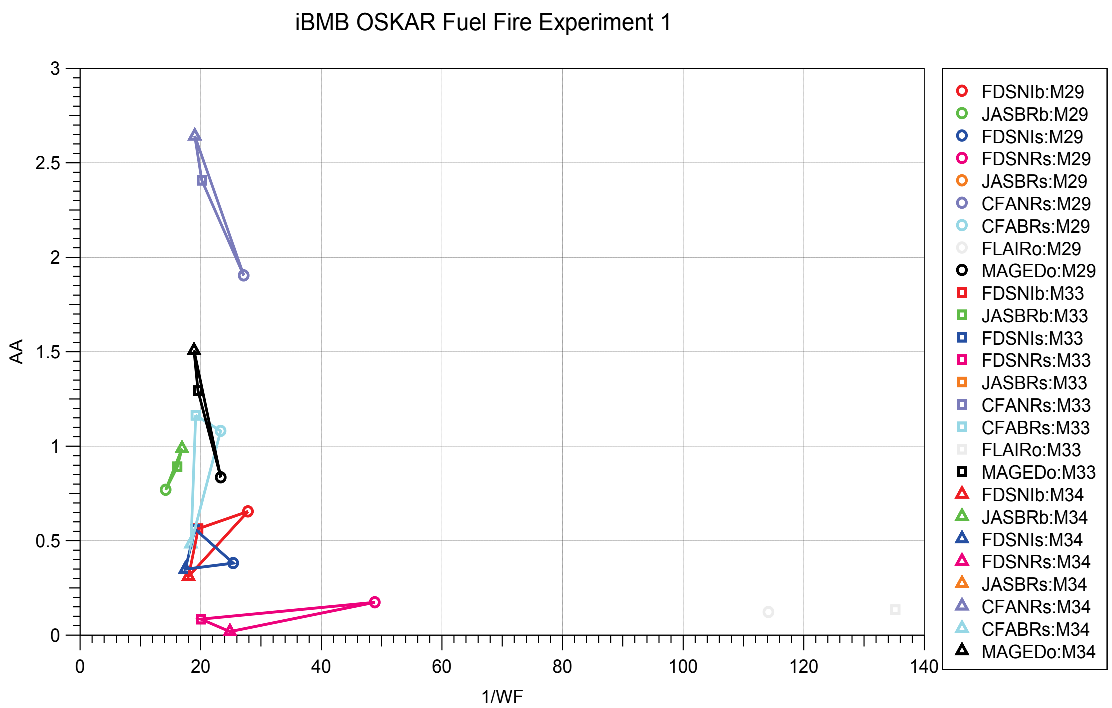


Fig. 2-24 Evaluation of surface temperatures (M29, M33, M34) for Benchmark Exercise No. 4, Test 1

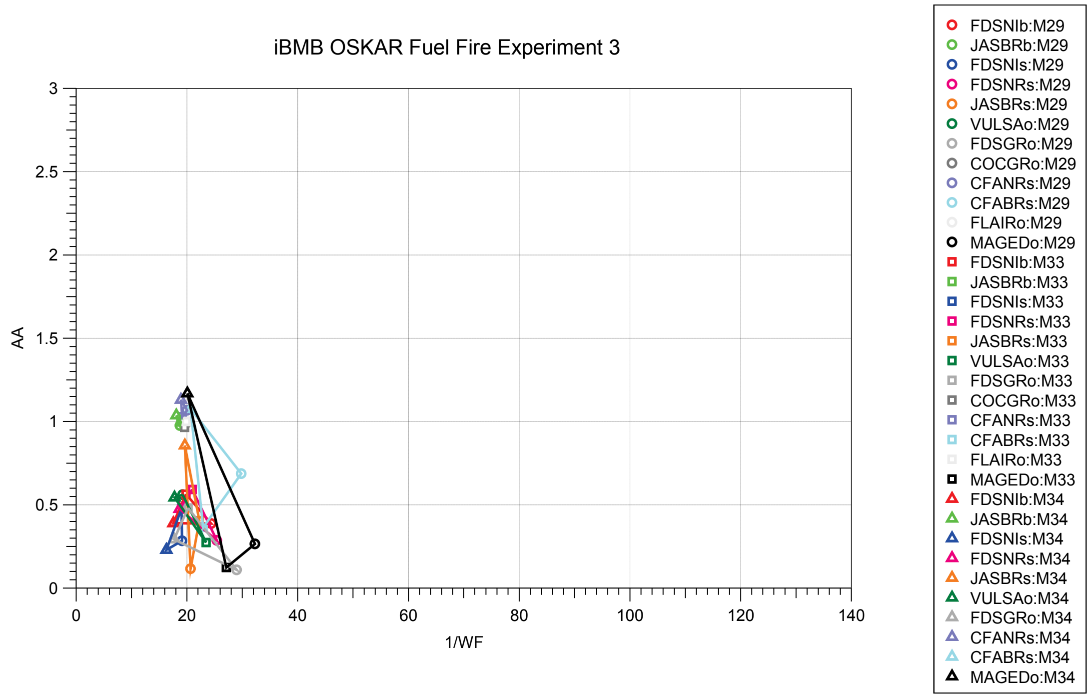


Fig. 2-25 Evaluation of surface temperatures (M29, M33, M34) for Benchmark Exercise No. 4, Test 3

For comparison some time curves are presented in Fig. 2-26. The large AA value of 2.5 corresponds to the large deviation of the time curve (CFAST-NRC-semi). Looking at the results for M34 in Test 3, the best result for semi-blind calculations was calculated by FDS (NIST). The maximum differences up to 100 K, leading to an relative error of approx. 50 %, are shown in the corresponding time curves.

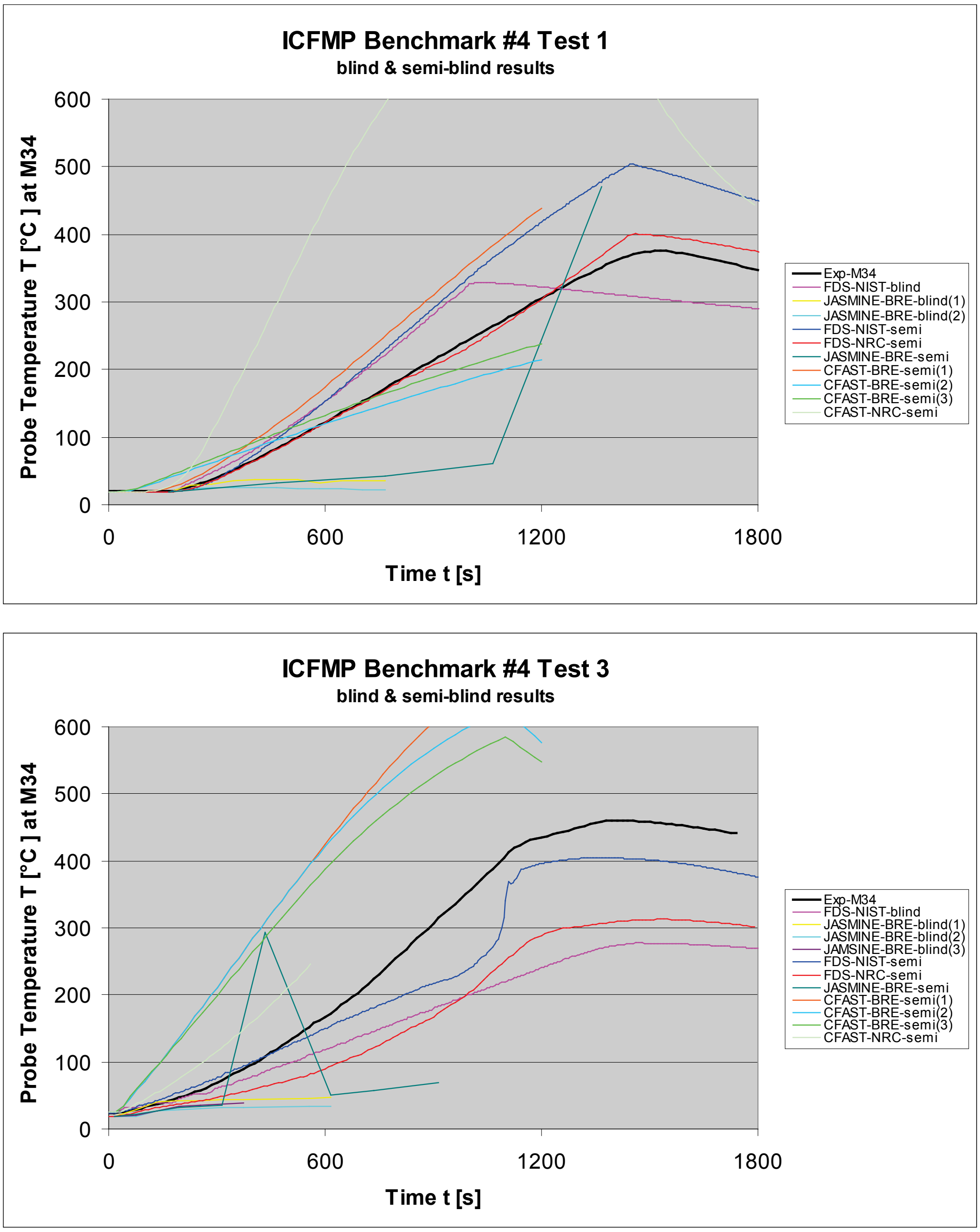


Fig. 2-26 Comparison of Benchmark Exercise No. 4, measurement M34 for blind and semi-blind calculations

The following conclusions can be drawn:

– The spreading of the results is larger for Test 1 compared to Test 3.

– Compared to the uncertainty of atmospheric temperatures the corresponding value for the surface temperatures is about two times higher for Test 3 and three to four times higher for Test 4. Also here the more inhomogeneous conditions in Test 1 may lead to higher deviations.

Oxygen Concentration

The difference between the results of the two experiments is because of the size of the opening at the front side of the facility, leading to different oxygen concentrations. The FFT results are presented in Fig. 2-27 and Fig. 2-28. The range of AA is between 0.2 and 0.6 and very similar for both experiments and in the same order as the temperature results. For Test 1 there is some stagnation of the measured data. This may be the reason for the deviation. The deviation in time characteristic is somewhat larger for Test 3.

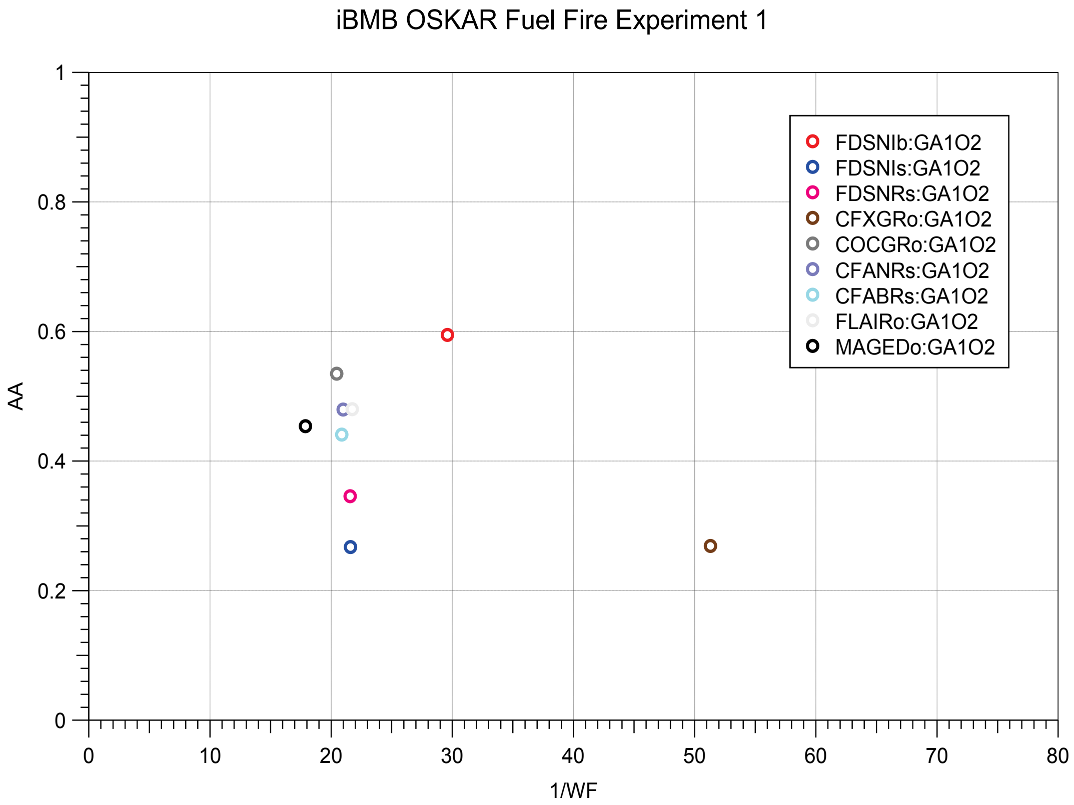


Fig. 2-27 Evaluation of the oxygen concentration at GA1 for Benchmark Exercise No. 4, Test 1

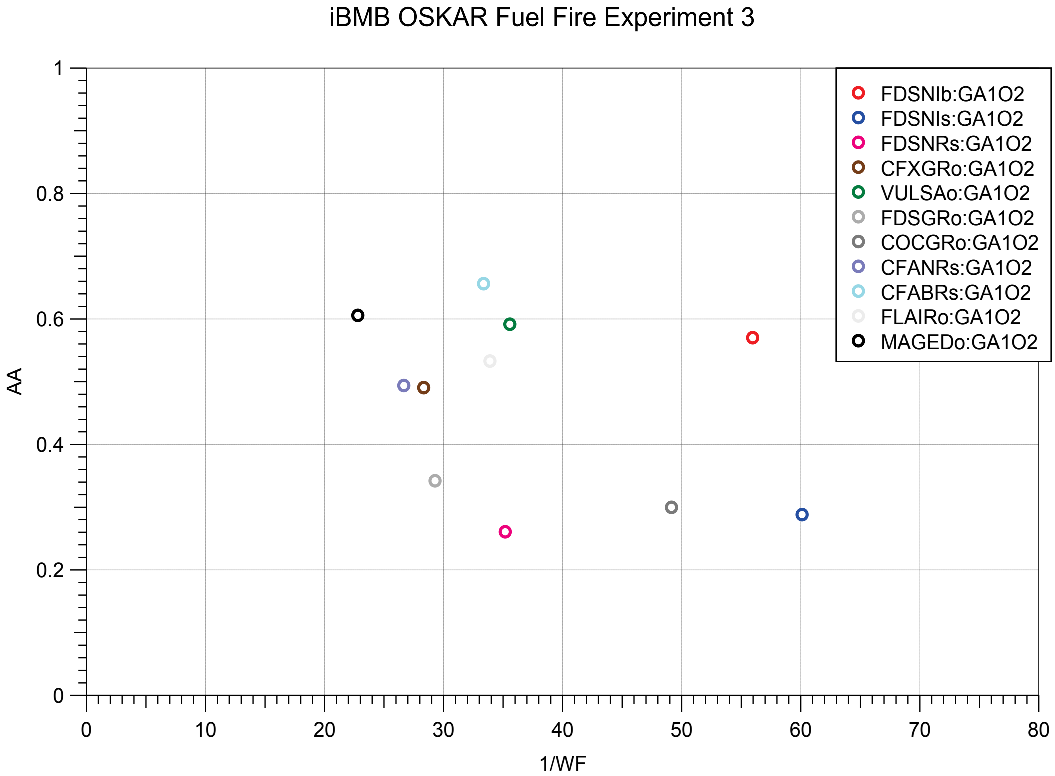


Fig. 2-28 Evaluation of the oxygen concentration at GA1 for Benchmark Exercise No. 4, Test 3

Using the FFT method to compare different simulations with experimental results gives a quick overview of the quality of the results in a quantitative way. This method has the advantage of not only considering the average deviation, but also the time characteristics of the results. Compared to other thermal hydraulic problems the deviations of fire simulations are usually much higher.

By reviewing the FFT results, the improvements between some blind and semi-blind results are evident (e.g. FDS calculations). There is no clear tendency that the use of CFD codes leads to better results. One exception may be the surface temperature calculation in zone models for Test 1. However, both type of codes had difficulty in simulating these experiments (under-ventilated conditions, strong heat fluxes) that is of concern.

2.4.4 Discussion

The code to code comparison is already presented in /KLE 06/. Here the main conclusions based on the code to code comparison and the results of the FFT analysis are discussed.

Additional Uncertainty Based on Blind Calculations

For Benchmark Exercise No. 4 some blind calculations have been performed with FDS and JASMINE. Regarding the atmospheric temperatures, the AA value is about a factor of 2 higher for blind calculations compared to semi-blind calculations. The situation is somewhat better for surface temperatures, although the deviations of the surface temperatures are quite high. It has to be pointed out though that only few results are compared here and these may not be representative. However, the possible influence of pyrolysis rate is evident.

There have been some discussions on the Benchmark process and the calculational procedure. With the process used in this project, blind calculations performed with various additional input parameters estimated separately by each participant, it is not possible to identify the reasons for the discrepancies between calculations and experimental data. Anyway, this shows the effect of unknown boundary conditions as is also the case for real applications. Additionally, real applications are usually more complex. Therefore, an additional uncertainty factor (about 2) has to be added to the existing model uncertainty under known boundary conditions.

Pyrolysis Rate

There is some additional uncertainty on the measured pyrolysis rate. Therefore, the results have been compared only up to 800 s. Fig. 2-29 shows the comparison of measured burned fuel mass rates for Tests 1 and 3. In the initial phase, the pyrolysis rate is slightly higher in Test 3. Later, the trend is reversed due to the lower oxygen concentration.

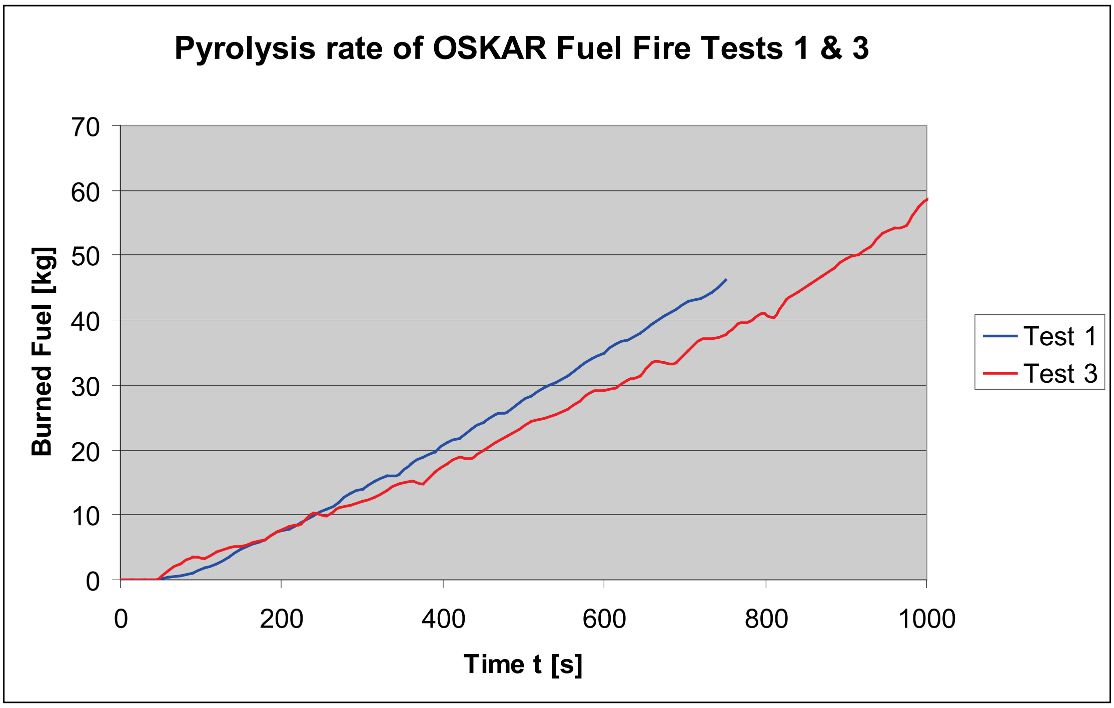


Fig. 2-29 Measured burned fuel mass of Benchmark Exercise No. 4, Tests 1 and 3

Atmospheric Gas Temperature and Shift of the Plume

In the following section the temperature predictions at the measurement level 2 are compared with the experiment. The main focus will be on the temperature distribution between the front side close to the opening and the backside of the compartment. The results are compared at about 600 s (see to analyze the shift of the plume the temperature distribution at level 2 is considered. The temperature difference M12 – M11 between backside and front side is somewhat larger for Test 1 compared to Test 3. The JASMINE calculations show a strong temperature difference between M12 and M14 for both tests. This indicates a strong shift of the fire plume, which was not found in the experiments. For all other CFD calculations the distribution seems to be more homogeneous compared to that of the experiment. However, most of the results concerning temperature distribution are within in range of uncertainty of the measurement data. The lumped parameter code COCOSYS does not use the momentum balance. Therefore, this code is not able to calculate a plume shift. Due to the higher oxygen concentration close to the opening, the front side temperatures are even higher (Tab. 2-13).) Only semi-blind and open calculations are considered.

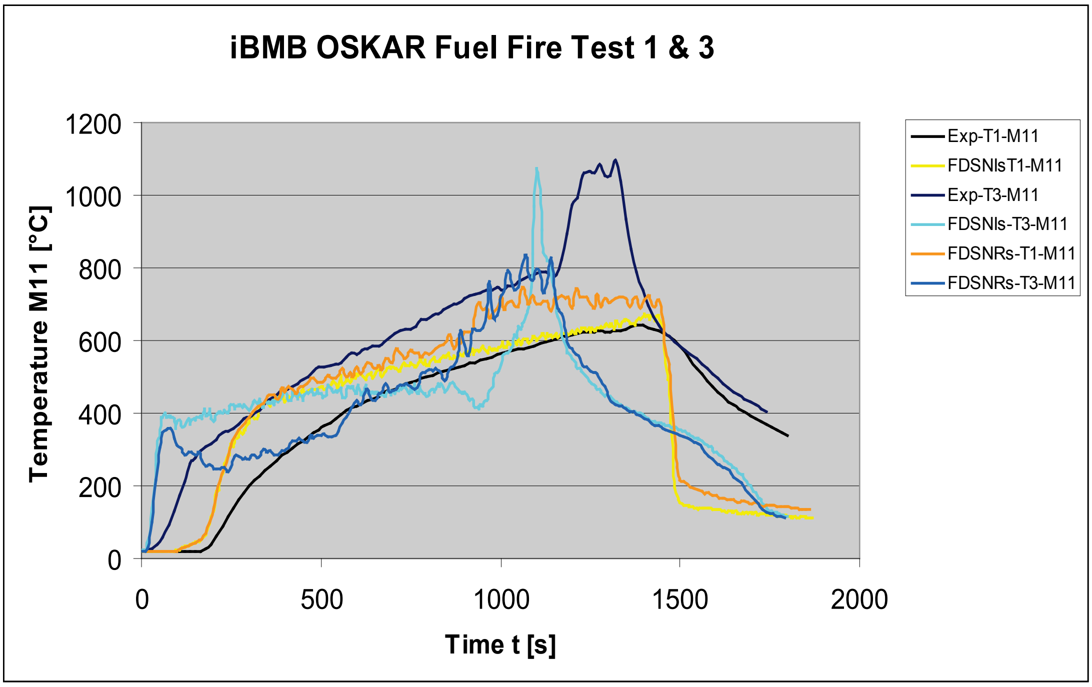
To analyze the shift of the plume the temperature distribution at level 2 is considered. The temperature difference M12 – M11 between backside and front side is somewhat larger for Test 1 compared to Test 3. The JASMINE calculations show a strong temperature difference between M12 and M14 for both tests. This indicates a strong shift of the fire plume, which was not found in the experiments. For all other CFD calculations the distribution seems to be more homogeneous compared to that of the experiment. However, most of the results concerning temperature distribution are within in range of uncertainty of the measurement data. The lumped parameter code COCOSYS does not use the momentum balance. Therefore, this code is not able to calculate a plume shift. Due to the higher oxygen concentration close to the opening, the front side temperatures are even higher.

Tab. 2-13 Temperatures M11 - M14 at about 600 s for Benchmark Exercise No. 4

Test 1							
Code	**M11**	**M12**	**ΔM12-11**	**M13**	**ΔM13-11**	**M14**	**ΔM14-11**
Exp	415	592	177	459	44	583	168
FDSNIs	507	618	111	483	-24	631	124
FDSNRs	527	584	57	503	-24	535	8
JASBRs	430	801	371	442	12	426	-4
CFXGRo	510	653	143	567	57	549	39
COCGRo	661	578	-83	630	-31	593	-68
Test 3							
Code	**M11**	**M12**	**ΔM12-11**	**M13**	**ΔM13-11**	**M14**	**ΔM14-11**
Exp	560	682	122	571	11	620	60
FDSNIs	461	532	71	464	3	551	90
FDSNRs	432	425	-7	425	-7	486	54
JASBRs	525	782	257	525	0	591	66
CFXGRo	577	564	-13	553	-24	584	7
VULSAo	599	620	21	-	-	-	-
FDSGRo	533	601	68	545	12	525	-8
JASBRo	458	742	284	464	6	475	17
COCGRo	555	489	-66	537	-18	533	-22

To analyze the shift of the plume the temperature distribution at level 2 is considered. The temperature difference M12 – M11 between backside and front side is somewhat larger for Test 1 compared to Test 3. The JASMINE calculations show a strong temperature difference between M12 and M14 for both tests. This indicates a strong shift of the fire plume, which was not found in the experiments. For all other CFD calculations the distribution seems to be more homogeneous compared to that of the experiment. However, most of the results concerning temperature distribution are within in range of uncertainty of the measurement data. The lumped parameter code COCOSYS does not use the momentum balance. Therefore, this code is not able to calculate a plume shift. Due to the higher oxygen concentration close to the opening, the front side temperatures are even higher.

Tab. 2-13 indicates that both semi-blind FDS calculations at about 600 s indicate lower temperatures for Test 3 compared to Test 1. This is underlined in Fig. 2-30 indicating that the continuous temperature increase in Test 3 is not well reproduced. This figure underscores that it is important not to just analyze peak temperatures only. It is necessary to evaluate the time characteristic of the results too, because possible fire propagation strongly depends on the time characteristic of the thermo dynamics inside the fire compartment.



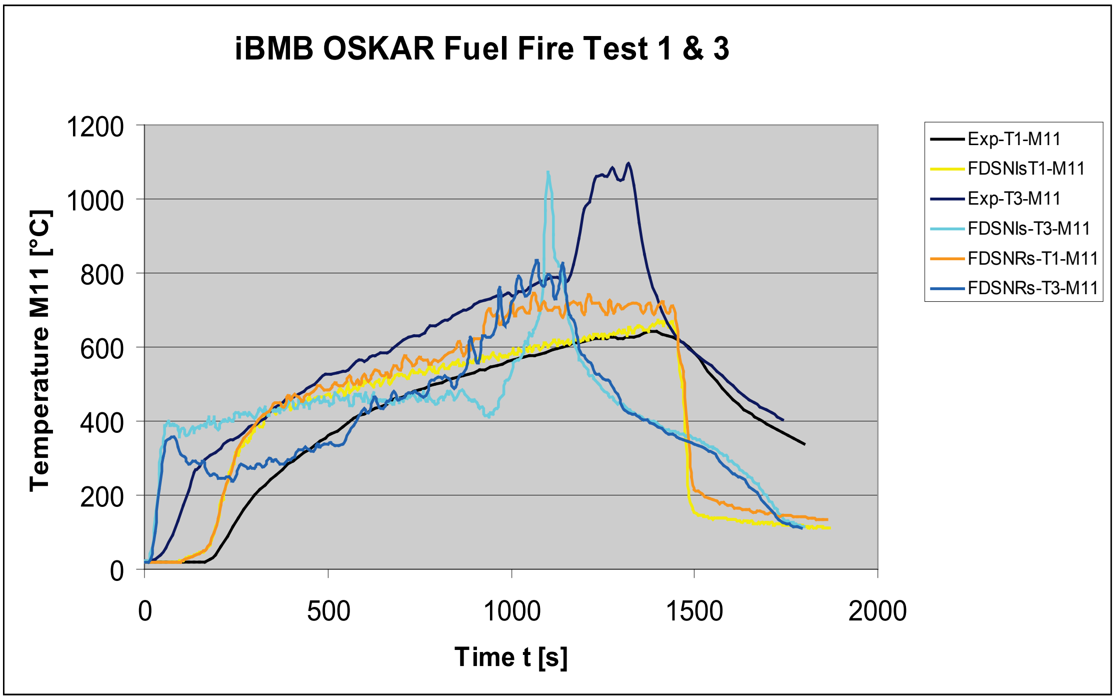


Fig. 2-30 Comparison of atmospheric temperatures between Benchmark Exercise No. 4, Tests 1 and 3

Oxygen Concentration

Key parameters for the oxygen concentration inside the fire compartment are the combustion efficiency, the ventilation conditions, and the reaction schemes modeled, particularly for CO and soot production. Here, Test 3 gives some answers for the specification of the LOL value, which should be set to 0 Vol.-%. The results for Test 3 have not really improved in the open calculations compared to the semi-blind ones. This indicates the difficulties in simulating under-ventilated conditions. This indicates possible difficulties to simulate under-ventilated boundary conditions (see Fig. 2-31).

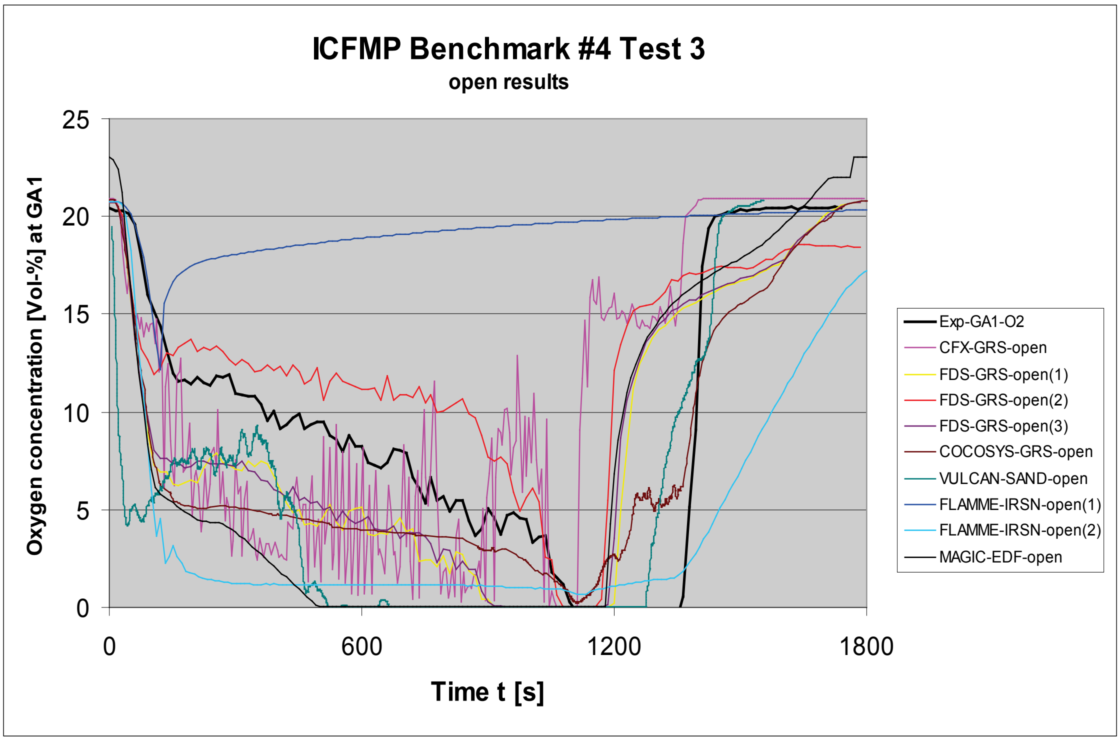


Fig. 2-31 Comparison of open calculations for oxygen concentration in Benchmark Exercise No. 4, Test 3

Target Simulation

One of the main tasks of fire simulation for NPP fire safety analysis is the calculation of thermal loads to different types of target. First it has to be pointed out, that not all codes are able to simulate more complex targets like the barrel container. Most of the participants analyzed the material probes only, and often only the surface temperature was delivered. For this reason the surface temperatures M29, M33 and M34 are only considered here.

Based on the FFT analysis it is seen that the deviations of some code are larger for Test 1. As an example, the results for the surface temperature at the concrete type material probe are repeated here to obtain an understanding about the possible deviations (see Fig. 2-32).

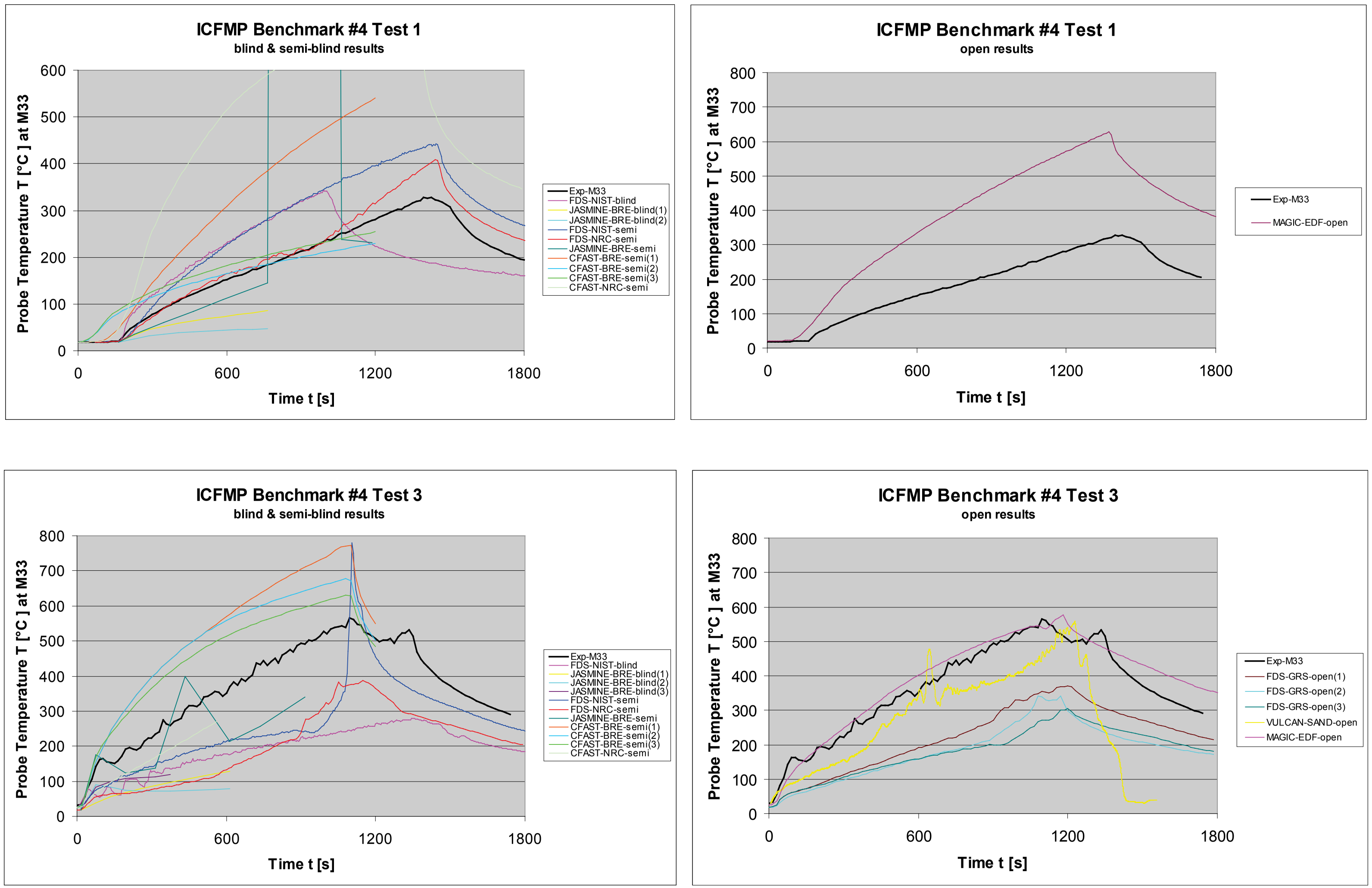


Fig. 2-32 Comparison of the concrete surface temperature M33 for Benchmark Exercise No. 4, Tests 1 and 3

2.4.5 Conclusions

The fuel pool fire Tests 1 and 3, performed in the OSKAR test facility at iBMB, University of Braunschweig - Institute of Technology at the end of 2003, have been included in the benchmarking and validation exercises of the International Collaborative Fire Model Project as Exercise No. 4. The main difference between the two experiments carried out is the size of the door area. Both experiments give first indications on the effects of ventilation and fuel controlled fires as well as on the thermal loading on different types of targets. Previous Benchmark Exercises within the ICFMP had shown that the simulation of these two phenomena should be improved.

During the Benchmark procedure, the participants performed different types of calculations. These were totally blind simulations without knowledge of any of the measurements, semi-blind calculations with knowledge of the pyrolysis rate only, and completely open calculations with knowledge of all experimental results. It has been demonstrated that the pyrolysis rate has a strong influence on the calculation results. Limited information on the pyrolysis rate affects the results to some extent. This finding was supported from the comparison of the (admittedly few) blind and semi-blind simulations. This overall result of Benchmark Exercise No. 4 should be somehow considered in the estimation of uncertainty parameters as an input in, for example, PSA studies.

The simulation of under-ventilated fires is more difficult for the fire codes. In particular, the high transient behavior at the final phase of Test 3 leads to a wide range of simulation results. Unfortunately, the measured pyrolysis rate is no longer valid in this phase, and so the ‘specified’ pyrolysis rate may not be reliable at this time. It should be mentioned, however, that many of the possible fire scenarios in real nuclear power plants will lead to under-ventilated conditions. Therefore, this issue should be further investigated and the models should be further improved.

Some codes have difficulty in simulating more complex targets. Most of the codes are able to simulate the material probes. The range of the results is larger compared to that for the gas temperatures. As this information is significant for estimating failures of safety related equipment, the models should be further developed and enhanced.

2.5 Benchmark Exercise No. 5

This chapter represents the summary of the ICFMP Benchmark Exercise No. 5: Flame Spread in Cable Tray Fires. Four full-scale cable tray fire experiments, carried out at iBMB, University of Braunschweig – Institute of Technology, were used. Detailed information about the specification, the experimental results and the results of the calculations that have been performed are provided in /RIE 06/. Benchmark Exercise No. 5 has considered the results of cable fire experiments with different types of cables, carried out in support of various projects for the German authorities as well as for nuclear industry in the past /HOS 98/ and /HOS 03/.

2.5.1 Specific Objectives

A major objective of the actual cable fire experimental series was the investigation of the effects of a naturally ventilated fire on vertically routed (worst case) bundled power and I&C (*i*nstrumentation & *c*ontrol) cables with different cable insulation materials (PVC (*p*oly*v*inyl *c*hloride) and FRNC (*f*ire *r*etardant *n*on-*c*orrosive)). PVC and FRNC cables are frequently used in German nuclear power plants and also represent standard cables in other NPP worldwide PVC cable insulation is chemically a thermoplastic and a typical FRNC cable insulation is a thermosetting material. It has been found /HOS 03/ that pre-heating of a cable could have strong effects on its fire behavior. Therefore pre-heating effects have been investigated in Benchmark Exercise No. 5. Four experiments have been performed, two tests with FRNC cables (Test 1 without pre-heating and Test 2 with pre-heating) and two tests with PVC cables (Test 3 without pre-heating and Test 4 with pre-heating).

The measured data from the experiments are the basis for fire simulations by the institutions from different countries participating in the ICFMP. Four different fire models have been examined: CFAST, COCOSYS, FDS and CFX. The list of calculations performed is given in Tab. 2-14. A major question for Benchmark Exercise No. 5 was whether the state of the art computational fire codes are able to predict the pyrolysis process, and in consequence the flame spread, of burning cable bundles in a given fire scenario.

Tab. 2-14 Models used for Benchmark Exercise No. 5

Model Type	Code	Code Version	Modeler (Institution)	Blind (b), Open (o) Calculation	Tests Calculated
Zone	CFAST	3.1.7	M. Dey (NRC/NIST)	o[1]	Test 4
Lumped Parameter	COCOSYS	2.2dev	W. Klein-Heßling (GRS)	b o	Test 1, Test 3 Test 1 - Test 4
CFD	CFX	10.0	M. Heitsch (GRS)	o	Test 1
	FDS	4.0	K. McGrattan (NIST)	b, o	Test 1 - Test 4
		3.1.5	M. Dey (NRC/NIST)	o[1]	Test 4

[1] open calculation: Tests are simulated only for the first 20 minutes (phase of pre-heating)

Another important aspect of cable fires in nuclear power plants is the risk of functional failures. Therefore within these tests short circuits as well as the loss of conductivity of the cables have been measured.

2.5.2 Problem Specification

The four cable fire experiments have been carried out in a special fire compartment (iBMB test facility, see Fig. 2-33) with an inner floor area of 3.6 m x 3.6 m = 12.96 m². The inner compartment height is 5.6 m, giving a compartment volume of 72.6 m³ respectively. Note that the same test facility has been used for Benchmark Exercise No. 4. The air exchange takes place through an opening of 0.7 m width and 3.6 m height, which is reduced by a wall of 1.4 m height to an area of approx. 1.5 m². Smoke gases released are collected in a hood with an exhaust duct located over the opening and leading to a smoke gas cleaning system. The gases are analyzed according to ISO 9705 /ISO 93/ and the heat release rate has been derived.

In case of pre-heating a pool fire of 0.5 m² pool area, filled with ethanol, has provided the primary pilot fire. During the phase of pre-heating a maximum gas temperature of 200 °C has been measured close to the surface of the cables. For measuring the mass loss rate of the liquid pool, the pan has been mounted on a weight scale.

The cable tray is directly ignited / inflamed by means of a propane gas burner. In the case of FRNC cables 150 kW output power and in the case of PVC cables 50 kW output power has been used. In case of pre-heating (Test 2 and Test 4) the ignition burner is activated after 1200 s. The pre-fabricated 4 m height trays filled with bundled cables are mounted on a weight scale. Fig. 2-34 shows a diagram of a vertical tray with two bundles (left side) and (right side) the positions for the temperature measurements on the surface and in the center of the cables (T, two positions each, at 9 levels), and the position of the heat flux (WS, 5 levels) and the function loss measurements (FL) at 12 individual cable conductors from cables at the right and left side of the both cable bundles.

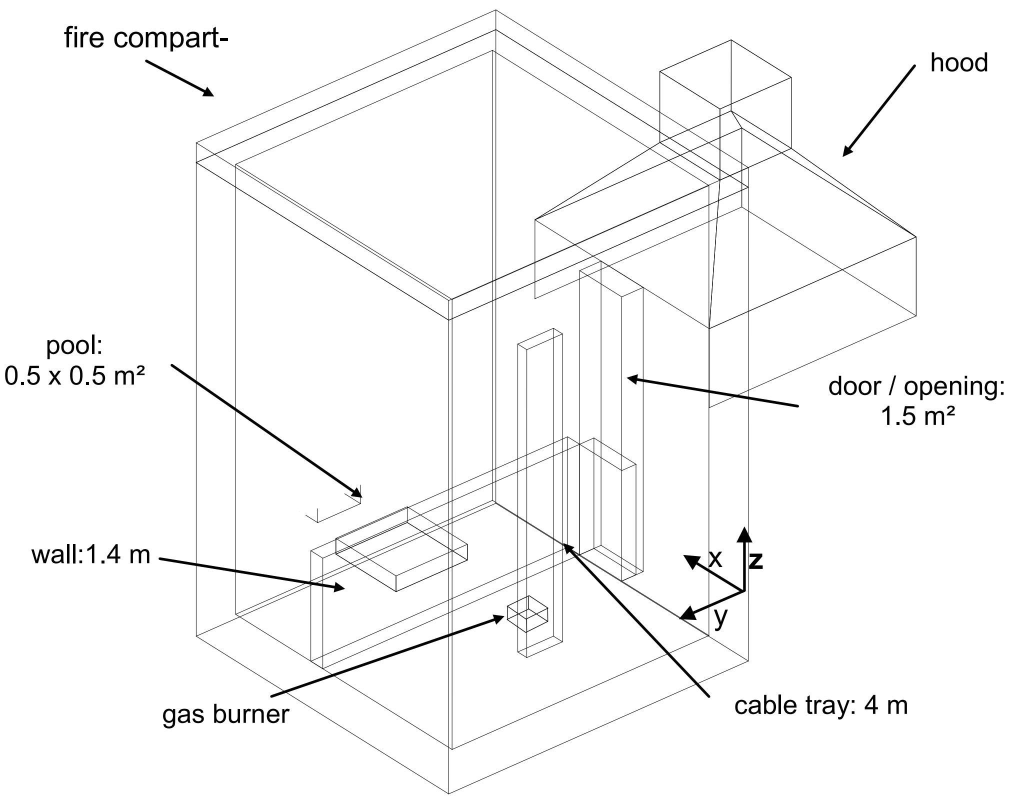


Fig. 2-33 Top view of the fire compartment for the Benchmark Exercise No. 5 cable fire tests (iBMB test facility)

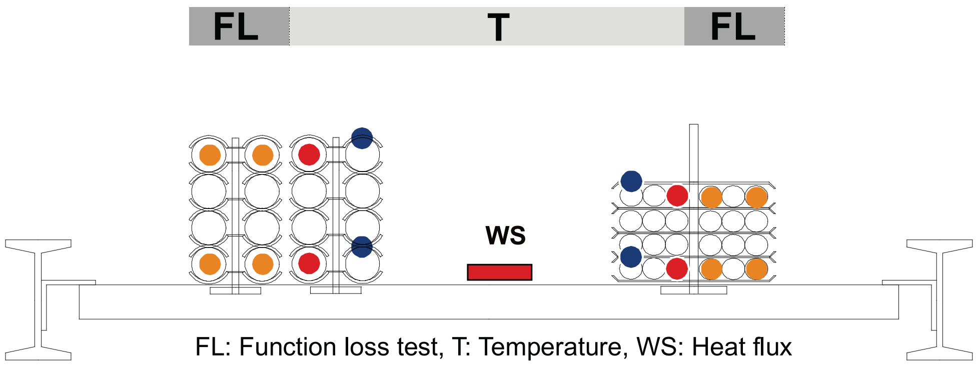


Fig. 2-34 Vertical cable tray: Cross section of two cable bundles on the tray, left: power cables, right: I&C cables and measurement points

During Benchmark Exercise No. 5 intensive work has been done to provide modelers with thermo-physical input data for the cables. Different types of tests have been performed, but specially Cone-Calorimeter experiments. The critical heat flux, ignition temperature, effective heat of combustion, density, thermal conductivity and specific heat values are given for the sheath insulation material. For the heat of gasification only an effective value could be derived from Cone-Calorimeter data.

2.5.3 Results

Experiments

A brief overview over the results from the Benchmark Exercise No. 5 test series is given in the next two figures. The HRR from Test 1 (FRNC, without pre-heating) and Test 2 (FRNC, with pre-heating) and the corresponding ignition burner power output are shown in Fig. 2-35 and for Test 3 (PVC, without pre-heating) and Test 4 (PVC, with pre-heating) in Fig. 2-36, accordingly. The pre-heating times from Test 2 and Test 4 of 1200 s are neglected in the figures for comparison. The heat release rate resulting from the combustible material is low in the case of FRNC insulation material (see Fig. 2-35). In case of pre-heating, slightly higher values are observed, with a maximum of up to 100 kW. An increase of the burner output of up to 300 kW after 1800 s (Test 2) and 2400 s (Test 1), respectively, have no significant effects on the HRR. In case of PVC insulation material (see Fig. 2-36, Test 3), the cables (power cables as well as I&C cables) ignited after a short time and a heat release rate with a peak at 330 kW after approx. 720 s (12 min). In case of Test 4 (see Fig. 2-36) with pre-heated cables, the I&C cables ignited notably later and the power cables could not be ignited with a 50 kW burner power output. As a consequence of increasing the burner capacity to up to 100 kW after approx. 900 s (15 min), the power cables ignited and a second peak heat release rate at 200 kW was found.

The tests show that the FRNC insulated cables have significantly better characteristics in case of fire. No substantial flame spread takes place in Test 1, even in case of pre-heating up to 200 °C in the vicinity of the cables in Test 2. While PVC insulated cables could be ignited with a burner output of 50 kW, for FRNC cables a burner output of 150 kW was necessary.

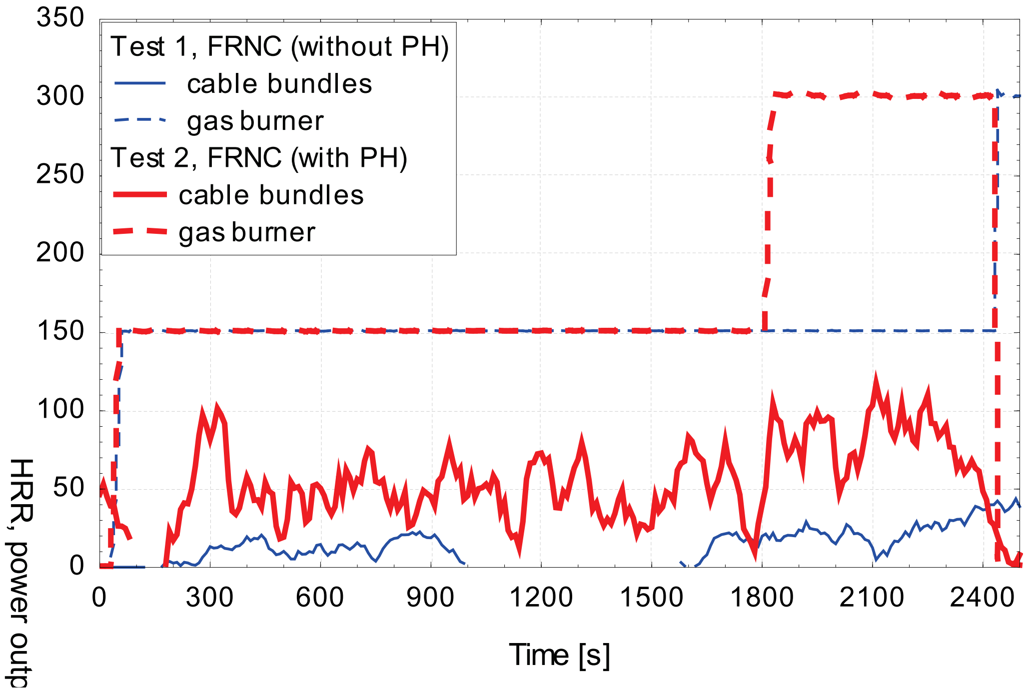


Fig. 2-35 Heat release rate (HRR) of FRNC cable bundles and gas burner power output for Benchmark Exercise No. 5, Tests 1 and 2, with and without pre-heating (PH)

In Test 3, a continuous average flame spread rate from 40 cm/min over the length of the cable tray has been derived from the experimental data for I&C cables. In Test 4 (PVC, with pre-heating) the power cables could not ignited with 50 kW power output from the gas burner, but could with 100 kW. It has been concluded that it is difficult to interpret the influence of pre-heating on ignition and flame spread.

The test series indicate that the burning behavior of a pre-heated PVC cable is similar to that of an aged PVC cable. If a flammable cable is pre-heated then plasticizers could emit from the cable, a process which normally leads to better fire characteristics.

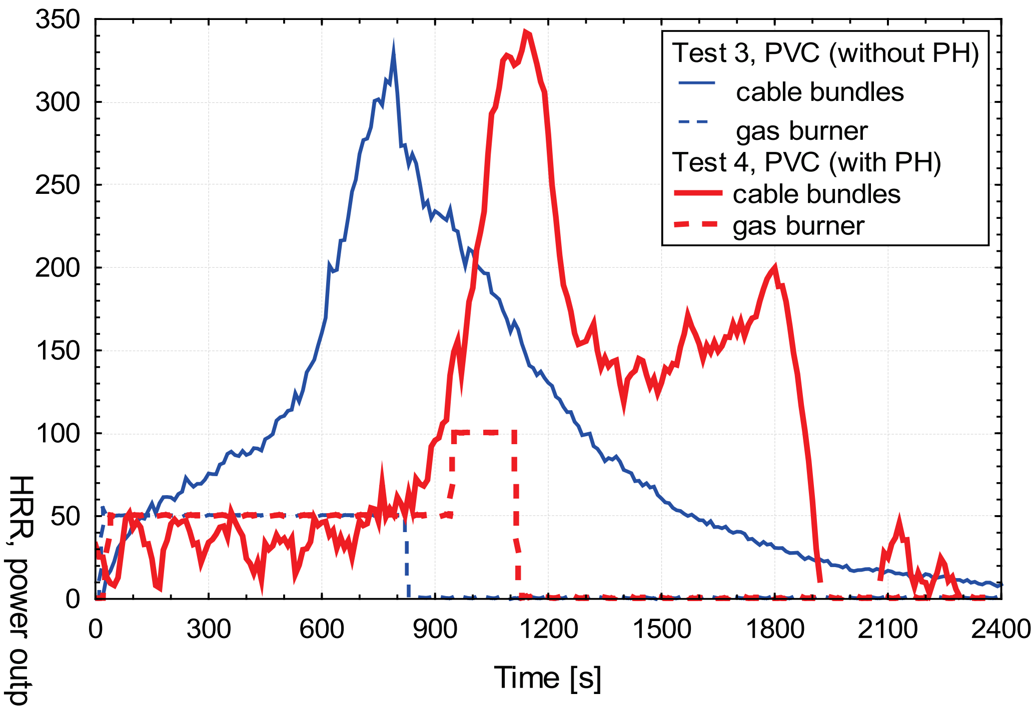


Fig. 2-36 Heat release rate (HRR) of PVC cable bundles and gas burner power output for Benchmark Exercise No. 5, Tests 3 and 4, with and without pre-heating (PH)

Function Loss Tests

Short circuits occur first as 'conductor to conductor' shorts and later as 'conductor to tray' shorts (shorts to ground). The time period until short circuits occur strongly depends on the pre-heating of the cables. Without pre-heating, the short circuit times are a factor of two higher than in case of pre-heating. In one case with pre-heating PVC insulated I&C cables failed after only 100 s. The average time to loss of function of PVC insulated I&C cables with pre-heating, according to the experiments, is approx. 220 s. The short circuit times of power cables are nearly two times higher than those of I&C cables and are independent of the cable insulation material. FRNC insulated cables show better characteristics in all tests and are ignited with a substantially higher burner output as mentioned above. For further details see /RIE 06/

Calculations

In Tab. 2-15 details about the different fire models used in Benchmark Exercise No. 5 are given. Blind and open calculations have been performed. On the basis of the results from the blind calculations the COCOSYS code has been enhanced in two respects:

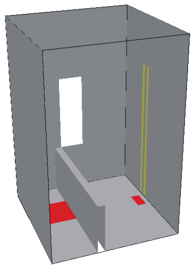
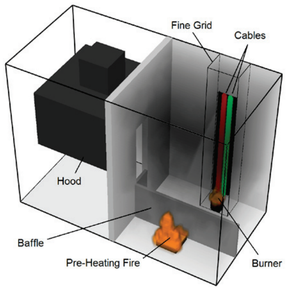
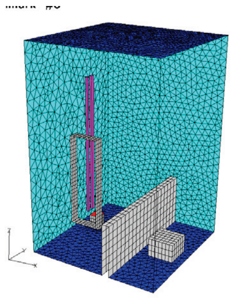
- The heat transfer into the cables close to the burner has been improved,
- A remaining mass fraction for incomplete burn down of cables has been introduced.

In the other fire models no changes in the code have been made in the versions that have been used.

Additional calculations have been performed by M. Dey (NRC/NIST) with FDS (CFD) and CFAST (zone model). These calculations are restricted to Test 4 (PVC insulated cables) and only the time of pre-heating (first 1200 s) has been considered. The calculations have been used to study the performance of the two codes considering a scenario of an ethanol pool fire. Because this work was not conducted with the intention to study flame spread phenomena it will not be discussed in this summary. Nevertheless, this work does give information about the performance of two models if the heat release rate is given.

In Fig. 2-37 the measured pyrolysis rate of the cables (MLR_Cables), the input (CFX, COCOSYS) and the calculated MLR_Cables (FDS) for Test 1 (FRNC, no pre-heating) is shown as an example for the 'results' of the open calculations. In this context, note that only FDS has a sub-model to predict the pyrolysis rate of a burning object. Fig. 2-38 shows the measured and the calculated surface temperature of the I&C cables at the cable tray at 1.5 m height (2 m above the compartment ground) again for Test 1.

Tab. 2-15 Details on the different fire models used in Benchmark Exercise No. 5 regarding the pyrolysis rate for modeling flame spread on a cable tray

Model Type	**Lumped Parameter**	**CFD**	
Code **Code Type**	**COCOSYS** **2.2 developer version**	**FDS 4.0**	**CFX 10.0**
Modeler (Institution)	W. Klein-Heßling (GRS)	K. McGrattan (NIST)	M. Heitsch (GRS)
			
Cable bundle	one rectangular slab without core	one rectangular slab without core	one rectangular slab with metal core
Thermal model cable slab	1-dimensional (only side of burner)	1-dimensional (all sides independent)	3-dimensional
Pyrolysis model	empirical data	finite rate	experimental data
Calculation of pyrolysis rate	pyrolysis rates for different material temperatures derived from database	pyrolysis rate in the environment of a given ignition temperature is calculated with an Arrhenius law (thermoplastic model)	a fixed pyrolysis rate is used, when a given ignition temperature is reached at one point at the cable slab
Data (input)	pyrolysis rates at different material temperatures are derived from different (older) tests in the same facility	thermal properties, heat of gasification and ignition temperature from given Cone Calorimeter data	pyrolysis rate from test results of Benchmark Exercise No. 5
Possibility of prediction	in principle	yes	No

Model Type	**Lumped Parameter**	**CFD**	
Code **Code Type**	**COCOSYS 2.2 developer version**	**FDS 4.0**	**CFX 10.0**
Modeler (Institution)	W. Klein-Heßling (GRS)	K. McGrattan (NIST)	M. Heitsch (GRS)
Performance of prediction of pyrolysis rate for PVC and FRNC cables	PVC: pyrolysis rate is 'calculated' in acceptable agreement; FRNC: pyrolysis rate is 'calculated' extremely high (for open calculations it is set to zero)	PVC: pyrolysis rate too low; FRNC: pyrolysis rate too high	(pyrolysis rate is given as input)
Performance of prediction of surface temperature	PVC: results are acceptable for such kind of calculation; FRNC: great differences	behavior of a thermoplastic material, if pyrolysis takes place; the material burns nearly at a given ignition temperature	FRNC: temperatures in the near field of the ignition burner comparable, in the far field too low
Remark:	universality of the database is not proven	the only model with a 'real' pyrolysis model included	only Test 1 has been simulated

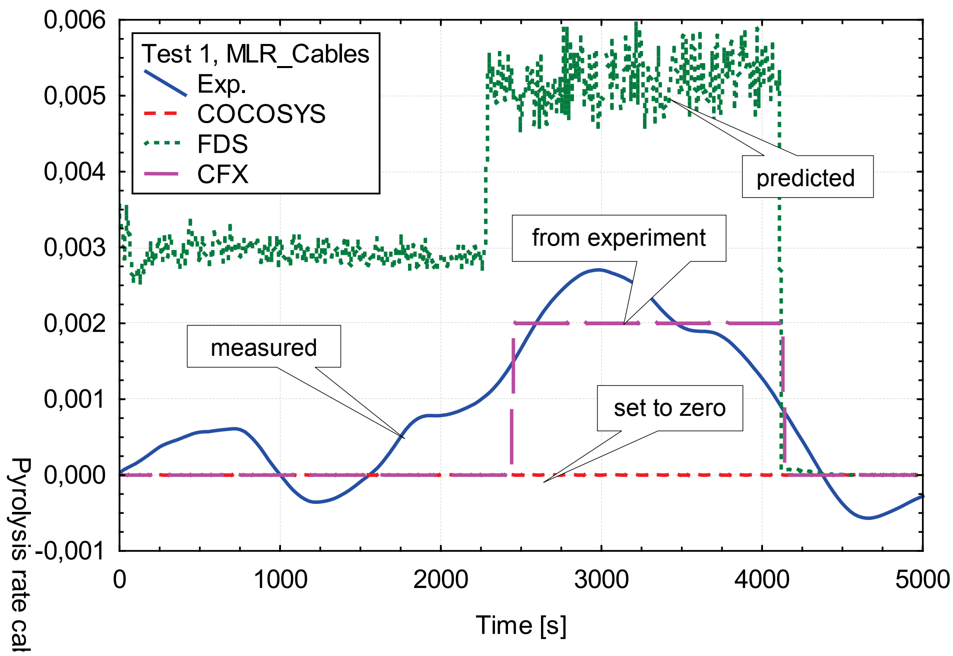


Fig. 2-37 FRNC cables pyrolysis rates (MLR_Cables) for Benchmark Exercise No. 5, Test 1 – comparison of experimental data, input data and code calculations

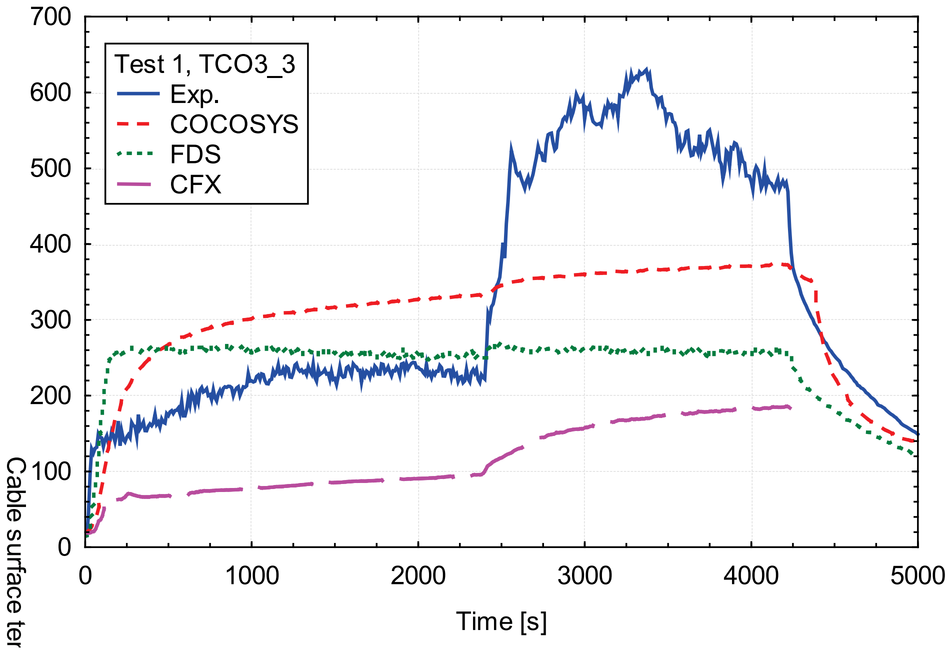


Fig. 2-38 FRNC I&C cable surface temperatures (TCO3_3) for Benchmark Exercise No. 5, Test 1 - comparison of measured data and calculation results

In FDS a thermoplastic pyrolysis model has been deployed and the specified thermophysical data derived from experimental Cone Calorimeter measurements have been used as input. In the model, nothing accounts for charring or for the lateral heat conduction in the metal core. Furthermore, the complex cable bundle structure must be replaced with a rectangular slab because of the structure of the underlying numerical grid. The thickness of the solid is not fixed to the gas phase grid, only the exposed surface area. The calculated gas temperatures in the direct environment of the cable tray are in a good agreement with the experimental data. But the calculated heat fluxes did not follow the experimental results and are notably too low (see Fig. 2-39, Test 2, upper one). The predicted pyrolysis rates are slightly too high in the case of FRNC cables (Test 1 and Test 2) and too low in case of PVC cables (Test 3 and Test 4). If pyrolysis takes place the material starts burning nearly at a given ignition temperature. This is the effect of the use of a thermoplastic model. In this case the predicted cable surface temperatures did not follow the experimatal data (see Fig. 2-39, Test 3, lower one).

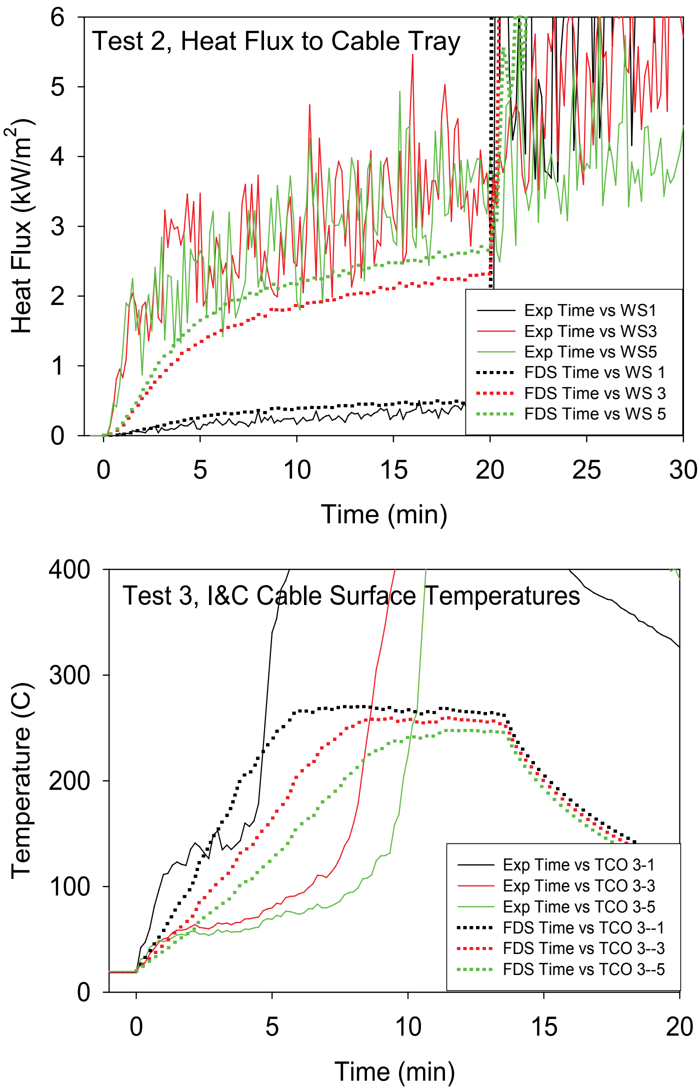


Fig. 2-39 FDS predictions for Benchmark Exercise No. 5 - Heat flux to cable tray (Test 2, left side), PVC I&C cable surface temperatures (Test 3, right side)

In COCOSYS, an empirical approach has been chosen to calculate the heat release rate and the flame spread of a given cable tray fire scenario. The model uses a specified pyrolysis rate for the cables, represented also by a rectangular slab. The propagation velocity depends on the assigned surrounding temperature of the target. A database for this property was derived from earlier experimental results, obtained in the same compartment under similar conditions. During the ICFMP Benchmark calculations, the COCOSYS code was further developed in various respects. The heat transfer into the cables works considerably better now.

The calculated cable surface temperatues are in a good agreement with the experimental data (see Fig. 2-40) in the open calculations (blue curves). Some problems still exist concerning the stability in those zones close to the vertical trays. This problem has to be solved in the future.

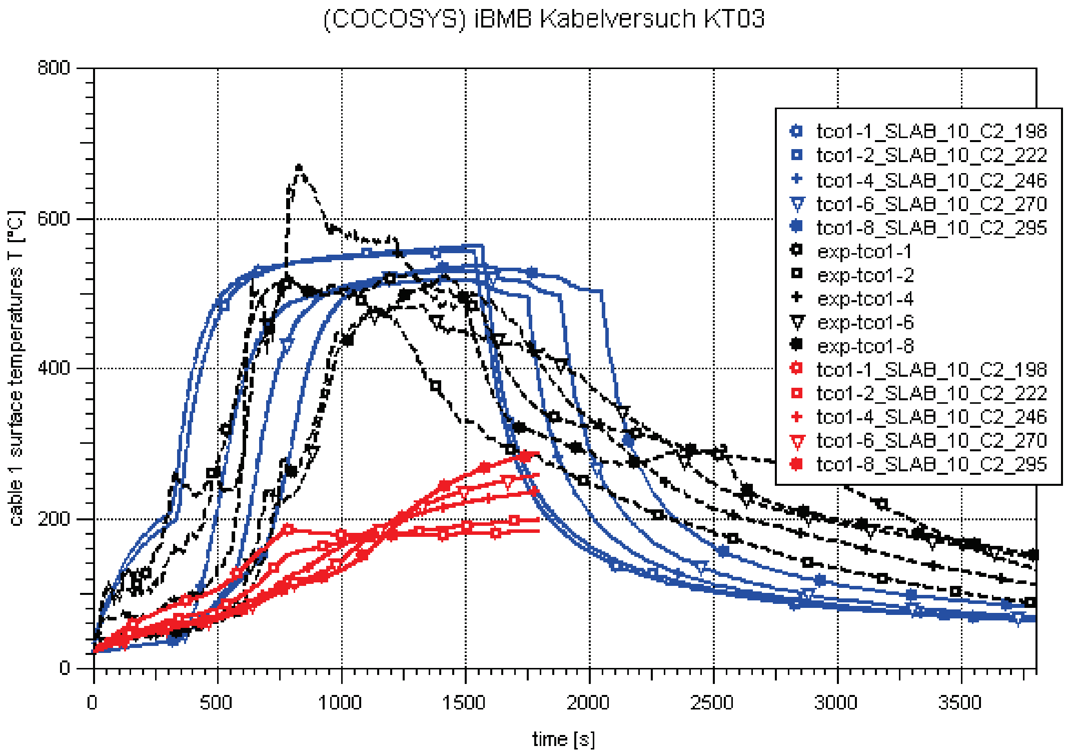


Fig. 2-40 COCOSYS (2.2dev) predictions for Benchmark Exercise No. 5, Test 3 - PVC power cable surface temperatures

In CFX, while no pyrolysis model is included, the basic elements for checking the ignition temperature at each boundary cell of a solid does exist, and this can be coupled to a specified pyrolysis rate. The work to build up such a model has been started but is not yet finished. Because of some problems with this approach only Test 1 of Benchmark Exercise No. 5 has been calculated. The exercise to model a burning cable has therefore been simplified in that a constant pyrolysis rate (from the experimental data) is initiated once the ignition temperature at any one of the CFD cells at the cable bundle is reached. The calculated gas temperatures are in better agreement with the experimental data in the direct environment of the cables for the first level of the gas burner with 150 kW power output. However, the predicted gas temperatures are too low for the second phase with 300 kW power output (see Fig. 2-41).

In consequence, the resulting surface temperatures of the cables do not follow the experimental data in this phase of the burner output. The original task of Benchmark Exercise No. 5 was to predict the pyrolysis and not to prescribe it. For the future it will be of great interest if sub-tools for modeling the pyrolysis of a complex cable can work in a more sufficient way.

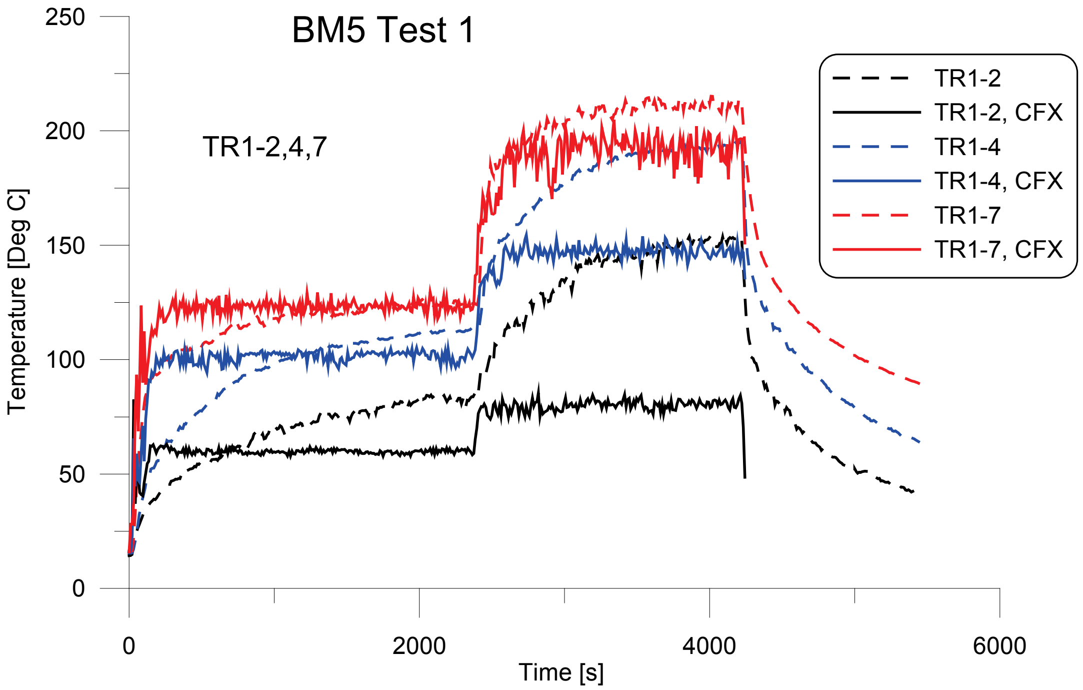


Fig. 2-41 CFX 10.0 predictions for Benchmark Exercise No. 5, Test 1 - Calculated gas temperatures in the room

2.5.4 Discussion

It should be noted that most of the codes could predict the main quantities such as gas temperature, heat flux, gas velocity, etc. reasonably well provided the heat release rate from the fire is given and the fire scenario is not too complex. This has been demonstrated in the other ICFMP Benchmark Exercises /DEY 02/, /KLE 06/, and /MCG 07/. However, to predict the HRR and flame spread for a given application, such as in Benchmark Exercise No. 5, is a completely different task.

It is very difficult to predict HRR and flame spread on complex fire sources such as cables. As a first step, it would be useful to model a complex object as a collection of smaller ones, each having properties similar to the solid material.

Cable bundles could be treated as a collection of small cylinders, for which the interaction with each other would be almost completely separate from the gas phase grid. As there are no standards to derive thermo-physical data from a set of Cone Calorimeter tests, it will be necessary to have clear guidelines for the procedure for determining such data.

2.5.5 Conclusions

At the time being, none of the codes applied in Benchmark Exercise No. 5 for calculating the ignition, pyrolysis and flame spread of realistically routed cables work at a level such that it is possible to use them as a reliable predictive tool for predicting such phenomena. It is obvious that there is a need for the development and enhancement of sub-models for pyrolysis.

Because of continued flame spread, the data of Test 3 (PVC, no pre-heating) are particularly appropriate for the validation of fire spread models. The pyrolysis models have to demonstrate that they can predict the results of Test 1 as well as those of Test 2, because no flame spread occurs in the case of FRNC cables. This may indicate that a computer code, which just performs well if flame spread occurs, may not be suitable to handle complex materials.

For a development of pyrolysis models for cables more small-scale cable fire experiments have to be performed and only one parameter should change per test. Preheating effects, different insulation materials, orientation, all play an important role in a realistic cable fire.

Benchmark Exercise No. 5 also shows that the input parameters for a pyrolysis model are highly sensitive, since a model will work only with the correct thermo-physical data for the material used. Up to now, there are no set rules on how to measure the different properties, such as heat of gasification, ignition temperature and heat of combustion.

Because of the complexity in developing a complete deterministic flame spread model for cables there is a need for further measurement of empirical data for fire spread (pyrolysis growth) on complex items, e.g. cable trays.

3 Discussion

3.1 Project Accomplishment and Participants Perspectives

Since commencing in October 1999, the project has made significant progress towards achieving its original goals. For Phase I the primary objective was to examine the capability of current numerical fire models by means of a series of Benchmark Exercises conducted by participating organizations, and this has now been completed with some success. A broad selection of representative fire models has been examined, ranging from hand-calculations and spreadsheet applications, through zone and lumped-parameter models to the most computationally demanding, namely CFD. While participants were from Europe and the United States only, they came from diverse backgrounds, ranging from fire engineering students, consulting firms, public bodies to the code developers themselves.

A wide range of scenarios have been examined in the five Benchmark Exercises, ranging from relatively small rooms to a turbine hall size enclosure, and from simple box-like geometries to more complex examples with multiple compartments or sloping roofs. Local as well as fully-developed (post-flashover) fires have been included, and in some cases the fires have been ventilation controlled. Natural and mechanical ventilation has been studied.

A combination of blind, semi-blind and open calculations have been conducted to help verify and validate the selected fire models and fire modeling approaches for the range of scenarios investigated. This has contributed to the verification and validation process for the different fire modeling approaches (zone, CFD, etc.). Conclusions have been drawn regarding where fire models can reliably be used, and also where more caution is required. In depth analysis of the results from the Benchmark Exercises has allowed the strengths and weaknesses of the current generation of fire models to be reviewed, and to identify where further advances are required. The work has laid the foundation for the generation of guidance on the use and interpretation of fire models for nuclear power plant applications.

The results of the ICFMP have identified a range of phenomena which all types of fire models can be expected to predict with some reasonable degree of accuracy.

All models predicted, with some confidence, hot gas layer temperature and depth, once the fire power and boundary heat losses were properly accounted for, and where the fire was well ventilated and the geometry not overly complex, e.g. in the near-sealed upper deck turbine hall case in Benchmark Exercise No. 2. Oxygen depletion, i.e. the onset of conditions where combustion is likely to cease due to a lack of oxygen, was similarly reasonably well predicted by the range of fire models investigated. Vent flow through vertical openings, e.g. doors, was as expected a straightforward task in most cases.

It has been demonstrated that zone models are able to account for irregular ceiling shapes provided the volume of the space is included appropriately and the layer depth interpreted correctly, e.g. in Benchmark Exercise No. 2. Although requiring some effort, mechanical ventilation was applied successfully in the application of zone models.

Cases where local three-dimensional effects are important, e.g. the maximum temperature under a ceiling where a fire plume impinges, could be predicted by CFD and, perhaps to a lesser extent, lumped-parameter models. Furthermore, while difficult for general two-layer zone models, post-flashover fire conditions could be reasonably modeled by CFD and lumped-parameter models, e.g. in Benchmark Exercise No. 4.

As important as clarifying where models can be reliably applied, is to identify where they are not currently suited, and the ICFMP has made important contributions here. Of particular relevance to nuclear power plants is the challenging task of predicting the response of cables and cable bundles subject to fire conditions, and ultimately to predict spread of fire along a cable or within a cable tray. Benchmark Exercise No. 5 demonstrated that this remains a challenge for existing cable and pyrolysis sub-models and that these models need improvement to provide more accurate predictions of cable fires. Nonetheless, an empirical based approach, using experimentally measured cable behavior information as an integral part of the fire model, may offer a short term solution. It should be noted that it is not only the thermal response and electrical failure of the cable that is difficult to predict, but also the modeling of the incident flux to the cable. The challenge of predicting thermal fluxes, and in particular radiation fluxes where the T^4 dependence makes the phenomena highly nonlinear, was shown to be a main area of uncertainly in fire modeling in all Benchmark Exercises.

While predicting the pyrolysis (burning rate) of cables is understandably a very difficult task calculating the pyrolysis of 'simpler' fuels such as hydrocarbon pools also proved a challenge. Fire models do not, in general, include a pyrolysis sub-model, and even where one is provided it is generally in a simple form and unlikely to be very accurate, as illustrated in Benchmark Exercise No. 4. The fundamental issues are the same as for cables, i.e. the heat transfer inside the fuel and the incident heat flux are both critical phenomena that are difficult to model with sufficient accuracy for pyrolysis and fire spread calculations.

Limitations peculiar to zone models were identified, e.g. predicting flows across horizontal vents as in the turbine hall example in Benchmark Exercise No. 2. Post-flashover fire conditions also posed a problem for the two-zone fire models investigated.

Some of the problems that can be encountered in verifying and validating fire models have been identified too. The process adopted in the Benchmark Exercises lent itself towards a qualitative verification and validation of the fire models. By contrast, the U.S. NRC Verification and Validation activity /NRC 07/ has adopted a more formal process, whereby all parameters and sub-model selection choices for the computer models were tightly specified, and the verification and validation was arguably more quantitative. However, the U.S. NRC exercise did not include blind calculations, which is an important contribution made by the ICFMP. Important lessons have been learned for future benchmarking and analysis.

The ICFMP has allowed modeling tasks and phenomena requiring further development to be identified. Perhaps most important here is the task of predicting the heating and failure of safety critical items such as cables. Ignition, pyrolysis and flame spread are also an important task for which model development is required. In both cases, the use of empirical measured data may provide a practical near term solution. Other modeling issues for which further research and development is required include natural flows through horizontal (e.g. ceiling) vents, in particular for zone models, the prediction of soot yields and radiation fluxes, and smoke flows between compartments via vents and ducts.

3.2 ICFMP Results from the Benchmark Exercises No. 1 to 5

The results from the five ICFMP Benchmark Exercises have provided important insights into the performance of the current generation of fire models for a wide range of nuclear power plant applications. The process of blind and open calculation has helped to identify the strengths and weaknesses of fire models in a robust and trustworthy way. Comparisons of calculation against experimental measurement, and also of calculation against calculation, have provided an important contribution to this process.

Section 2 of this Summary Report highlights the main results and findings for each Benchmark Exercise. Below the main uncertainties and parameter sensitivities are discussed.

3.2.1 Uncertainties

During the course of the ICFMP a number of phenomena and modeling parameters have been shown either to be inherently uncertain in nature or to lead to uncertainty in the predictions.

Throughout the ICFMP work the definition of the fire source arguably presented the biggest uncertainty. Not only are the fire dimensions and pyrolysis rate difficult to specify, but the physical processes of combustion efficiency, soot and toxic gas yields and radiative fraction also present challenges to the fire modeler. While it is in theory possible to model these phenomena, in practice they generally require ‘engineering judgment’.

For blind calculations the choice of the pyrolysis rate will obviously lead to uncertainties if the actual rate, subsequently used in open calculations, deviates to any significant extent from the value in the actual experiment. For a well controlled fire, e.g. as in Benchmark Exercise No. 3, this should ideally be only a second order uncertainty. For fire sources with less control, e.g. fuel pool, wood crib or other more complicated objects, the uncertainly introduced may be quite significant, as illustrated in Benchmark Exercise No. 4. However, even for the ‘simpler’ fire sources such as a spay burner there may be a notable deviation between prior estimation and actual value. For Benchmark Exercise No. 3 the actual pyrolysis (fuel supply) rate varied by as much as 15 %, which will have influenced the gas temperatures by as much as 10 %.

Other quantities may then be subject to even higher uncertainty, e.g. for radiation flux where the T^4 dependency is important. Errors in the processing of the experimental data to derive the fuel supply rate for the semi-blind and open calculations for Benchmark Exercise No. 3 illustrated further the significance of experimental uncertainties.

Soot yield and associated radiative fraction, as well as combustion efficiency, are also significant sources of uncertainty in both blind and open calculations. The soot yield and radiative source term are particularly important for calculating target response, and so there is a corresponding significant level of uncertainty in the target heating and response calculations.

There may be uncertainty in model predictions where the level and details of natural and/or mechanical ventilation is not well known. In Benchmark Exercise No. 4 a ventilation flow through the mechanical ventilation system was known to the analysts but could only be estimated, and will have had some bearing on the conditions inside the test enclosure, and perhaps also at the main vent to the outside, i.e. influencing the distribution of ventilation between the main (door) vent and the mechanical system. Where enclosures are nearly sealed there is always uncertainly in the actual leakage (infiltration) area and details. However, the predictions from various Benchmark calculations involving near sealed compartments were relatively insensitive to the precise area and location of the modeled leakage. Obviously, below a certain leakage area pressure effects become important, but otherwise the dependency was not significant.

3.2.2 Parameter Sensitivities

The physical phenomena and model parameters for which predicted results were most sensitive are summarized in the following. Re-iterating the point made above, fuel pyrolysis rate, whether a user-defined input or calculated by the fire model, is the most sensitive physical parameter. It can significantly influence the predictions, as illustrated in Benchmark Exercises No. 3 and No. 4, the latter in particular illustrating that the difference between using estimated (blind) and measured (semi-blind / open) pyrolysis rates can lead to differences in target temperatures of the order of a factor of two.

Analogous to pyrolysis rate, heat of combustion, combustion efficiency and radiative fraction are also sensitive parameters.

The combination of these three terms controls, to a large extent, the convective power of the fire, and this in turn directly influences the smoke temperature and entrainment rate. The appropriate setting of the convective power is important in obtaining a good match between prediction and measurement for smoke filling cases, as illustrated in Part I of Benchmark Exercise No. 2 where differences of the order of 15 % were observed in the upper layer temperature for CFAST when varying the convective power by 40 %.

Soot and combustion product concentrations, in combination with gas temperature, have a strong influence on radiation fluxes, for which target heating is particularly sensitive. Factors of the order times two in the incident radiation flux to a target were seen in various Benchmark calculations as a consequence of changes in the gas temperature field.

Boundary thermal inertia is another sensitive parameter. In the extreme limit, varying the thermal property of the ceiling and walls of an enclosure from adiabatic (no heat loss) to highly conducting (e.g. steel) can have an influence greater than those parameters directly influencing the convective power of the fire source.

While the above physical parameters are all important in respect to the sensitivity of the model predictions, perhaps an even more important parameter is the user itself. It is the user (e.g. fire engineer, computer modeler) who will often decide the radiative fraction, fuel heat of combustion etc., and thus having a significant bearing on the final outcome of the modeling.

As also indicated above, a number of physical phenomena were found, in the course of the ICFMP Benchmark Exercises, to only weakly influence the predictions. These include the choice of ambient values, the setting of lower oxygen limit and the exact details of enclosure leakage modeling.

4 Conclusions

The International Collaborative Fire Modeling Project (ICFMP) has provided an open international collaborative forum for experts to discuss performance of fire models over the course of its eight year lifetime from 2000 to 2007. Its accomplishments include:

- Establishing a web portal that allowed members to share information via a discussion forum and a document library,
- Organizing and documenting five Benchmark Exercises that are summarized in this document,
- Supporting contributions such as a zone model validation database and
- Inspiring new experiments and independent code validation projects.

The ICFMP filled a void at a crucial time from the perspective of the nuclear industry and its regulatory environment, while the U.S. standard NFPA 805 /NFP 01/ for risk-informed fire protection was finalized and adopted. Thereafter risk-informed methods were accepted by the U.S. NRC, and the use of fire modeling was more formally codified in a joint industry and regulatory guidance document for Fire PSA, NUREG/CR-6850 /EPR 05/. A new international market for fire modeling services was essentially developed which required, at its foundation, a solid technical basis for the applicability of fire models. The ICFMP anticipated this need and its contribution to the required technical basis is summarized in this document.

The timely need for an organization such as the ICFMP was a major factor in its success and the development of the five Benchmark Exercises. Many contributors to the ICFMP were from government bodies or laboratories, but the open nature of the ICFMP contributed to its success by allowing contributors from private organizations. It is important to maximize the number of potential contributors for varied reasons: To examine user effects on code performance, to increase the talent pool of fire modelers, and to encourage innovation. The web portal was another contributor to success of the ICFMP by facilitation correspondence and report preparation between meetings.

The ICFMP could not have existed without financial support of government bodies and institutions, their willingness to conduct experiments and share data, and their cooperation by providing contributors and resources for ICFMP functions.

Experiments were conducted in part due to the influence of the ICFMP. In this regard, the ICFMP provided an essential international forum that affirmed the need for such work, and also a forum for use of the experimental data.

New code validation efforts and experiments outside of the ICFMP can be traced to the existence of the ICFMP. In this regard, the ICFMP provides a foundation for code comparison standards, because it inspires a formal code validation report in support of the U.S. regulation. Also in this regard, the ICFMP provides leadership for the future of fire science, exemplified by the international collaboration for the PRISME experiments currently under way in France.

From the technical point of view, the ICFMP Benchmark Exercises have provided important information:

- From the first Benchmark Exercise, it was clear that while computer codes were reasonably capable of evaluating a common scenario, user effects were evident and crucial sub-models and phenomena were noted. This has translated into sensitivity analysis as a good practice in fire modeling for Fire PSA. The accuracy of blind calculations is particularly impacted by user effects. Differences between model predictions and experimental results for blind calculations compared to semi-blind / open calculations demonstrate the difficulty model users face choosing input values for design model simulations. Guidance documents for nuclear power plant fire modeling applications are needed to assist model users in choosing appropriate modeling parameters.

- Zone models were shown to be reasonable for evaluation of smoke layer temperature and elevation, despite complexities associated with some experimental configurations. Variation between results and data could occur for both zone and CFD models, such as seen with vent flows. Overall, this implies that Fire PSA can be conducted using zone models, provided that their limitations are recognized,

- User effects continue to be an issue, and user guidance documents that discuss sensitivity of results to key inputs: Fire heat release rate, vent characteristics, target detail, etc. would be useful for a nuclear power plant Fire PSA,

- Under-ventilated fire conditions still poses a modeling challenge and

- Modeling of cable pyrolysis, ignition, and flame spreading also poses a substantial modeling challenge.

The ICFMP has supported further the progress of fire modeling and the validation and verification of computer programs for Fire PSA. The challenges mentioned above should be taken up by future international collaborative efforts. In addition to the technical insights described above, this project has provided valuable insights in terms of techniques for model evaluation. For instance, from this project it is obvious that blind calculations can provide insights into the user's capabilities and the importance of model user guidance, but provide less insights into the predictive capability of the models themselves. Other lessons learned from this project should lead to improvements in the standard guides for assessing predictive capabilities of fire models.

5 Future of the ICFMP

The future of the ICFMP is under discussion during preparation of this Summary Report on Benchmark Exercises No. 1 to 5. Main points of the discussion held during the April 2007 meeting are presented here. There was no firm consensus on the topic, and a future workshop was recommended, perhaps in conjunction with a PRISME project meeting.

The future of the ICFMP essentially is contingent upon several factors:

- Uniqueness of its mission, and the ability to perform work outside the scope of existing research programs and
- Resources provided by supporting organizations, including the availability of key personnel who may be involved in related projects,
- Continuation of the open nature of the forum and its ability to obtain non-proprietary data.

Continuation of the ICFMP is motivated a number of potential projects that transcend existing national and international programs related to nuclear power plant fire safety. A list of 10 such projects created by the ICFMP includes suggested Benchmarks and topical evaluations, and further suggestions were discussed during the April 2007 meeting.

Suggested Benchmark Exercises include:

- Target heating in divided compartments, a topic that is in part investigated by OECD PRISME project,
- Validation exercises to examine and help resolve issues identified in previous Benchmarks, notably Benchmark Exercise No. 3 and the suggested divided compartment benchmark. New exercises would also focus better on sensitivity analysis and quantification of uncertainty and
- New fire modeling application exercises for several specifically suggested plant geometries. Standard problems for model application would use real plant information, and the broad issue of fire model applications would be investigated by comparing and contrasting the results of various models and modelers.

Topical evaluations include:

- Detector response modeling, including evaluation of existing detector codes and how such models might be applied for nuclear plant applictations,
- A Practical Users Guide providing suggestions on how to model important scenario features such as heat loss, ventilation, smoke spreading between compartments, and local effects such as flame impingement,
- Review and suggestion of specific code input data related to generic phenomena, such as values for flow coefficients,
- Development of heat release rate curves for cable trays,
- Review of cable modeling methods and recommendations for cable dysfunction criteria and
- Updating the Validation Database Report (VDR) which describes experimental data pertinent to model application to nuclear power plants.

The uniqueness and openness of ICFMP were identified as significant factors in favor of its continuation. The list of potential projects above has only minor overlap with currently existing major programs. These potential ICFMP efforts would be complementary to those of other programs. Furthermore, such ICFMP efforts are quite timely due to the increased importance of Fire PSA. The openness of ICFMP is a clear distinguishing factor that sets ICFMP apart from nearly all existing major programs, since those programs involve proprietary information within single countries or within chartered organizations of countries. Openness of the ICFMP is an advantage at a time when many persons are interested in fire modeling for nuclear power plant PSAs.

The resource issue was identified as a significant factor against future ICFMP activity. This issue has two aspects: Some ICFMP personnel are deeply involved in current international projects and would probably not have enough time to participate, and the ICFMP is competing for funding of existing major national and international projects.

The future of the ICFMP will hopefully be resolved at least in 2008 through consideration of the issues presented here.

6 Acknowledgements

In addition to the authors identified providing input to this Summary Report, several experts from various institutions contributed to the ICFMP in many ways.

A group of specialists from different expert institutions participating in the ICFMP contributed to Benchmark Exercise No. 1 as mentioned in /DEY 02/ either through the performance of analysis in the Benchmark Exercise, and/or by providing peer comments at various stages of the Exercise. The Industry Management Committee, UK and the National Institute of Standards and Technology (NIST), USA sponsored or collaborated with the organizations represented at the corresponding meetings.

The experimental measurements for Benchmark Exercise No. 2, Part I were collected by VTT as part of the European Coal and Steel Community project *NFSC2*, and are used by permission of the executive committee, SERDEC.

The test series used for Benchmark Exercise No. 3 was co-sponsored by the US Nuclear Regulatory Commission and the National Institute of Standards and Technology (NIST). Anthony Hamins and Alex Maranghides of NIST conducted the tests. Jonathan Barnett at Worcester Polytechnic Institute, USA, and Chantal Casselman at IRSN, France provided project management and technical support to the ICFMP group.

Alan Coutts at WSMS, USA, Jason Floyd at Hughes Associates, USA, Bijan Najafi and Francisco Joglar-Billoch at SAIC/EPRI, USA, Bernard Gautier and Laurent Gay at EdF, France, Peter Rew at WS Atkins Consultants, UK, Olaf Riese at iBMB, Germany, Jürgen Will at HHP Braunschweig, Germany, Walter Jones at NIST, USA, Robert Kassawara at EPRI, USA, Naeem Iqbal at NRC/NRR, USA, and Alan Wylie and Geoff Jones at HSE/NII, UK all contributed to Benchmark Exercise No. 3 either by providing peer comments, participating in meetings to discuss the test plan and results, or indirectly by sponsoring participants for the project.

The test series used for the Benchmark Exercises No. 4 and 5 were co-sponsored by Federal Ministry for Economy and Labour (BMWA) within the frame of the project RS 1146, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the German Federal Authority for Radiation Protection (BfS) within the frame of the projects SR 2449 and SR 2491.

The tests were performed by Institut für Baustoffe, Massivbau und Brandschutz (iBMB), University of Braunschweig - Institute of Technology, Germany sub-contracted by GRS.

Dietmar Hosser, Reinhold Dobbernack, Olaf Riese, Hans-Joachim Wolff and Mark Klingenberg were the key iBMB staff for the Benchmark Exercises No. 4 and No. 5 test series.

Heinz Peter Berg from BfS, Germany, Chantal Casselman from IRSN (France), Monideep Dey (USA), Walter-Klein-Heßling from GRS, Germany, and other members of the institutions participating in the ICFMP project all contributed to the Benchmark Exercises either by providing peer comments, participating in meetings to discuss the test plan and results, or indirectly by sponsoring participants for the project.

Olavi Keski-Rahkonen (retired) and Simo Hostikka at VTT, Finland, as well as James Oldham and Doug Brandes (retired) at Duke Energy, USA hosted the 7^{th}, 8^{th} and 9^{th} ICFMP meetings where the Benchmark Exercises No. 3 to 5 were planned and discussed, and also provided peer reviews and technical support.

All the ICFMP Benchmark Exercises as well as this document would not have been possible without the help and expertise of all the above.

7 References

/AST 05/ American Society for Testing and Materials ASTM International
ASTM E1355-05a, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models, ASTM International, West Conshohocken, PA, www.astm.org, 2005

/DEY 02/ Dey, M. K., Ed.
Evaluation of Fire Models for Nuclear Power Plant Applications: International Panel Report on Benchmark Exercise No. 1, Cable Tray Fires, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, NUREG 1758, Washington, June 2002, also National Institute of Standards and Technology (NIST), NISTIR 6872, June 2002

/EPR 05/ Electric Power Research Institute (EPRI) and United States Nuclear Regulatory Commission (NRC)
EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 1: Summary and Overview and Volume 2: Detailed Methodology, EPRI 1011989, NUREG/CR-6850 Final Report, September 2005

/HAM 06/ Hamins, A., et al.
Report of Experimental Results for the International Fire Model Benchmarking and Validation Exercise 3, NUREG/CR-6905, NIST Special Publication 1013-1, National Institute of Standards and Technology, Gaithersburg, Maryland, originally published in November 2003 as NISTIR 1013, revised as 1013-1, May 2006

/HOS 98/ Hosser, D., W. Siegfried, J. Will
Untersuchungen zum Brandverhalten von Kabelanlagen und zur Schutzfunktion von dämmschichtbildenden Anstrichen und Kabeln, Bericht Nr. U 97 073 iBMB, Auftrags-Nr. SR 2207 – 81030 –UA-1313 BMU, February 1998

/HOS 01/ Hostikka, S., M. Kokkala, J. Vaari
Experimental Study of the Localized Room Fire - NFSC2 Test Series, VTT Research Notes 2104, 200

/HOS 03/ Hosser, D., O. Riese, M. Schmeling
Durchführung von vergleichenden Brandversuchen mit unterschiedlichen Kabelmaterialien und Kabelschutzsystemen, VGB Kraftwerkstechnik GmbH, VGB-Kennziffer SA 'AT' 11/00, June 2003

/INT 00/ International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications, Summary of Planning Meeting, October 24-25, 1999, University of Maryland, College Park, Maryland, USA, Draft, NUREG/CP-0170, April 2000

/ISO 93/ International Standards Organization (ISO)
ISO 9705-1: Fire Tests - Full-scale Room Test for Surface Products (Room Corner Test), International Organization for Standardization, www.iso.org, 1993

/ISO 99/ International Standards Organization (ISO)
Fire Safety Engineering - Part 3: Assessment and Verification of Mathematical Fire Models, International Organization for Standardization, www.iso.org, 1993

/KLE 06/ Klein-Heßling, W., M. Röwekamp, O. Riese
Evaluation of Fire Models for Nuclear Power Plant Applications, Benchmark Exercise No. 4: Fuel Pool Fires Inside A Compartment, International Panel Report, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) Report Number GRS-213, ISBN-Nr.: 978-3-931995-80-5, November 2006

/LEO 94/ Leonardi, M., et al.
The FFT Based Method Utilisation in the Frame of the UMAE, Special Workshop on Uncertainty Analysis Methods, AEA Technology, London, March 1-4, 1994

/MCG 07/ McGrattan, K.
Evaluation of Fire Models for Nuclear Power Plant Applications: Benchmark Exercise #3, International Panel Report, National Institute of Standards and Technology (NIST), NISTIR 7338, 2007

/MIL 04/ Miles, S.
International Panel Report on Benchmark Exercise #2 - Pool Fires in Large Halls, BRE Report Number 212214, 2004

/NFP 01/ National Fire Protection Association (NFPA)
Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants, NFPA 805, 2001 Edition, Brainerd, MA, 2001

/NRC 07/ United States Nuclear Regulatory Commission (NRC)
Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Vols. 1-7, NUREG-1824 and EPRI 1011999, U.S. Nuclear Regulatory Commission, Washington, DC and Electric Power Research Institute (EPRI), Palo Alto, CA; 2007

/RIE 06/ Riese, O., D. Hosser, M. Röwekamp
Evaluation of Fire Models for Nuclear Power Plant Application Benchmark Exercise No. 5: Flame Spread in Cable Tray Fires, International Panel Report, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) Report Number 214, ISBN-Nr.: 978-3-931995-81-2, November 2006

List of Figures

Liste of Tables

Acronyms and Initialisms

BE	Benchmark Exercise
BRE	Building Research Establishment
CFD	Computational Fluid Dynamics
EdF	Electricité de France
FDS	Fire Dynamics Simulator
FHA	Fire Hazard Analysis
FFT	Fast Fourier Transformation
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HGL	Hot Gas Layer
HRR	Heat Release Rate
iBMB	Institut für Baustoffe, Massivbau und Brandschutz
ICFMP	International Collaborative Fire Modeling Project
IPSN	Institute de Protection et Securité Nucléaire
IRSN	Institute de Radioprotection et Securité Nucléaire
LOL	Lower Oxygen Level
NEA	Nuclear Energy Agency
NFPA	National Fire Protection Association
NIST	National Institute of Standards
NPP	Nuclear Power Plant

NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
PRISME	Propagation d’un Incendie pour des Scénarios Multi-locaux Élémentaires
PSA	Probabilistic Safety Analysis
PVC	Polyvinylcloride
PWR	Pressurized Water Reactor
SFPE	Society of Fire Protection Engineers
VTT	Valtion Teknillinen Tutkimuskeskus
WPI	Worcester Polytechnique Institute