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International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications: Proceedings of 5th Meeting

Held at
National Institute of Standards and Technology
Gaithersburg, MD 20899
May 2-3, 2002

U.S. Nuclear Regulatory Commission
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Abstract

The 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was hosted by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce and held at NIST headquarters at Gaithersburg, Maryland on May 2 and 3, 2002. The organizing Committee for the meeting included Moni Dey from the U.S. Nuclear Regulatory Commission (U.S. NRC), and Anthony Hamins from NIST. Thirty three participants from five countries attended the international meeting.

The purpose of the 5th meeting was mainly to discuss the results of Benchmark Exercise # 2, "Pool Fires in Large Halls," conducted in the project. Validation and regulatory applications of fire models were also presented and discussed in the meeting. The results presented for Part I of Benchmark Exercise # 2 were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters. The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. The validation and application of several, diverse fire models, ranging from empirical equations organized in worksheets to zone, lumped-parameter, and computational fluid dynamic (CFD) models, were presented and discussed at the meeting. The discussions emphasized the need to validate and determine the accuracy of such models, especially to understand the differences in the predictive capabilities and margins of uncertainty for the different types of models over a range of fire scenarios. This information is needed to establish safety factors and implement effective applications of these models in a regulatory framework. The need to define credible fire scenarios and generate data for fire sources, especially cable tray fires, was emphasized.

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Executive Summary

The 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was hosted by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce and the U.S. Nuclear Regulatory Commission (NRC), and held at NIST headquarters in Gaithersburg, Maryland on May 2 and 3, 2002. Thirty-three participants from five countries, France, Germany, UK, Finland, and the US attended the international meeting. Seventeen organizations including regulatory agencies, research institutions, nuclear utilities, industry groups, professional organizations, consultants, and academia were represented at the meeting.

The objective of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications 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 (NPP) fire safety analysis. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current state-of-the-art fire models (empirical, zone, lumped-parameter, and computational fluid dynamic) for fire safety analysis in NPPs. The second phase will implement beneficial improvements to current fire models that are identified in the first phase, and extend the validation database of those models.

The 1st planning meeting of the project was held at the University of Maryland at College Park, USA, on October 25-26, 1999. The summary of the 1st meeting and details of the objectives and plans established for the project can be found in NUREG/CP-0170 (April 2000). The 2nd meeting of the collaborative project was hosted by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France and held at the IRSN offices at Fontenay-aux-Roses, France on June 19 and 20, 2000. The objective of the 2nd meeting was to discuss the definition of the 1st benchmark exercise in the project for analyzing cable tray fires in nuclear power plants. The summary of the 2nd meeting can be found in NUREG/CP-0173 (July 2001). The 3rd meeting of the collaborative project was hosted by the Electric Power Research Institute (EPRI) and held at the EPRI offices in Palo Alto, California on January 14-15, 2001. The objective of the 3rd meeting was to discuss the results of the 1st benchmark exercise. Since the results of the 1st benchmark exercise were documented in NUREG-1758 (June 2002), formal proceedings of the 3rd meeting were not published. The 4th meeting of the collaborative projected was hosted by GRS, Germany and included discussions to finalize the report of the 1st benchmark exercise. A summary of the 4th meeting can be found in Report No. GRS-A-3106.

The purpose of the 5th meeting was mainly to discuss the preliminary results of the 2nd benchmark exercise in the project on pool fires in large halls. The purpose of the 2nd benchmark exercise was to challenge the limits of zone fire models by analyzing pool fires in large multi-level spaces, like in a turbine building in a nuclear power plant. A summary of the technical discussion on the 2nd benchmark exercise is provided below. Since the meeting was co-hosted by NIST and the NRC, opening remarks were provided by representatives of the two organizations detailing their interests and research objectives in this topic area. Mark

Cunningham, Chief of the Probabilistic Risk Analysis Branch in the Office of Nuclear Regulatory Research, NRC described NRC's goals and plans for research to support risk-informed regulation, specifically for fire protection in nuclear power plants. James Hill, Deputy Director of the Building and Fire Research Laboratory provided a broad overview of the mission and programs at NIST for building and fire research. His talk was followed by a summary of ongoing projects at the Fire Research Division at BFRL, NIST provided by Anthony Hamins. Remy Bertrand of IRSN, France ended the opening session with a discussion of future fire research at IRSN in France, including the selection and identification of fire scenarios and research needs. A session was organized on the regulatory applications of fire models which included presentations of simple analytical tools for use in the inspection process, nuclear utility interests for the application of fire models in nuclear power plants, and the development of a fire modeling guide for nuclear power plant applications. A summary of this session is provided below. A session on the validation of fire models included presentations of extensive efforts by various organizations to validate fire models. The meeting was concluded with a discussion of future efforts in the collaborative project.

Validation and Regulatory Applications of Fire Models

Papers were presented on the regulatory application of fire models by a user in a utility, and staff in a regulatory agency and industry research group. The papers identified the need for technology transfer from the research community to users, and education and training of both regulatory inspectors and plant staff. Increased dialogue between inspectors and plant staff and use of the same tools will lead to a common understanding of the models. There is a need for guidance on the use of models, and a good user interface for effective application of the models to prevent misuse. Worksheets based on empirical models available from handbooks were presented both by regulators and industry as a 1st systematic application of quantitative fire hazard analysis for nuclear power plants. These worksheets provide a means to transition from qualitative to quantitative inspection methods, and also serve as a design guide to support day-to-day operations. However, presenters and participants noted that although these empirical models provide a good start, they should not be treated as "gospel." It is necessary to establish the margins of uncertainty in these correlations by conducting validation exercises. These margins can then be used to establish safety factors in fire hazard analysis methods that will lead to acceptability of the analysis methods.

Participants also presented descriptions and validation results of a wide range of zone, lumped-parameter, and CFD models. Participants discussed and identified a need to transition from simple to more comprehensive and accurate tools. In order to identify the right tools for various regulatory applications, it is necessary to benchmark the different tools to develop their accuracy for a wide range of fire scenarios.

Participants discussed and noted that any type of fire model analysis requires establishing credible fire scenarios. Participants noted that current documents on the use of fire models in NPP applications have not addressed this item as yet. The absence of such information is a challenge in the current inspection process. Fire scenario definition should be identified as a priority in the research plan. Flame spread rate data in cable trays was also identified as a priority research item. The development of a comprehensive database of mass loss rate profiles for combustible materials in NPPs is essential for the efficient and broader application of fire models in fire safety analysis.

Technical Results of Benchmark Exercise # 2, Part I, "Pool Fires in Large Halls

The results presented for Part I were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters, that impact the results presented in Part I.

For the purpose of calculating layer height and temperature, for which most of the measurement data had been collected, the zone model (CFAST) appeared to be fit for purpose. This was encouraging given the complexity introduced by the roof shape, for which an 'equivalent' flat ceiling sufficed. Analyses of the size and location of the 'infiltration' openings for case 1 and 2 indicated that the predictions were not sensitive to these parameters. This finding was supported by zone, lumped parameter, and CFD models.

While different models were in broad agreement, participants had not always agreed on the most sensitive parameters, i.e. what parameters were particularly critical in terms of their influence on the final predictions. An example here was the heat losses to the walls and ceiling.

The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. 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 (and hence the predicted temperatures being higher than the measured ones). By selecting an appropriate balance of convective heat release rate (by modifying the combustion efficiency and/or radiative fraction) and heat losses to the boundaries, modelers could replicate the measured layer temperature quite closely.

Finally, there was a general trend to predict lower layer depths (i.e. closer to the floor) than those derived from the measurement data. This is perhaps a consequence of the post processing of the thermocouple data to derive smoke layer information.

Foreword

The U.S. Nuclear Regulatory Commission, in collaboration with the National Institute of Standards and Technology (NIST), U.S. Department of Commerce, is pleased to publish the proceedings of the 5th meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. Since the inception of the project in 1999, the U.S. NRC and NIST established an inter-agency memorandum of understanding and collaborated in conducting research to provide the necessary technical data and tools to support the use of fire models in nuclear power plant fire safety analysis. The joint sponsorship of the 5th meeting of the project and publication of these proceedings is one product of this collaboration. As is apparent from these proceedings, the international collaborative project is resulting in a significant exchange of useful technical information between participants in the project. The U.S. NRC appreciates and values the technical information provided by all participants in this project. It would be difficult for a single organization to generate the diverse technical information collected through such a broad collaborative effort. The U.S. NRC is pleased to be a partner and provide its contribution to the international collaboration through its participation in the project and publication of these proceedings.

Scott Newberry, Director
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

Acknowledgments

Support for administration and audio-visual arrangements for the meeting was provided by Wanda Duffin and Kevin McGrattan. Walter Jones and George Mulholland hosted the lunches for the participants at the NIST executive dining room.

Acronyms and Initialisms

BRE	Building Research Establishment
CIB	International Council for Research and Innovation in Building and Construction
CFAST	Consolidated Model for Fire and Smoke Transport
CFD	Computational Fluid Dynamics
COCOSYS	Containment Code System
EdF	Electricite de France
EPRI	Electric Power Research Institute
FDS	Fire Dynamics Simulator
GRS	Gesellschaft fuer Anlagen-und Reaktorsicherheit
HRR	Heat Release Rate
iBMB	Institut fuer Baustoffe, Massivbau und Brandschutz
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JASMINE	Analysis of Smoke Movement in Enclosures
NII	H. M. Nuclear Installations Inspectorate
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Analysis
VTT	Valtion Teknillinen Tutkimuskeskus
WPI	Worcester Polytechnic Institute

1 Introduction

The objective of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications 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 (NPP) fire safety analysis. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current state-of-the-art fire models (empirical, zone, lumped-parameter, and CFD) for fire safety analysis in NPPs. The second phase will implement beneficial improvements to current fire models that are identified in the first phase, and extend the validation database of those models.

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The 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was hosted by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce and held at NIST headquarters at Gaithersburg, Maryland on May 2 and 3, 2002. The organizing Committee for the meeting included Moni Dey from the U.S. Nuclear Regulatory Commission (U.S. NRC), and Anthony Hamins from NIST. The following thirty three participants from five countries attended the international meeting:

1. Stewart Miles, BRE, UK
2. Olavi Keski-Rahkonen, VTT, Finland
3. Remy Bertrand, IPSN, France
4. Chantal Casselman, IPSN, France
5. Marina Roewekamp, GRS, Germany
6. Walter Klein-Hessling, GRS, Germany
7. Doug Brandes, Duke Power Co., USA
8. Bijan Najafi, SAIC/EPRI, USA
9. Francisco Joglar-Billoch, SAIC/EPRI, USA
10. Doug Beller, NFPA, USA
11. Jonathan Barnett, WPI, USA

12. Fred Mowrer, UMD, USA
13. Boro Malinovic, Fauske Associates, USA
14. Marty Plys, Fauske Associates, USA
15. Alan Coutts, Westinghouse, USA
16. Amber Martin, Westinghouse, USA
17. Fred Emerson, NEI
18. Phil DiNenno, Hughes Associates/NEI, USA
19. Jim Hill, NIST, USA
20. Anthony Hamins, NIST, USA
21. Kevin McGrattan, NIST, USA
22. Walter Jones, NIST, USA
23. George Mulholland, NIST, USA
24. Jason Floyd, NIST, USA
25. Louis Gritzo, SNL, USA
26. Steve Nowlen, SNL, USA
27. Mark Cunningham, NRC, USA
28. Moni Dey, NRC, USA
29. JS Hyslop, NRC, USA
30. Naeem Iqbal, NRC, USA
31. Mark Salley, NRC, USA
32. Chris Bajwa, NRC, USA
33. Sharon Steele, NRC, USA

The purpose of the 5th meeting was to discuss the preliminary results of the 1st part of the 2nd benchmark exercise in the project on pool fires in large halls. The specification of the 2nd part of the exercised was also discussed. Other topics discussed at the meeting included the regulatory application and validation of fire models. The full agenda of the 5th meeting is included in Appendix A.

2 Background

The first task of the collaborative project was to undertake a benchmark exercise to evaluate the current capability of fire models to analyze the hazard associated with cable tray fires of redundant safety systems in nuclear power plants. These systems are required to shutdown the reactor during an emergency, and when located inside the same compartment must be separated by a specified distance to ensure that a fire in one system does not cause the other to fail also. The exercise involved a series of hypothetical scenarios to predict cable damage inside an emergency switchgear room, and were fairly tightly specified in respect of the input and modeling parameters to be used. Due to the size of the room and the nature of the fire scenarios, the differences in the conclusions obtained using the various fire models were not significant. Target cable damage was predicted to be unlikely in almost all cases studied. A summary of the main results, findings and conclusions is included in NUREG-1758 (June 2002).

This section summarizes the second benchmark exercise. The main objectives taken into consideration when selecting the second benchmark exercise were:

- To examine scenario(s) that provide a harder test for zone models, in particular with respect to fire spread in large volumes representative of, say, a turbine hall.
- If possible, to make use of experimental data to fulfil the requirement of more thoroughly testing the predictive capability of both zone and CFD fire models. Again, the emphasis when selecting scenarios was on large smoke filling volumes.

Benchmark Exercise # 2 is divided into two parts. For the first part there are experimental measurements of temperature and velocity against which model predictions can be compared. The second part extends the scope of the exercise to examine the consequence of larger fires, but for which there are no experimental measurements against which to compare.

Part I includes three cases, based on a series of full-scale experiments inside a test hall with dimensions 19 m high by 27 m long by 14 m wide (i.e. floor area 378 m^2). Each case involves a single fire (2 - 4 MW), and for which there are experimental measurements of gas temperature and doorway velocity. The height of a turbine hall within an NPP (c. 25 m) is similar to that of the test hall although it is acknowledged that the area of a turbine hall (c. 3500 m^2) is much greater. However, the test hall is one of the largest enclosures for which fire test data is available for comparison with model predictions. The preliminary results of Part I were presented and discussed at the 5th meeting.

Part II includes three additional cases for which experimental measurements do not exist, but extend the scope of the benchmark exercise to examine the effect of a bigger fire and larger floor area representative of a hydrocarbon pool fire in a real turbine hall. These are optional cases for participants to investigate if time and resources allow. The specification of Part II was discussed at the 5th meeting.

Although most input parameters are defined, Benchmark Exercise # 2 does in a few respects involve a greater degree of user judgement in setting up the problem compared to the first benchmark exercise. This applies in particular to the treatment of the sloping roof (with zone models) in Part I. Appendix B includes the full specification document for Benchmark Exercise # 2.

3 Meeting Summary

The following provides a summary of the main topics discussed at the meeting, the 2nd benchmark exercise, and the validation and regulatory application of fire models. Summary papers submitted for the proceedings and slides used by the presenters are included in Appendices C and D, respectively.

3.1 Benchmark Exercise # 2, "Pool Fires in Large Halls"

Summary

Session IV was devoted to the second benchmark exercise (Fire in a Large Hall). This has been selected to challenge fire models in respect to issues not addressed in the first exercise, e.g. effects of fire in a large volume representative of, say, a turbine hall. Furthermore, it includes some scenarios for which there are experimental measurements, allowing comparisons to be undertaken.

Benchmark Exercise # 2 is divided into two parts. For the first part there are experimental measurements of temperature against which model predictions can be compared. The second part extends the scope of the exercise to examine the consequence of larger fires, but for which there are no experimental measurements to compare against.

The session was devoted mainly to presentations and discussions on simulations of Part I, where various participants had made comparisons between predicted and measured data. This was followed by a discussion of the format for Part II of the benchmark exercise, so that the problem definition could be finalized before participants undertook simulations.

Benchmark Exercise # 2 - Part I

S. Miles introduced Part I at the start of the session. It includes three cases, based on a series of full-scale experiments inside a test hall with dimensions 19 m high by 27 m long by 14 m wide. Each case involves a single fire, in the range 2 to 4 MW, and for which there are experimental measurements of gas temperatures at various locations inside the hall, in particular at the location of three vertical thermocouple trees.

The problem specification included in Appendix B contains full details of the tests, and the requirements for the numerical simulations. It was released in conjunction with a summary of the measurement data against which to compare predictions, and so Part I is therefore an informed study rather than a blind simulation exercise. Nevertheless, participants have been invited to make quantitative comparisons between predictions and measurements, and to draw conclusions where possible.

Six presentations were made at the meeting, covering ten sets of predictions, including three examples of CFAST, two of FDS, two of JASMINE and one each of COCOSYS, HADCRT and CFX.

Presentations

Jonathan Barnett - Class Exercise using CFAST, JASMINE and FDS

The presentation was made by J Barnett on behalf of nine students studying performance-based fire design as part of an undergraduate course at Worcester Polytechnic Institute. Most students had some experience in the fire protection industry. However, prior to the exercise they had only had limited experience of zone models, and none had any CFD experience.

The students had been divided into three groups, one group using FDS, one group using JASMINE (via the JOSEFINE user interface) and one group using CFAST. The presentation focussed more on general observations rather than detailed comparisons. With all three models the students had found the sloping roof a challenge. For the zone model (CFAST) an equivalent flat ceiling had been specified. For both CFD models they had found setting up the sloping roof to be time consuming. Probably the biggest 'complaint' of the CFD models was the long simulation times compared to zone models, making sensitivity analysis difficult. Another issue was in calculating layer heights and temperatures from CFD data.

Two options had been investigated for setting the height of the equivalent flat ceiling in CFAST; conserving the enclosure volume and conserving the enclosure surface area. However, it was found that the choice had no significant effect on the results. The students had been unsuccessful in specifying mechanical exhaust ventilation for case 3.

Predictions for gas temperature were considered to appear reasonable for all models. Given that they had used the models with little, or no, prior fire modelling experience and were left in the main unsupervised, the outcome of the exercise was quite promising. However, the students had found the models quite difficult to use, and stressed the need for good guidance on their use.

Walter Klein-Hessling - COCOSYS (lumped parameter) and CFX-4 (CFD)

W Klein-Hessling presented work that he had undertaken with the lumped parameter model COCOSYS and that his colleague, W Heitsch, had performed with the CFD model CFX-4. Most work had been undertaken with COCOSYS at this stage.

COCOSYS had been set up with approximately 500 (lumped parameter) control volumes, with individual ones located the thermocouple locations so that a detailed comparison against those measurements could be made. The COCOSYS simulations had taken about three hours for each case.

Reasonable agreement between predicted and measured temperatures at the three thermocouple trees had been achieved with COCOSYS once the combustion efficiency had been reduced by a further 40%. In the specification document a plume radiative fraction of 20% had been suggested, which had been equated to a reduced combustion efficiency. Another useful finding from the COCOSYS study was that varying the location of the infiltration openings for case 1 and 2 had little effect on the results. Heat loss to the walls and ceiling had been varied, but while this modified the gas temperatures by up to 20°C, this was less than the effect produced by reducing the combustion efficiency.

COCOSYS had under predicted the plume temperature, which is a consequence of there being no plume model and the control volumes above the fire being relatively large (compared to those typically used in CFD). Furthermore, the spread in temperatures at the thermocouple column locations was greater in the COCOSYS results than in the measurements, which may be a consequence of not solving for momentum conservation. It was suggested that the COCOSYS pyrolysis model could have been used, which predicts the mass release rate of fuel. However, additional information about the fire source would have been required.

Only preliminary simulations had been performed with CFX. However, the temperature predictions were currently too high. Furthermore, numerical stability problems had been encountered, especially with case 3 (with mechanical ventilation). The problem of generating layer interface and temperature information from a CFD simulation was raised. The CFX simulations had taken about one week each.

A general remark was made that the use of a fixed convective heat transfer coefficient (10 J s-1 m-2 K-1) was too simplistic.

Amber Martin - CFAST (zone)

This presentation was from a practicing consultant's perspective. CFAST version 3.1.6 had been used to simulate Part I. As the presenter had not received the experimental summary data, the simulations had been performed blind. It was encouraging to see that the CFAST predictions for layer height and temperature were in line with those produced by the other participants. Upper layer temperatures were quite close to the measurements, and the predicted layer height descended to a lower value than that indicated by the measurement data. As for the other CFAST participants, an equivalent flat ceiling had been modeled (conserving enclosure volume).

Boro Malinovic - HADCRT (lumped parameter)

This presentation covered the second of the lumped parameter models. HADCRT was developed initially for explosions and other accidents, but is being extended to include fire modelling. In contrast to the COCOSYS simulations, relatively few 'junctions' were employed and so the modelling was more akin to that of a zone model. Consequently, simulations took only a few minutes.

The upper layer temperature predictions were quite close to the experimental values but the layer was predicted to descend closer to the floor. Although radiation had been ignored in the simulations reported, about 20 to 25 % of the heat was transferred to the boundaries (by convection).

It was suggested that a parametric analysis of the effect of varying the size and location of the infiltration openings for case 1 and 2 be performed, as this may be important. In particular, it may influence the lower layer temperature.

Kevin McGrattan - FDS (CFD)

The FDS simulations were undertaken as specified, except that 35% of the heat release rate was assigned to plume radiation (instead of 20%). FDS version 2 was used, with five mesh blocks (one at the plume with a mesh resolution of 10 cm and four in the rest of the hall with a resolution of 40 cm). A total of approximately 200,000 grid cells were used in the simulations. Using this grid, good agreement between predicted and measured temperatures at the three thermocouple columns was demonstrated.

There was some discrepancy in the plume temperatures, particularly at the lower thermocouple location (about 100°C discrepancy for case 1). This was attributed to limitations of the combustion model, and it was suggested also that if the plume had leaned slightly in the experiments then this feature would most likely be missed in the simulation, which would still 'pick up' the hot temperature on the plume centre-line. Better plume temperature agreement was achieved in case 2 and 3 (with the larger fire size), which was attributed to there being more grid cells across the width of the plume compared to case 1.

Earlier simulations had been undertaken with a single mesh block, resulting in a coarser grid at the plume. The temperature agreement was not as good with this grid, with the predicted values being too high. This was attributed to the grid size being too great, with the result that the air entrainment was under-predicted and thus the ceiling layer was then too hot. It was stressed that grid size in the plume was critical in the LES approach, and that 6 to 8 grid cells across the diameter of the fire source were required. This led onto a discussion on how engineers should be guided on this, and also on related numerical and modeling issues.

Stewart Miles - JASMINE (CFD) and CFAST (zone)

This presentation covered simulations using JASMINE and CFAST (used in conjunction with the FAST graphical interface). A sensitivity analysis had been performed with CFAST on a number of parameters, in particular the heat losses to the boundaries and the size and location of the infiltration openings for case 1 and 2. A more limited sensitivity analysis had been undertaken with JASMINE, examining again the boundary heat losses and the infiltration openings. A grid sensitivity analysis had been performed with JASMINE.

In common with the approach adopted by other participants, CFAST was run with a flat ceiling with a height set to conserve the volume of the enclosure for most simulations. Sensitivity to ceiling height had been investigated. 'Baseline' CFAST simulations were performed using the specified combination of sheet metal and mineral wool. However, to investigate the sensitivity to boundary heat loss, simulations had been performed with metal only, mineral wool only and non-conducting (adiabatic) surfaces. For case 1 and 2 the sensitivity to the size and location of the 'infiltration' openings had been investigated. Here the original 0.5 m^2 openings were replaced first by 0.01 m^2 openings and then by two large (16 m^2) openings. The effect of increasing/decreasing the height of the openings (above the floor) had been studied too.

The CFD (JASMINE) simulations had been performed using a numerical mesh of approximately 130,000 elements. A mesh resolution sensitivity study, using a mesh with eight times the number of elements, was reported. Heat losses to the boundaries had been modeled using a thermal penetration model, assuming only the mineral wool material. The effect of increasing the boundary heat losses (by modifying the thermal properties of the material) had been investigated.

The presentation reported that probably the most important finding, demonstrated by both the zone and CFD models, was the sensitivity of the gas temperatures to the conduction losses at the walls and ceiling. In the CFAST simulations the closest agreement with measurement was obtained by using either a sheet metal and mineral wool two-layer combination or by using the sheet metal alone. In the JASMINE simulations closer agreement with measurement was obtained when the conduction losses were increased. It was suggested that the conduction into the steel might be important. The smoke layer height, however, seemed to be less sensitive to the boundary conduction loss calculation.

The CFAST study indicated that while the upper layer temperature is sensitive to the choice of ceiling height, the layer height is sensitive only during the initial stage of the fire. Both the zone model and CFD simulations had indicated that the exact choice of 'infiltration' openings in case 1 and 2 was not critical.

Reasonable agreement has been shown between measured plume temperatures and those predicted in the JASMINE simulations. The mesh refinement study had indicated some sensitivity to this parameter, with the finer mesh producing results closer to those measured.

Summarizing Remarks

The results presented for Part I were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters.

For the purpose of calculating layer height and temperature, for which most of the measurement data had been collected, the zone model (CFAST) appeared to be fit for purpose. This was encouraging given the complexity introduced by the roof shape, for which an 'equivalent' flat ceiling sufficed. Analyses of the size and location of the 'infiltration' openings for case 1 and 2 indicated that the predictions were not sensitive to these parameters. This finding was supported by zone, lumped parameter and CFD models.

While different models were in broad agreement, participants had not always agreed on the most sensitive parameters, i.e. what parameters were particularly critical in terms of their influence on the final predictions. An example here was the heat losses to the walls and ceiling.

The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. 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 (and hence the predicted temperatures being higher than the measured ones). By selecting an appropriate balance of convective heat release rate (by modifying the combustion efficiency and/or radiative fraction) and heat losses to the boundaries, modelers could replicate the measured layer temperature quite closely.

Finally, there was a general trend to predict lower layer depths (i.e. closer to the floor) than those derived from the measurement data. This is perhaps a consequence of the post processing of the thermocouple data to derive smoke layer information.

<u>Benchmark Exercise # 2 - Part II</u>

Part II is a 'hypothetical' example for which there are no experimental measurements. However, the dimensions of the building are greater than in Part I, and have been selected to more closely represent a turbine hall.

The current specification for Part II (as at the time of the meeting) was summarized by S Miles. The fire source was representative of a large hydrocarbon pool fire. 'Target' cables and beams had been included, for which the likelihood of thermal damage was to be estimated. Although the building geometry was rectangular, in some of scenario cases there was the added complexity of an internal ceiling, effectively dividing the space into two connected compartments. There then followed a general discussion on what, if any, modifications should be made before participants proceeded to model the cases.

Modelers seemed keen to undertake simulations of Part II. However, while some participants wished for a bigger fire (> 200 MW), others wanted a smaller one. It was decided to keep the fire size as it was currently specified (i.e. growing to about 70 MW). The other main changes that were agreed or suggested were:To reduce the number of cases to be modelled to three.

- To include the internal ceiling, dividing the hall into a lower and upper deck, in all cases.
- To introduce a second opening in the internal ceiling.
- To increase the mechanical extraction rate to 24 m3s-1 and 120 m3s-1 for the cases where this is included.

There was an interest in the ability of models to predict the flow distribution through the hatch opening(s), which might be quite complex. It was agreed to add the calculation of net up/down mass and heat fluxes through the opening(s) to the list of predicated variables.

Note that following the meeting the specification for Part II was revised and presented on the web pages of the collaborative project for comment. The final specification was made available to participants on 5th June 2002.

3.2 Validation and Regulatory Applications of Fire Models

Three papers were presented on the regulatory application of fire models by a user in a utility, and staff in a regulatory agency and industry research group. The papers identified the need for technology transfer from the research community to users, and education and training of both regulatory inspectors and plant staff. Increased dialogue between inspectors and plant staff and use of the same tools will lead to a common understanding of the models. There is a need for guidance on the use of models, and a good user interface for effective application of the models to prevent misuse. Worksheets based on empirical models available from handbooks were presented both by regulators and industry as a 1st systematic application of quantitative fire hazard analysis for nuclear power plants. These worksheets provide a means to transition from qualitative to quantitative inspection methods, and also serve as a design guide to support day-to-day operations. However, presenters and participants noted that although these empirical models provide a good start, they should not be treated as "gospel." It is necessary to establish the margins of uncertainty in these correlations by conducting validation exercises. These margins can then be used to establish safety factors in fire hazard analysis methods that will lead to acceptability of the analysis methods.

Participants also presented descriptions and validation results of a wide range of zone, lumped-parameter, and CFD models. Participants discussed and identified a need to transition from simple to more comprehensive and accurate tools. In order to identify the right tools for various regulatory applications, it is necessary to benchmark the different tools to develop their accuracy for a wide range of fire scenarios.

Participants discussed and noted that any type of fire model analysis requires establishing credible fire scenarios. Participants noted that current documents on the use of fire models in NPP applications have not addressed this item as yet. The absence of such information is a challenge in the current inspection process. Fire scenario definition should be identified as a priority in the research plan. Flame spread rate data in cable trays was also identified as a priority research item. The development of a comprehensive database of mass loss rate profiles for combustible materials in NPPs is essential for the efficient and broader application of fire models in fire safety analysis.

3.3 Future Tasks and Benchmark Exercises

Session V of the meeting included presentations and discussion of proposed benchmark exercises for the project. Participants agreed to proceed with planning of these proposed exercises (which are summarized below) at the 6th project meeting scheduled for October 2002.

I. Benchmark Exercise # 3, "Cable Targets in Single Compartment Fires": This benchmark exercise will entail blind simulation of tests in a full-scale single compartment that will be sponsored by NRC and conducted at NIST. The size of the compartment will be representative of those in NPPs, and the fire source will be moderate sized hydrocarbon fires. The goal of these tests is to confirm the findings of Benchmark Exercise # 1 and focus on the issues that arose from that exercise, namely, the prediction of heat flux incident on target cable trays and the thermal response of the target.

II. Benchmark Exercise # 4, "Large Kerosene Pool Fires": This benchmark exercise will entail blind simulation of large kerosene pool fires in a single compartment. The tests will be sponsored by GRS and conducted at iBMB. The goal of the tests is to develop basic data for simulating kerosene fires under different boundary conditions, and to examine the ability to calculate the fire effects for selected scenarios. The benchmark exercise will focus on one of the test scenarios in the program.

III. Benchmark Exercise # 5, "Flame Spread in Cable Tray Fires": This benchmark exercise will entail simulation of cable tray fires and their effects in a single compartment. The tests will be sponsored by GRS and conducted at iBMB. Vertical and horizontal cable trays, different types of cables, and degree of cable preheating will be examined in the test program. The benchmark exercise will focus on one of the test scenarios in the program.

IV. Benchmark Exercise # 6, Target Heating in Divided Compartments: This benchmark exercise will entail the blind simulation of tests in the compartment used in Benchmark Exercise # 3, but divided with half walls to be more representative of NPP compartments. The exercise will focus on the effects of the half walls on flow and radiation shielding within the compartment. These tests will be sponsored by NRC and conducted at NIST.

V. Benchmark Exercise # 7: This benchmark exercise will be conducted in the compartment used for Benchmark Exercises #s 3 and 6 and focus on examining issues that are identified in those exercises and require further examination. These tests will be sponsored by NRC and conducted at NIST.

Appendix A: Agenda for Meeting

Agenda

5th Meeting of the International Collaborative Fire Model Project

Co-sponsored by the U.S. Nuclear Regulatory Commission, and the National Institute of Standards and Technology, U.S. Department of Commerce

May 2-3, 2002
National Institute of Standards and Technology,
Gaithersburg, Maryland, USA

Meeting Co-chairs: **Moni Dey, U.S. NRC and Anthony Hamins, NIST, USA**

Meeting Location: Lecture Room E, Administration Building (101), NIST, Gaithersburg, Maryland

May 2, 2002

8:30-9:50 AM ***Session I: Opening Remarks and Research Programs***

Session Chair: Anthony Hamins, NIST, USA

Introductions: **Workshop Participants**

Opening Remarks and Research Programs

1. "U.S. NRC Goals and Plans for Research to Support Risk-Informed Regulation," **Mark Cunningham**, Chief, Probabilistic Risk Assessment Branch, Office of Nuclear Regulatory Research, U.S. NRC

2. "Mission and Programs at NIST for Building and Fire Research," **James Hill**, Deputy Director, Building and Fire Research Laboratory (BFRL), NIST, USA

3. "Summary of Ongoing Projects at the Fire Research Division at BFRL, NIST," **Anthony Hamins**, Leader, Analysis and Prediction Group, BFRL, NIST, USA

4. "Future Fire Research at IPSN: Selection and Identification of Fire Scenarios and Research Needs," **Remy Bertrand**, IPSN, France

9:50-10:10 AM ***Coffee Break***

10:10-11:40 AM ***Session II: Regulatory Applications of Fire Models***

Discussion Leader: Moni Dey, U.S. NRC

1. "First Applications of a Quantitative Fire Hazard Analysis Tool for Inspection in U.S. Commercial Nuclear Power Plants," **Naeem Iqbal** and **Mark Salley**, U.S. NRC

2. "Risk-Informed Applications of Fire Models," **Doug Brandes**, Duke Power Company, USA

3. "EPRI Fire Modeling Project: A Guide for Nuclear Power Plant Applications," **Bob Kassawara, Bijan Najafi**, and **Francisco Joglar-Billoch**, EPRI, USA

11:40 AM - 1:00 PM ***Lunch***

1:00 - 4:45 PM ***Session III: Validation of Fire Models***

Discussion Leader: Anthony Hamins, NIST, USA

4. "Summary of Validation Studies for the FLAMME_S Code," **Chantal Casselman**, IPSN, France

5. " Zone Model Validation for Room Fire Scenarios," **Olavi Keski-Rahkonen & Simo Hostikka**, VTT, Finland

6. "The Zone Fire Model, MAGIC : A Validation and Verification Principle," **Bernard Gautier,** EdF, France

7. "Enhancements to the FIVE Methodology, **Fred Mowrer**, UMD, USA

Break

8. "Zone Modeling Theory, Applications and Certainty - the Verification and Validation of CFAST," **Walter Jones**, NIST, USA

9. "CFD Simulation of a 3.5 MW Oil Pool Fire in a Nuclear Power Plant Containment Building Using Multi-block Large Eddy Simulation," **Jason Floyd**, NIST, USA

10. "Verification, Validation, and Selected Applications of the VULCAN and FUEGO Fire Field Models," **Louis Gritzo**, SNL, USA

4:45-5:30 PM "NIST Large Fire Facility," George Mulholland, NIST, USA
Presentation and tour of test facility.

7:30 PM ***No Host Dinner - Joe's Crab Shack, Kentlands, Gaithersburg***

May 3, 2002

8:30 AM - 12:00 Noon — ***Session IV: Preliminary Results of Benchmark Exercise # 2, Part I, Evaluation of Fire Models for Nuclear Facility Applications: Pool Fires in Large Halls***

Discussion Leader: Stewart Miles, BRE, UK

1. "Specification of Benchmark Exercise # 2, Part I," **Stewart Miles**, BRE, UK

Preliminary Results

	Presenter	*Code Exercised*
2.	**Walter Klein-Hessling**, GRS, Germany	COCOSYS (lumped parameter)
3.	**Mathias Heitsch**, GRS, Germany	CFX (CFD)
4.	**Jonathan Barnett**, WPI, USA	WPI Class Exercise
5.	**Amber Martin and Alan Coutts**, Westinghouse, USA	CFAST (zone model)
6.	**Boro Malinovic**, Fauske Associates, USA	HADCRT (lumped parameter)

12:00-1:00 PM — ***Lunch***

1:00-2:30 PM — ***Session IV Continued: Benchmark Exercise # 2***

Discussion Leader: Stewart Miles, BRE, UK

7.	**Kevin McGrattan**, NIST, USA	FDS (CFD)
8.	**Stewart Miles**, BRE, UK	JASMINE (CFD), CFAST

9. "Proposal for Part II of Benchmark Exercise # 2, **Stewart Miles**, BRE, UK

10. Comments on Proposal for Part II of Benchmark Exercise # 2, **Workshop Participants**

2:30-2:45 PM — ***Break***

2:45-4:00 PM — ***Session V: Future Tasks and Benchmark Exercises***

Discussion Leader: Moni Dey, U.S. NRC

1. "Detector Response Modeling," **Doug Beller**, NFPA, USA

2. "A New Model for the Time Lag of Smoke Detectors," **Olavi Keski-Rahkonen**, VTT, Finland

3. "Proposed Benchmark Exercise for Cable Fire Tests in NPP-Type Compartments," **Marina Rowekamp**, GRS, Germany

4. "Proposed Benchmark Exercise for Kerosene Pool Fire Tests in Containment Building," **Marina Rowekamp**, GRS, Germany

5. "Challenges in use of State-of-the-Art Fire Modeling Tools in Nuclear Power Plant Applications," **Bob Kassawara, Bijan Najafi**, and **Francisco Joglar-Billoch,** EPRI, USA

6. "NRC Plans for Fire Tests for Model Benchmark Exercises," **Moni Dey**, U.S. NRC

4:00-5:00 PM ***Session VI: Task Scheduling and Project Management***

Discussion Leader: Moni Dey, U.S. NRC

5:00 PM ***Workshop Concludes***

5:00-5:30 PM ***Optional Tour of NIST Fire Detector Laboratory***

All papers are allotted 20 minutes for presentation and 5 minutes for discussion.

Appendix B: Specification of Benchmark Exercise # 2

International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications

Specification for *Benchmark Exercise # 2*

Fire in a Large Hall

Issue 1 - February 2002

Introduction

In October 1999 the U.S. Nuclear Regulatory Commission and the Society of Fire Protection Engineers organised a planning meeting of international experts and practitioners of fire models to discuss the evaluation of numerical fire models for nuclear power plant applications [1]. Following this meeting an international collaborative project was set up with a view to sharing knowledge and resources from various organisations and to evaluate and improve the state of the fire modelling methods and tools for use in nuclear power plant fire safety.

The first task of the collaborative project was to undertake a benchmark exercise to evaluate the current capability of fire models to analyse the hazard associated with cable tray fires of redundant safety systems in nuclear power plants. These systems are required to shutdown the reactor during an emergency, and when located inside the same compartment must be separated by a specified distance to ensure that a fire in one system does not cause the other to fail also. The exercise involved a series of hypothetical scenarios to predict cable damage inside an emergency switchgear room, and were fairly tightly specified in respect of the input and modelling parameters to be used. Results and analyses were presented at a meeting at EPRI, California, in January 2001. Due to the size of the room and the nature of the fire scenarios, the differences in the conclusions obtained using the various fire models were not significant. Target cable damage was predicted to be unlikely in almost all cases studied.

This document defines the second benchmark exercise. It has been selected to challenge fire models in respect to issues not addressed in the first exercise, e.g. effects of fire in a large volume representative of, say, a turbine hall. Furthermore, it includes some scenarios for which there are unpublished experimental measurements, allowing comparisons to be undertaken.

Objectives of *Benchmark Exercise # 2*

Benchmark Exercise # 1 [2] focussed on an evaluation of fire models for predicting cable damage in an emergency switchgear room. A summary of the main results, findings and conclusions is included in the Technical Reference Report [3].

The main objectives taken into consideration when selecting the second benchmark exercise were:

1. To examine scenario(s) that provide a harder test for zone models, in particular with respect to fire spread in large volumes representative of, say, a turbine hall.

2. If possible, to make use of experimental data to fulfil the requirement of more thoroughly testing the predictive capability of both zone and CFD fire models. Again, the emphasis when selecting scenarios was on large smoke filling volumes.

Summary of Selected Scenarios

Benchmark Exercise # 2 is divided into two parts. For the first part there are experimental measurements of temperature and velocity against which model predictions can be compared. The second part extends the scope of the exercise to examine the consequence of larger fires, but for which there are no experimental measurements against which to compare.

Part I includes three cases, based on a series of full-scale experiments inside a test hall with dimensions *19 m* high by *27 m* long by *14 m* wide (i.e. floor area *378 m^2*). Each case involves a single fire (2 - 4 *MW*), and for which there are experimental measurements of gas temperature and doorway velocity. The height of a turbine hall within an NPP (c. *25 m*) is similar to that of the test hall although it is acknowledged that the area of a turbine hall (c. *3500 m^2*) is much greater. However, the test hall is one of the largest enclosures for which fire test data is available for comparison with model predictions.

Part II includes three additional cases for which experimental measurements do not exist, but extend the scope of the benchmark exercise to examine the effect of a bigger fire and larger floor area representative of a hydrocarbon pool fire in a real turbine hall. These are optional cases for participants to investigate if time and resources allow.

Although most input parameters are defined, *Benchmark Exercise # 2* does in a few respects involve a greater degree of user judgement in setting up the problem compared to the first benchmark exercise. This applies in particular to the treatment of the sloping roof (with zone models) in Part I.

Scheduled Activities

1. February 2002

   Release final version of the problem definition for *Benchmark Exercise # 2*, to be made available from the collaborative project document library, together with a summary of the experimental measurement data analysis for the Part I cases. The released data for Part I will include temperatures at three thermocouple tree locations, velocities in the open doorways (case where they are open) and calculated layer height and upper layer temperature (derived from the thermocouple measurements and a two-zone assumption).

2. February to September 2002

   Participants to perform simulations of Part I, and if time and resource allows, Part II.

3. 2nd/3rd May 2002 (5th project meeting at NIST)

   Participants invited to present any preliminary numerical predictions and analysis for Part I at the 5th project meeting at NIST, USA. This will provide an opportunity for those participants who have started work on Part I of the benchmark exercise to discuss their initial results and findings.

4. 6th September 2002

   Participants to send to BRE their 'final' numerical predictions for Parts I and II (if undertaken) in either a text file or Excel spreadsheet. Participants should also provide a brief summary of the modelling assumptions used for each case reported. Guidelines on the information required are given in the case descriptions below.

5. October 2002 (6th project meeting at BRE)

   BRE to present an overview of the results based on the information supplied.

   Participants to present their results and findings for Parts I and II (if undertaken). This will follow a similar format to that adopted for the first benchmark exercise at the 3rd project meeting at EPRI, USA.

6. December 2002.

   Draft technical reference document on the second benchmark exercise released. To be compiled by BRE and including technical annexes from the other participants as for the first technical reference document.

Part I – Large Hall Tests

Introduction

The three cases defined here are based on a series of full-scale fire tests inside a large hall. In each case a pool of heptane burned for approximately five minutes, during which time gas temperatures were measured at three thermocouple columns and at two thermocouple locations directly above the fire source. In two cases the hall was nominally closed, while for the third case a mechanical extract system was operational and two 'doorway' openings were provided.

For each case, two tests were performed under nominally identical conditions. Performing a repeat test allowed the variation in measured values due to changing ambient conditions (and other factors) to be investigated. In all three cases the repeatability of the measurements was reasonably good. The mass release rate of fuel for each of the three cases given below is the average from the two tests for that case.

Geometry

Figure 1 shows the geometry of the hall, comprising a rectangular space with a pitched roof structure above. A Cartesian axis system is defined, with the origin as indicated. All dimensions are in metres. The four walls are labelled as *west* (*x=0*), *east* (*x=27 m*), *south* (*y=0*) and *north* (*y=13.8 m*). Here the *west* and *east* walls known collectively as the end walls and the *south* and *north* walls as the side walls.

In cases 1 and 2 there are two open doorways, *0.8 m* wide by *4 m* high, one located in each end wall. Both doorways open to the external ambient environment, and are located such that the centre is *9.3 m* from the *south* wall (*y=9.3 m*). The doorway openings are labelled as the *west* doorway (door 1) and the *east* doorway (door 2).

Figure 2 shows the internal geometry of the test hall for Part I, including the location of the fire source.

A single mechanical exhaust duct is located in the roof space, running along the centre *y*-plane. It has a circular section with a diameter *1 m*, and opens horizontally to the hall at a distance *12 m* from the floor and *10.5 m* from the *west* wall (*x=10.5 m*).

Figure 2 shows the location and dimensions of two obstructions were present inside the hall during the experiments and may have influenced the internal air movement. If included in simulation these should be treated as simple rectangular obstructions. The small circles indicate the location of the thermocouples and velocity probes, which are discussed below.

Figures 3, 4 and 5 contain plan, side and end views of the hall respectively, and should further clarify the geometry and dimensions.

Participants should decide for themselves how to incorporate the roof geometry. For a zone model it might be decided to set the (flat) ceiling height such that the volume of the hall is preserved. Participants are free to undertake a series of simulations using alternate strategies, and to comment on the findings.

Material properties

The walls and ceiling consist of a *1 mm* (*0.001 m*) layer of sheet metal on top of a *0.05 m* layer of mineral wool. The floor is constructed from concrete. Table 1 presents the thermal properties of the sheet metal, mineral wool and concrete materials.

Table 1 **Material properties for Part I**

Material		Thermal properties		
		conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)
metal sheet		54	7850	425
mineral wool		0.2	500	150
concrete		2	2300	900

If included by the participant, the internal obstructions can be modelled as concrete (properties as given in Table 1). However, as the choice of material properties for the internal obstructions is not likely to have an important bearing on the numerical predictions, the obstructions can optionally be treated as adiabatic, i.e. no heat transfer.

All surfaces are assumed to have an emissivity of 0.95, i.e. almost black body, and a convective heat transfer coefficient of $10\ J\ s^{-1}\ m^{-2}\ K^{-1}$.

Ambient conditions

Ambient pressure and temperature are 101300 $N\ m^{-2}$ and 20 *°C* respectively.

Ventilation conditions

Mechanical exhaust ventilation is operational for one case, with a constant volume flowrate of $11\ m^3 s^{-1}$ drawn through the *1 m* diameter exhaust duct. For this case there are two doorway openings as described above.

For the other two cases the mechanical exhaust system does not operate and the doors are closed. Ventilation is restricted to infiltration through the building envelope. Exact information on air infiltration during these tests is not available. However, following discussions with the scientists involved in the experiments, it is recommended that air infiltration be modelled by including four small, square openings to the outside ambient environment, each opening having an area $0.5\ m^2$. For the purpose of the benchmark exercise it is suggested that two openings be located in the *east* wall, one at floor level and *12 m* above the floor, and two at the opposite end of the hall in the *west* wall. Table 2 shows the co-ordinates of the centre of the four openings.

Note that air infiltration should be ignored in the two cases with mechanical ventilation and doors open.

Table 2 **Openings to simulate effect of air infiltration in Part I**

Opening (0.707m x 0.707m)	Co-ordinates of centre x (m)	y (m)	z (m)
1	0	6.9	0.354
2	0	6.9	12
3	27	6.9	0.354
4	27	6.9	12

Fire Source

A single fire source was used in each test, its centre located *16 m* from the *west* wall and *7.2 m* from the south wall (*x=16 m, y=7.2 m*) as indicated in Figure 2. For all tests heptane was burned on top of water in a circular, steel tray. The fuel surface was *1 m* above the floor. Two tray diameters were used, *1.17 m* for one case and *1.6 m* for the other two. The trays were placed on load cells, and the mass release rate then calculated from the time derivative of the load cell weight readings.

For the three cases defined below the fuel mass release rate ($\dot{m}_f$) is provided as an input parameter. The choice of combustion mechanism is left to the participant. However, it is suggested that the fuel rate of heat release be modelled as

$$\dot{Q}_f = \chi \dot{m}_f \Delta H_c \tag{1}$$

Here the heat of combustion (ΔH_c) is taken as $44.6 \times 10^6\ J\ kg^{-1}$. The recommended combustion efficiency (χ) value of *0.8* may be interpreted also as a radiative fraction of *0.2*. For the purpose of the benchmark exercise, it is suggested that as in the first benchmark exercise a value of *12%* be assigned to the lower oxygen limit parameter in those combustion models that make use of it. However, participants are encouraged to investigate other values if they believe this to be important.

Instrumentation

Data was obtained from the instrumentation described below, against which numerical predictions can be compared:

1. Three vertical thermocouple trees, located as shown in Figure 6, on the centre *y*-plane at distances *1.5 m, 6.5 m* and *20.5 m* from the *west* wall. The vertical distribution of thermocouples, the same for all three trees, is shown in Figure 7. Individual thermocouples are labelled as shown in Figure 7, where *T2.5*, for example, refers to the fifth thermocouple on tree number 2. Each thermocouple was a *0.1 mm* K-type. Note that the readings from these thermocouples were used to calculate a layer height and upper layer temperature as described below.

2. Two horizontal thermocouple grids centred directly above the fire source at a height of *7 m* and *13 m*. Both grids consisted of nine *0.5 mm* K-type thermocouples arranged in a 3 by 3 array. However, for the benchmark exercise attention is focussed only at the centre

thermocouple at each height, directly above the centre of the fire tray. These are labelled as *TG.1* and *TG.2* in Figure 7.

3. For the case with mechanical ventilation and open doorways, a vertical column of bi-directional probes to measure gas velocity was located in each doorway opening. Each column contained three probes located on the vertical centre-line of the opening at the heights shown in Figure 7. Note that a positive value indicated flow from the outside to the inside of the hall. The velocity measurements may be used to estimate the net flow of air through the opening.

Two-layer data reduction

A two-layer zone model will predict upper and lower layer properties, and the height of the interface separating the layers. Therefore, to make comparisons between experimental measurements and zone model predictions, the thermocouple data must be reduced in some way.

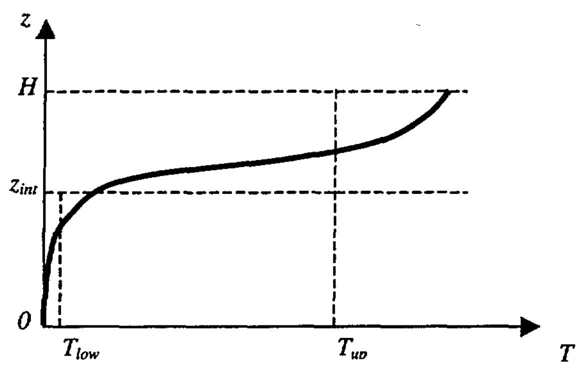
Participants will be provided with the measurement data for all thermocouple locations, and will be free to make their own data reduction to generate upper/lower layer and interface height 'measurements'. However, the method described below will be used as a 'baseline' method and the resultant layer values will be provided along with the 'raw' measurement data.

Furthermore, participants using CFD and network models will be invited to calculate 'upper layer' and 'lower layer' temperatures and an 'interface height' for comparison against zone model predictions. For consistency, the method described below, based on predictions of temperature at the thermocouple tree locations, should be used. If they wish, participants may in addition use their own methods for calculating 'upper layer' and 'lower layer' temperatures and an 'interface height' (and should document these methods).

Layer temperature and interface calculation

The one-dimensional analytical method presented here allows an upper layer temperature (T_{up}), lower layer temperature (T_{low}) and interface height (z_{int}) to be calculated given a discrete set of temperatures (T_i) at heights above floor level (z_i), $i=1,N$.

Consider a continuous function $T(z)$ defining temperature as a function of height z, from 0 (floor level) to H (ceiling).



Then, from the zone model concept and the conservation of mass, we may write

$$(H - z_{\text{int}})T_{up} + z_{\text{int}}T_{low} = \int_0^H T(z)dz = I_1 \quad (2)$$

$$\left(H - z_{\text{int}}\right)\frac{1}{T_{up}} + z_{\text{int}}\frac{1}{T_{low}} = \int_0^H \frac{1}{T(z)}dz = I_2 \qquad (3)$$

Algebra then gives

$$z_{\text{int}} = \frac{T_{low}\left(I_1 I_2 - H^2\right)}{I_1 + I_2 T_{low}^2 - 2T_{low}H} \qquad (4)$$

Here, T_{low} is taken as the temperature at the lowest discrete measurement location (T_1) and I_1,I_2 are calculated from the discrete data set using a quadrature rule, e.g. Simpsons Rule. T_{up} is then calculated by applying the mean value theorem over the interval $z=z_{int}$ to $z=H$

$$T_{up} = \frac{1}{H - z_{\text{int}}}\int_{z_{\text{int}}}^{H} T(z)dz \qquad (5)$$

In reducing the thermocouple tree data it is proposed that the average of the three values (one from each tree) is taken at each distance above the floor.

Exercises

The three cases to be simulated are summarised below. Details of geometry, material properties, ambient conditions, ventilation rates and instrumentation are as defined above. The specifications given here represent the 'baseline' scenarios. Participants are invited to perform study variations on these cases in order to gain insight into the performance of the fire models used. However, the three 'baseline' cases should be given priority, and furthermore *case 1* should be given highest priority.

The fire source should be taken as pure heptane, located as described above. For *case 1* the pool diameter is *1.17 m* while for *cases 2* and *3* it is *1.6 m*. Table 3 defines the fuel mass release rate for each case at discrete times in minutes. A piecewise linear polynomial should be assumed, i.e. interpolate linearly between the given points.

Table 4 summarises the ventilation conditions for the three cases. Natural leakage should be modelled as described above.

Each case should be modelled for the duration of the fire, assuming the fire to have stopped after the last entry in Table 3, i.e. 7.5 minutes of *case 1*, 7 minutes for *case 2* and 6 minutes for *case 3.*

Table 3 Fuel mass release rates for Part I

Case 1		*Case 2*		*Case 3*	
t (min)	*dm/dt (kg s^{-1})*	*t (min)*	*dm/dt (kg s^{-1})*	*t (min)*	*dm/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	0.06	5.75	0
		6.58	0		

Table 4 Ventilation conditions for Part I

Case 1	*Case 2*	*Case 3*
doors closed	doors closed	doors open (*0.8 m x 4m*)
no mech. exhaust	no mech. exhaust	mech. exhaust (*11 m^3 s^{-1}*)
natural leakage	natural leakage	ignore natural leakage

Reporting procedure

The reporting schedule is summarised in the Scheduled Activities above. This section documents the format to be adopted when submitting predictions to BRE in September 2002.

Participants should submit data in either a text file or Excel spreadsheet, and also summarise their findings and modelling assumptions.

The 'raw' prediction data at each reported time will occupy a single record (text file) or row (spreadsheet), with each quantity (e.g. layer height) occupying one field (text file) or column (spreadsheet). While the first field or column should be the time value, the ordering of the remaining fields/columns is left to the participant. However, each field/column should be clearly labelled and the units stated. Numbers may be formatted as deemed appropriate, e.g. fixed number of decimal places, scientific notation (1.5e+2), etc. As a hypothetical example, part of a text file format might appear as below,

Time(s)	T1.1(C)	T1.10(C)	V1.1(m/s)	Layer height(m)
0.	0.	0.	-0.05	19.
10.	0.	0.2	-0.06	19.
30.	0.1	2.8	1.1	16.

It is suggested that results be reported at 10-second intervals. However, this is a guideline only and not a formal requirement (sufficient points to produce representative graphs is the minimum requirement).

Table 5 includes a list of suggested variables to be reported for zone and CFD models (acknowledging that for network models the number of reported variables will be somewhere in between). If a fire model does not output a particular variable, then the participant should ignore it. The number of variables to be reported depends in part on the fire model, with CFD models allowing for a greater number of outputs. Participants are free to include other variables that they consider important.

In addition to the tabulated results, participants are asked to summarise the main modelling assumptions and inputs used. This will include a short summary on the following topics at least (one or two paragraphs on each topic):

- Heat release (combustion) mechanism. This could be a combustion model or a simple heat release source term. Issues such as the lower oxygen limit should be reported.
- Radiation treatment (if included. Important issues may include the treatment radiation transfer to solid surfaces, the absorption/emission in the gas phase and radiation from soot plume.
- The zonal approximations used and main empirical correlations (in the case of a zone model).
- The number of control volumes or elements (in the case of a CFD model), or equivalently the number of network elements (in the case of a network model).
- The turbulence model (in the case of a CFD model).
- Roof geometry assumptions (this relates mainly to zone models).

Table 5 Reported variables for Part I

Zone	CFD
Heat release rate of fire	Temperatures at thermocouple trees (T1.1,...,T1.10,T2.1,...,T2.10,T3.1,...,T3.10)
Interface height	Temperatures at plume thermocouples (TG1.1 & TG.2)
Upper layer temperature	Infiltration flow rate (cases 1 & 2)
Infiltration flow rate (cases 1 & 2)	Mass flow rate in/out door 1 (case 3)
Mass flow rate in/out door 1 (case 3)	Mass flow rate in/out door 2 (case 3)
Mass flow rate in/out door 2 (case 3)	Velocities at the two doorways (case3) (V1.1,...,V1.3,V2.1,...,V2.3)
Total heat loss rate to solid boundaries	Total heat loss rate to solid boundaries
Heat loss through mech. exhaust (case 3)	Heat loss through mech. exhaust (case 3)
Plume temperature	
	Interface height (using reduction of thermocouple tree data)
	Upper layer temperature (using reduction of thermocouple tree data)
	Total heat release rate (within whole hall)

Part II – Extended NPP Scenarios

Introduction

Part II has been added as an optional extension to the benchmark exercise. It includes three scenario cases inside a rectangular building with dimensions comparable to those of a real turbine hall. The fire size has been chosen to produce temperatures that may be capable of damaging equipment or cables.

As in Part I mechanical exhaust is specified in a sub-set of cases. Targets have been added to Part II to allow the onset of damage to be studied.

Geometry

Figure 8 shows the geometry and dimensions of the building, which are comparable to those of a real turbine hall. For the benchmark exercise there is a doorway opening in the *west* wall and at the opposite location in the *east* wall.

Material properties

To simplify the modelling task, assume the floor, walls and ceiling to be constructed from concrete, with the thermal properties as given in Table 1, and a thickness of *0.15 m*. Again, assume an emissivity of 0.95 and a convective heat transfer coefficient of $10\ J\ s^{-1}\ m^{-2}\ K^{-1}$.

Ambient conditions

As specified for Part I.

Ventilation conditions

Ventilation is provided in all three cases through a doorway opening in the *west* and *east* walls as shown in Figure 8. In two cases both openings have dimensions *1 m* wide by *4 m* high, while for the third case the openings are *4 m* square. Figure 9 shows the location and dimensions of the doorway opening more clearly. The dashed line indicates the location of the larger square doorway in the third case.

In two cases there is mechanical exhaust through 12 vents at ceiling level. Each vent is square with dimension *1 m*. Figure 8 shows the location of the 12 vents.

Fire Source

For all cases, heptane is burned in a square, *4 m* by *4 m*, tray such that the surface of the fuel is *1 m* above the floor. The fire is located centrally inside the hall as indicated in Figure 10. Fuel and combustion properties are as specified for Part I.

The mass release rate of the pool fire ($\dot{m}_f$) grows from zero to a steady value $1.55\ kg\ s^{-1}$ (derived from published data for heptane pool fires [4]) as follows,

$$\dot{m}_f = \alpha t^2 \qquad (6)$$

Here t is the time in seconds from the start of the fire, and α is a constant with value $5.325 \times 10^{-6}\ kg\ s^{-3}$. This value is derived from an assumed NFPA ultra fast t-squared growing fire [5]. Equation (6) defines the mass release rate for the first nine minutes, at which time it reaches the steady value $1.55\ kg\ s^{-1}$ which is maintained for the next 11 minutes (giving 20 minutes total duration).

Targets

To make Part II relevant to practical applications three cable targets have been introduced, similarly to the first benchmark exercise. Each cable is a *50 mm* (*0.05 m*) diameter power cable, assumed to consist entirely of PVC. The thermal properties of the cable material are the same as in the first benchmark exercise, repeated below in Table 6.

Table 6 Material properties for cable targets

conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)	emissivity	convective htc ($J\ s^{-1}\ m^{-2}\ K^{-1}$)
0.092	1710	1040	0.8	10

A structural beam target is included also. To simplify the modelling, this is approximated as a horizontally orientated rectangular slab of steel with cross-sectional dimensions of *0.15 m* wide and *0.006 m* thick. Table 7 provides the material properties to be assumed for the steel 'beam' target, where the conductivity, density and specific heat correspond to steel (0.5% carbon) at 20 °C [6]. It is assumed for the purpose of this exercise that property values are temperature independent. A damage temperature of *538 °C* is assumed.

Table 7 Material properties for 'beam' target

conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)	emissivity	convective htc ($J\ s^{-1}\ m^{-2}\ K^{-1}$)
54	7833	465	0.8	10

Figures 9 and 10 show the locations of the three cable targets and the 'beam' target. The cables extend the full length of the hall (x direction), and the 'beam' extends the full width (y direction). The centre-lines of the three cables are *1 m* from the south wall, and *9 m*, *15 m* and *19 m* above the floor respectively. The 'beam' centre-line is midway across the width of the hall and *0.5 m* below the ceiling.

Internal ceiling

For the exercises described below, an internal ceiling has been added for some cases, effectively dividing the turbine hall into two levels. This makes the geometry more representative of a 'real-life' situation.

It is assumed that the internal ceiling is located *10 m* above ground level and again constructed from *0.15 m* thick concrete (material properties as given in Table 1). Furthermore, there is a hatch opening with dimensions *10 m* by *5 m* within the internal ceiling, providing a connection between the lower and upper levels. Figure 11 shows the location of the internal ceiling and hatch opening.

Exercises

The exercises are divided into two groups of three, where there the first group (cases *1a*, *2a* and *3a*) does not include the internal ceiling (i.e. a single compartment), and the second group (cases *1b*, *2b* and *3b*) includes the internal ceiling (i.e. two compartments) and the hatch opening.

The cases to be simulated are summarised below in Table 8. Note that *case 1b* is the same as *case 1a* but with the addition of the internal ceiling, and likewise for the other cases. Each case lasts for 20 minutes, or until the participant decides there is no need to proceed further, e.g. the cables and 'beam' are damaged.

Case 1 takes highest priority in both the '*a*' and '*b*' groups. While the cases with the internal ceiling are perhaps the more interesting, and arguably warrant priority, it is acknowledged that these are more complex to model and so participants are free to concentrate on the 'simpler' single compartment cases if preferred.

Table 8 Cases for Part II

Case 1a	*Case 2a*
1m x 4m doorway openings no mechanical exhaust ventilation	*1m x 4m* doorway openings *16* $m^3\ s^{-1}$ mechanical exhaust ventilation (divided evenly between the 8 vents)
Case 3a	*Cases* 1b, *2b* and *3b*
4m x 4m doorway openings *80* $m^3\ s^{-1}$ mechanical exhaust ventilation (divided evenly between the 8 vents)	As for *cases 1a*, *2a* and *3a*, but with addition of the internal ceiling partition, dividing the volume into two levels

Reporting procedure

Predictions should be reported in September at the same time as for Part I.

<u>*Cases 1a*, *2a* and *3a*</u>

The format and variables for group '*a*' cases (single compartment) are as for Part I, with the following additions or amendments:

- The three vertical thermocouple trees are at the locations shown in Figure 10. These are of relevance to CFD models, where it is requested that gas temperatures be provided at 1-meter intervals in height (labelling the locations *T1.1* – *T1.19* etc similarly to that done for Part I).
- As for Part I, the gas temperature directly above the fire is requested at two locations (CFD models), but now at heights *9 m* and *19 m*.
- Three doorway velocities should again be considered at *0.5 m*, *1 m* and *3.5 m* height, on the vertical centre line of each opening.

- The total heat loss through the doorway opening should be provided if possible.
- Upper and lower layer oxygen concentration should be provided in the case of zone models. For CFD models the oxygen concentration at the thermocouple tree locations should be provided.
- For each cable target and the 'beam' target the following should be provided, where possible, at each reported time:

  ⇒ maximum incident flux

  ⇒ maximum surface temperature

  ⇒ maximum centre-line temperature

  Here the maximum refers to the maximum along the length of the cable or 'beam'. If they wish, participants may provide the values at the mid-point (i.e. at $x=40$ *m* for the cables and $y=20m$ for the 'beam') allowing a simpler conduction modelling approach to be used.

Participants should provide comments on the likelihood of damage to the targets, and if so at what time into the fire the damage occurs.

Cases 1b, 2b and *3b*

The reporting procedure is as for the group '*a*' cases above, except that the two levels should be accounted for. This means that interface heights and upper layer temperatures should be provided for each level (compartment). Furthermore, the transfer of mass and heat through the hatch opening should be reported.

Where gas temperatures are reported, these should be at the same locations as for the group '*a*' cases (except that there is no temperature at locations *T1.10* and *T2.10* because of the presence of the internal ceiling, and so a blank entry should be provided for this location).

References

1. International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications – Summary of Planning Meeting (24th-25th October 1999, University of Maryland, USA), NUREG/CP-0170, February 2000.

2. International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications – Benchmark Exercise # 1 – cable tray fires of redundant safety trains, 11 September 2000.

3. International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications – Technical Reference Report on Benchmark Exercise # 1, to be published.

4. Babrauskas, V. Estimating large pool fire burning rates. *Fire Technology*, vol. 19, pp. 251-261, 1983.

5. NFPA 204M - Guide for Smoke and Heat Venting. National Fire Protection Association, 1985.

6. SFPE Handbook of Fire Protection Engineering, 2nd Ed., National Fire Protection Association, 1995.

Acknowledgements

The experimental measurements for Part I were collected by VTT as part of the European Coal and Steel Community (ECSC) project *$NFSC_2$*, and are used by permission of the executive committee, SERDEC.

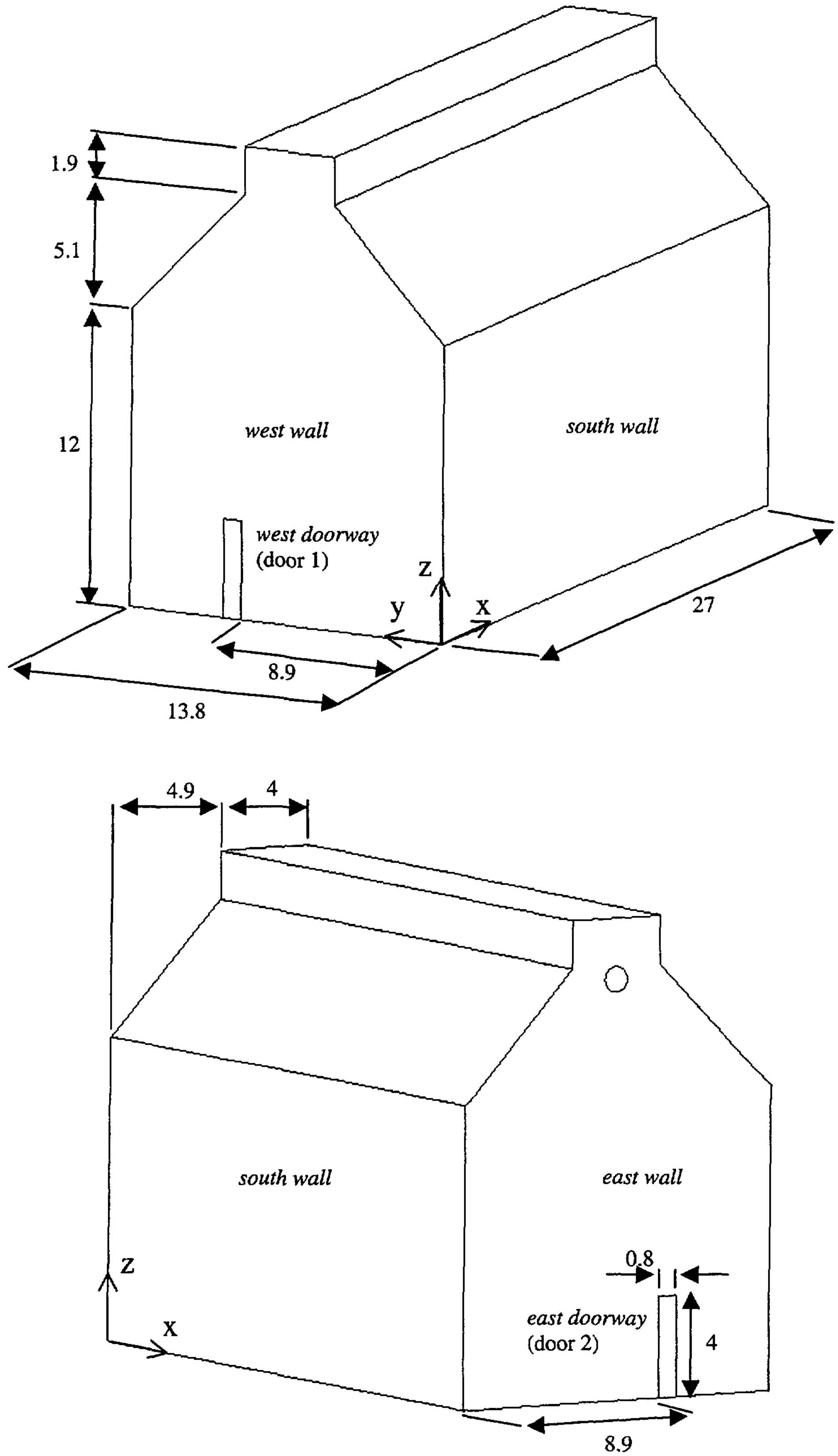
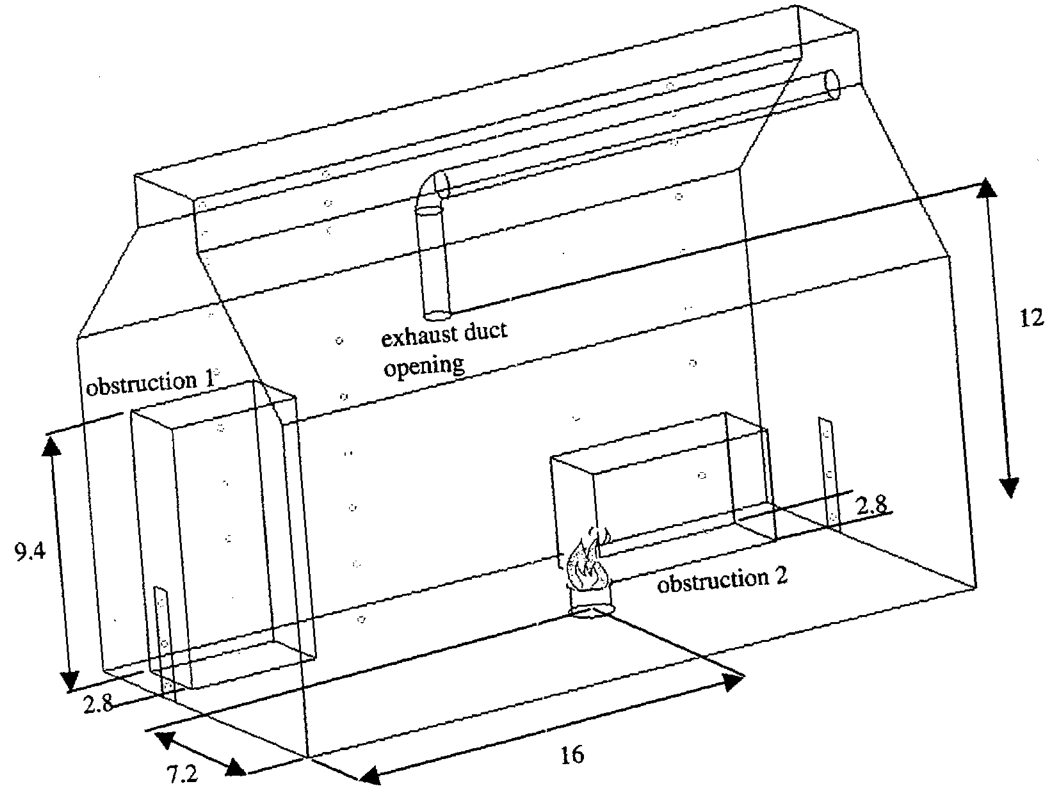


Figure 1 Hall and doorway dimensions for Part I



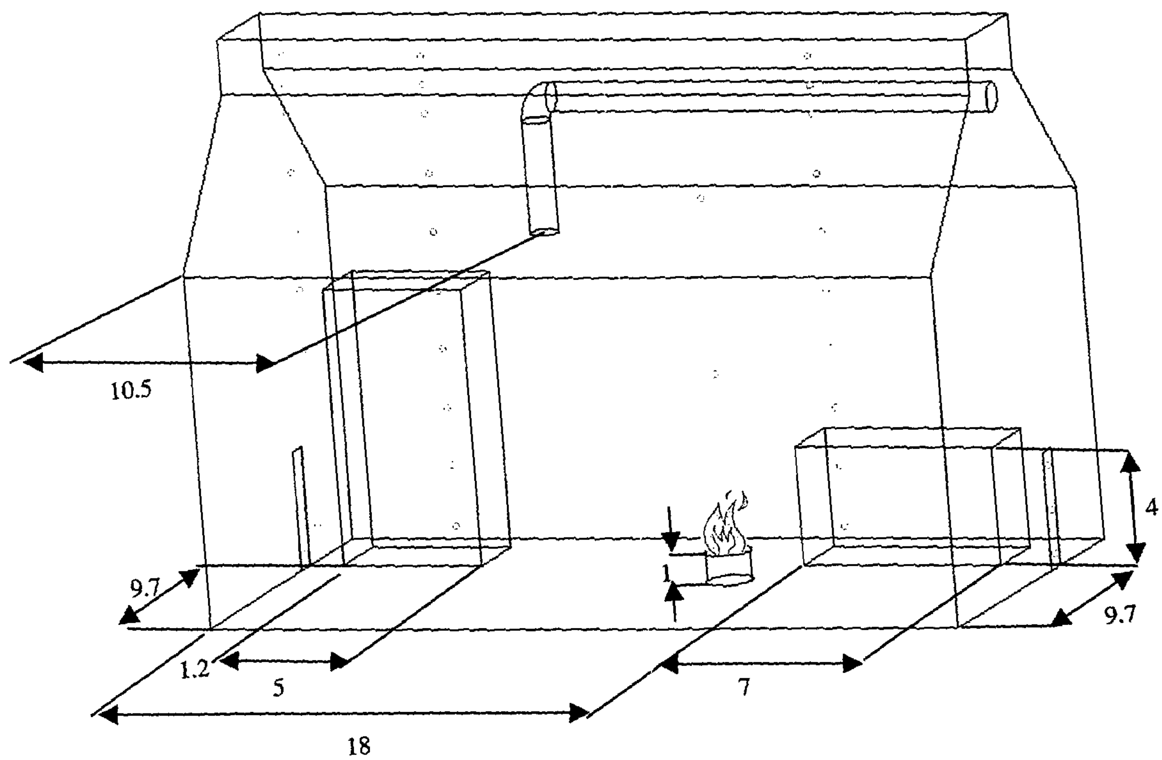


Figure 2 **Internal geometry for Part I**

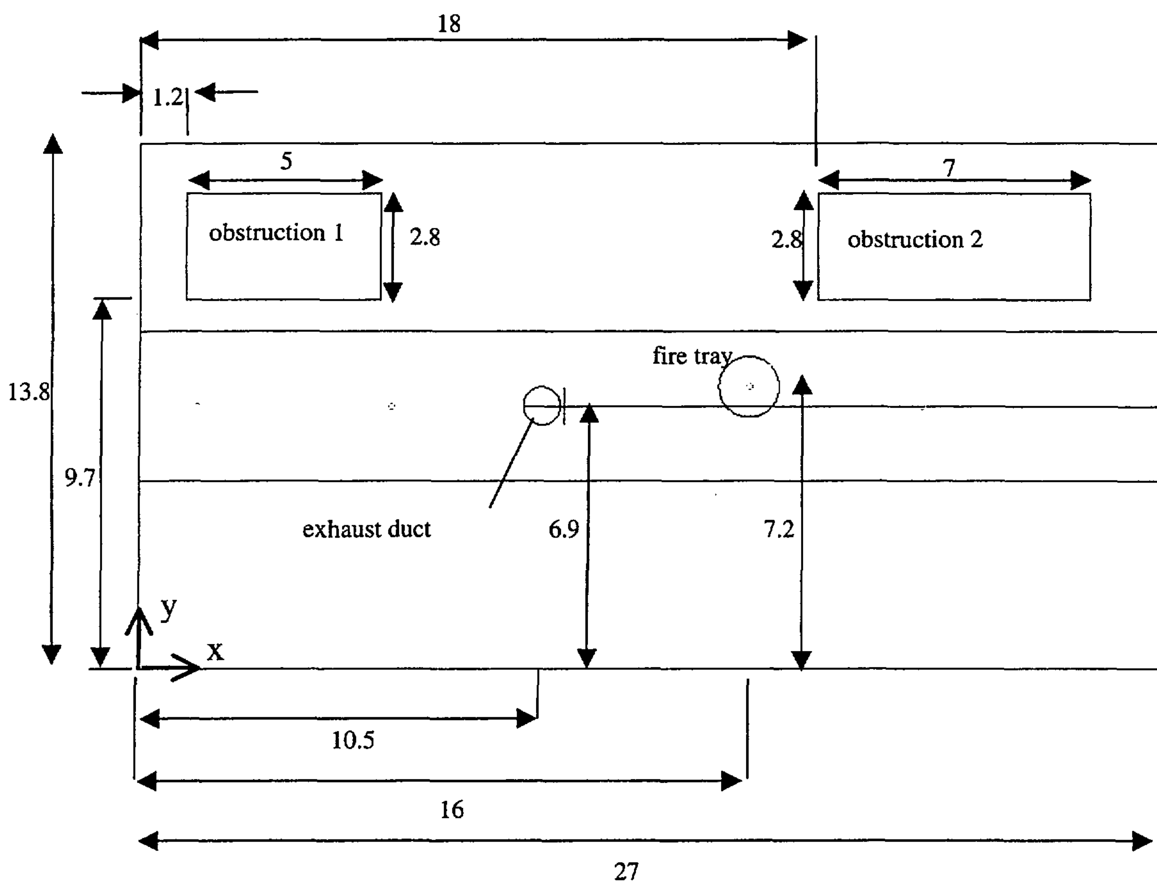


Figure 3 **Plan view for Part I**

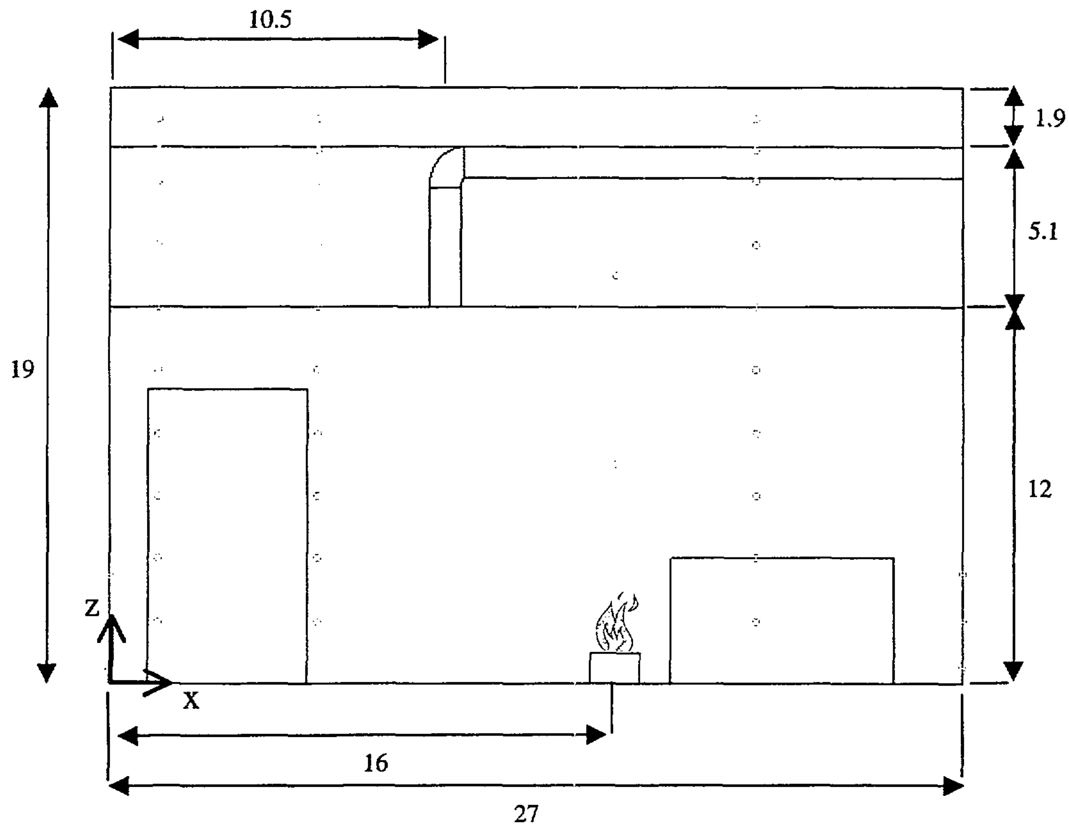


Figure 4 Side view for Part I

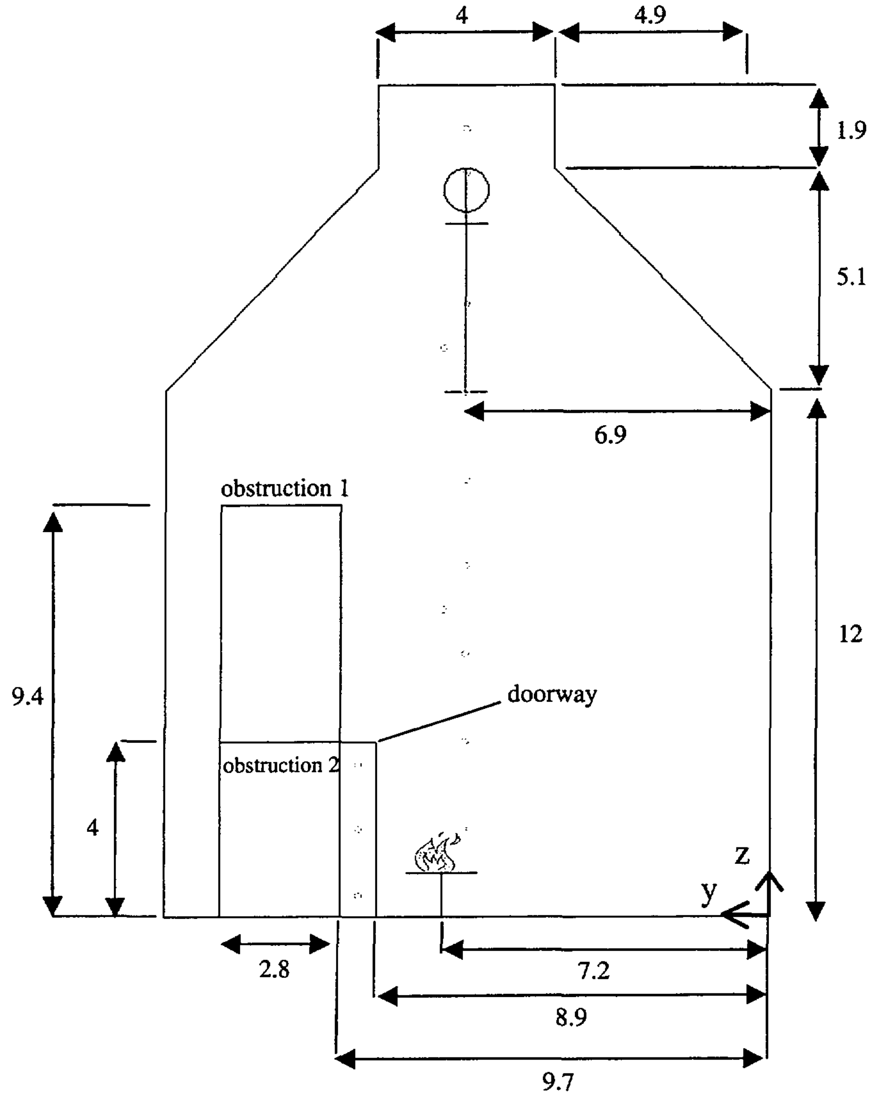


Figure 5 **End view for Part I**

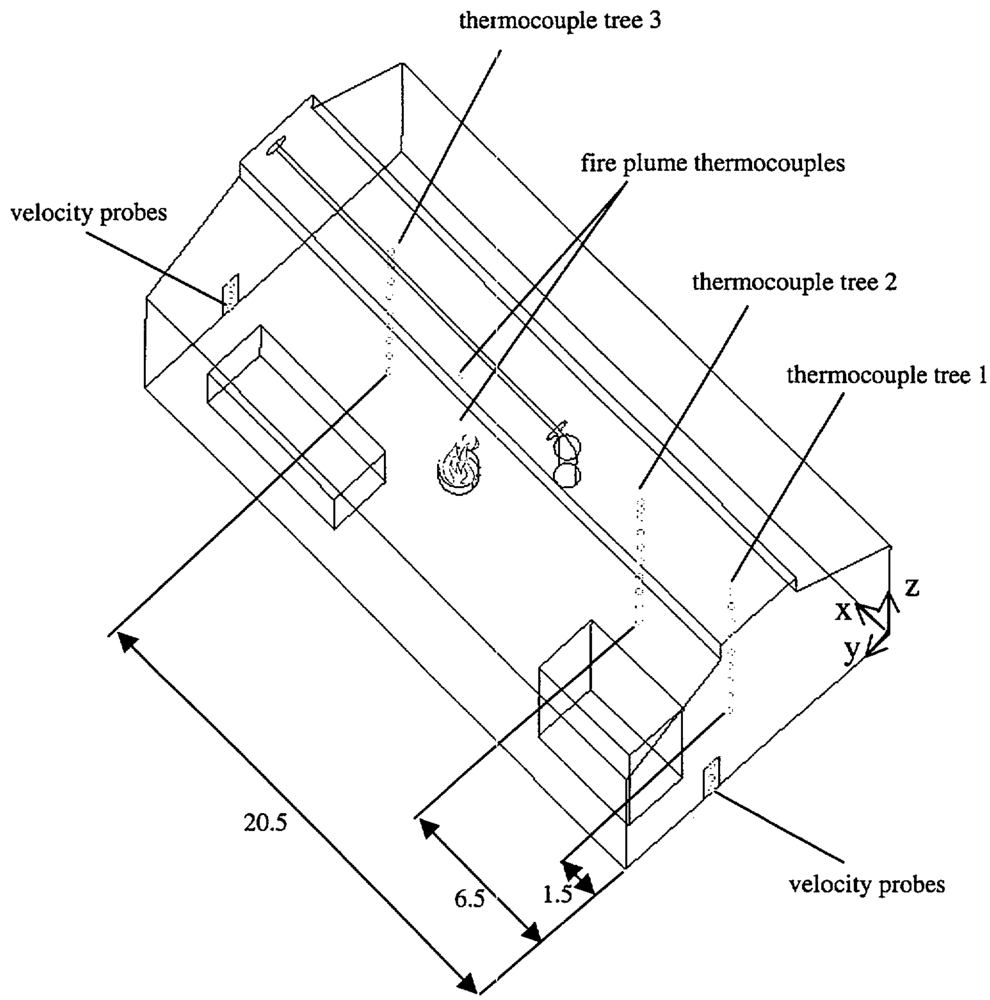


Figure 6 **Experimental instrumentation for Part I**

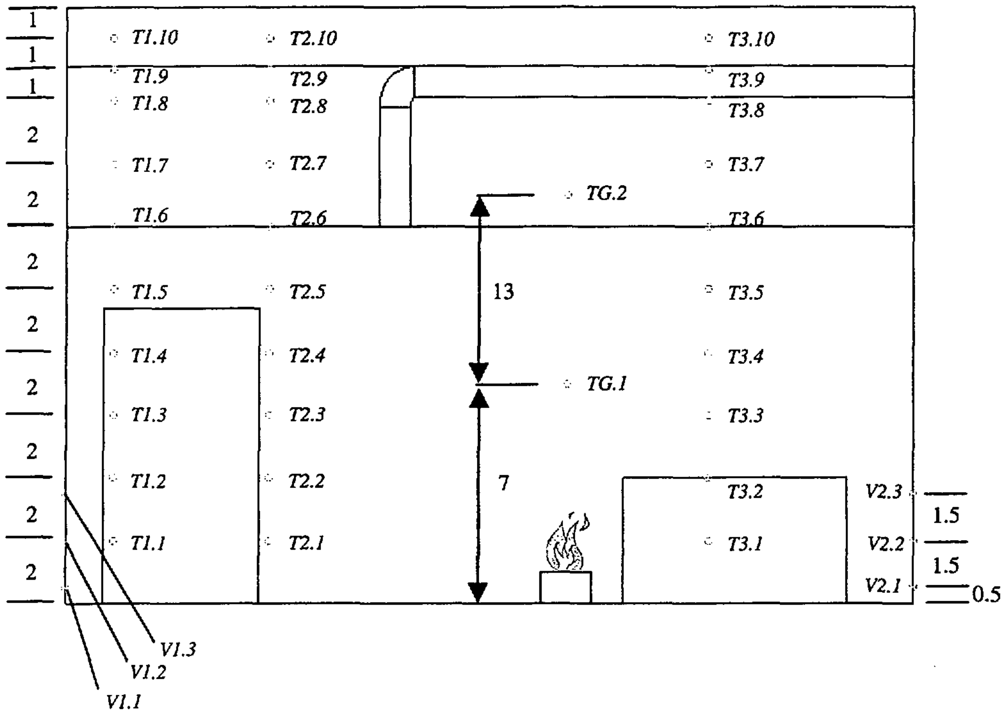


Figure 7 **Individual thermocouples and velocity probes for Part I**

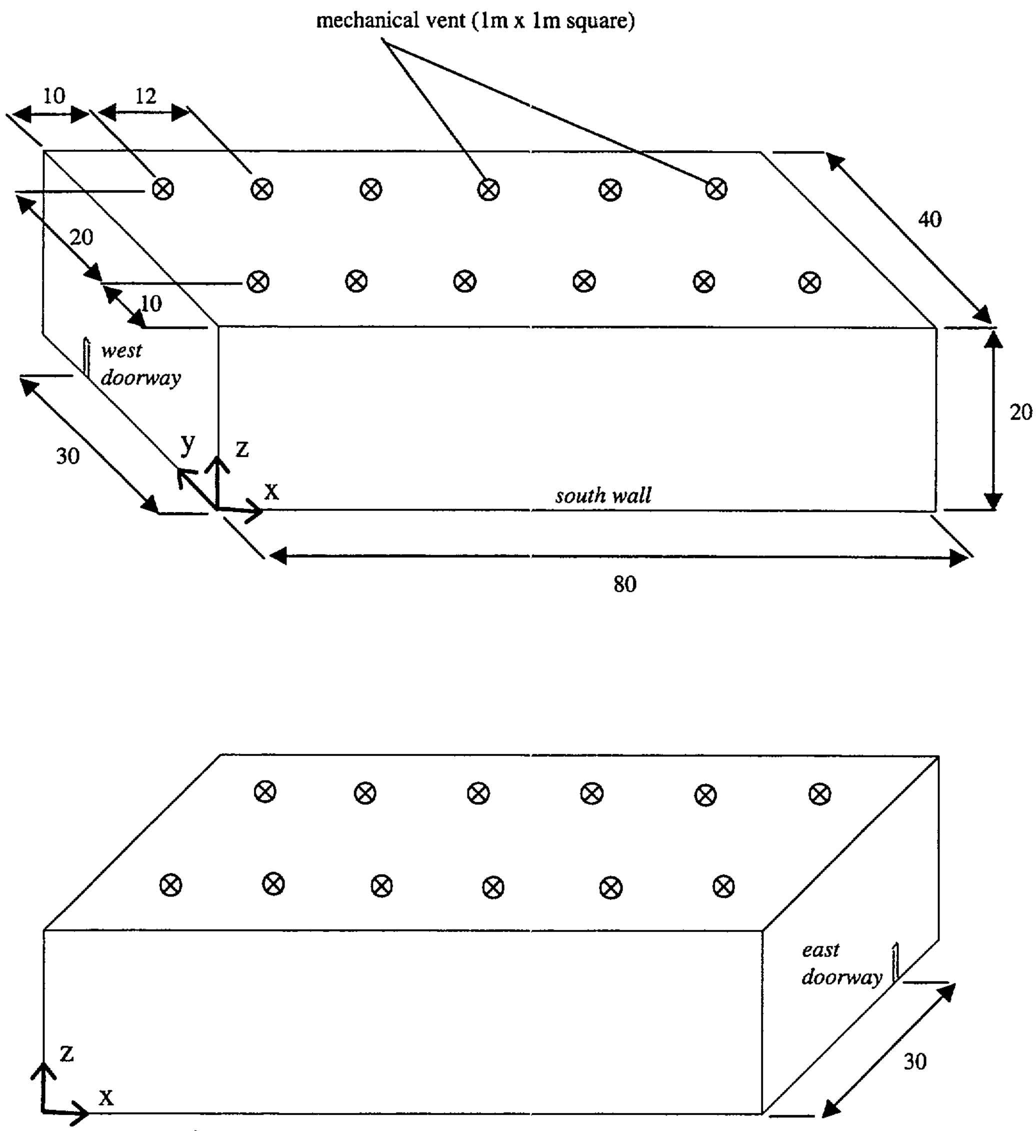


Figure 8 **Geometry for Part II**

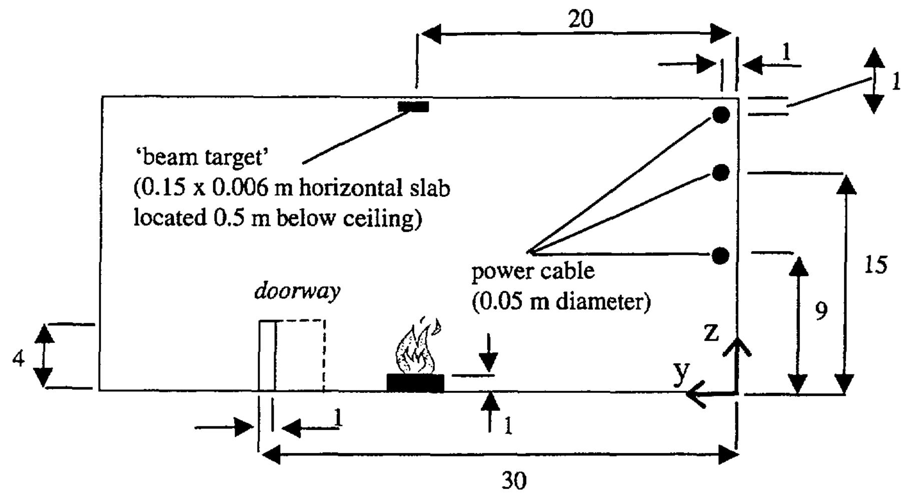


Figure 9 **End view for Part II**

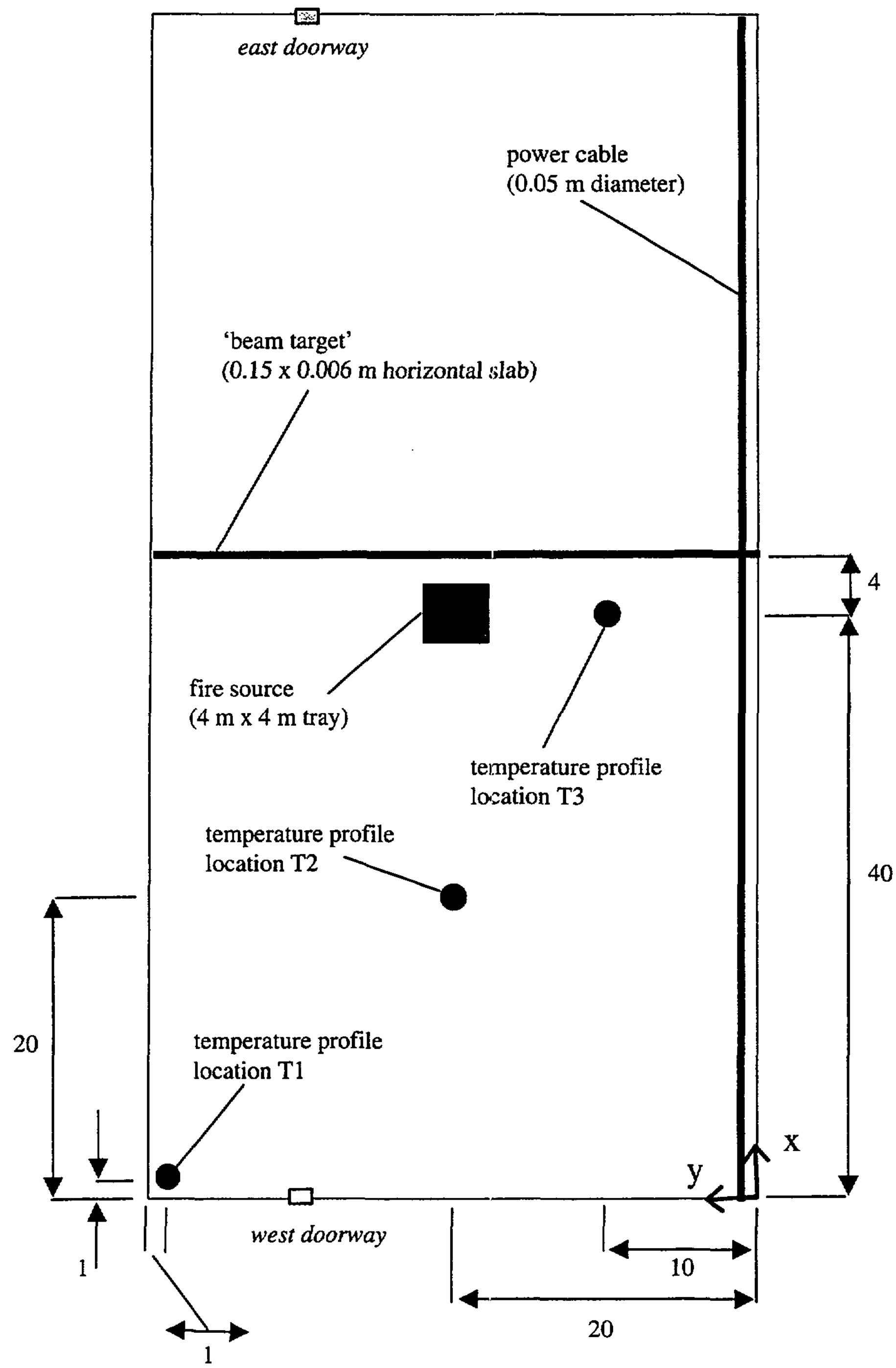


Figure 10 Plan view for Part II

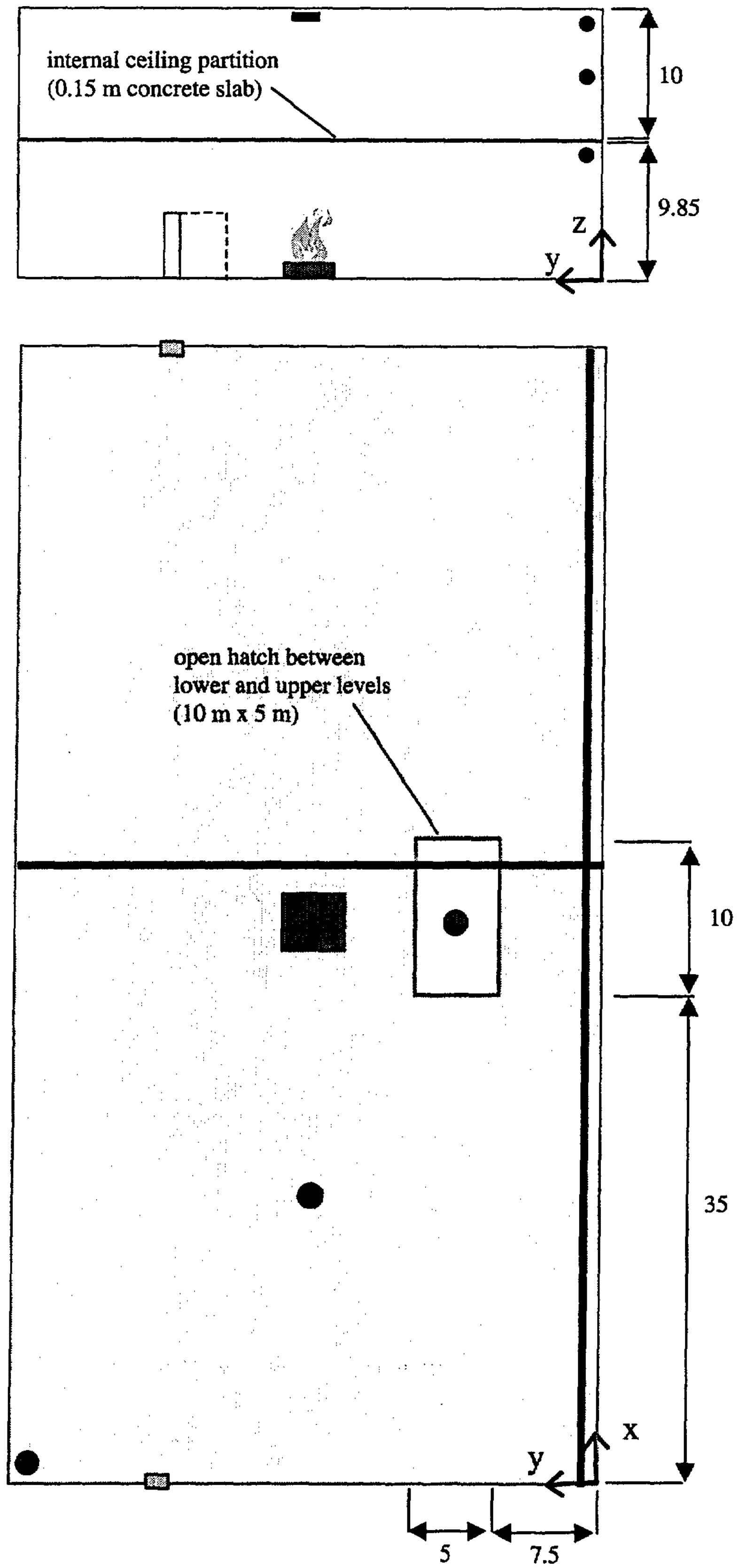


Figure 11 **Internal ceiling partition and hatch for Part II *cases 1b*, *2b* and *3b***

Appendix C: Summary Papers

CONTENTS

FIRE SAFETY RESEARCH AT NIST

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The Fire Research Division is one of four Divisions in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). The Division is composed of approximately 58 full time employees, 25 Guest Scientists and several post-doctoral associates. The technical background of the staff includes engineering, mathematics, chemistry, and physics. The Fire Research Division Budget in 2002 was approximately $13 M, with half of the support coming from government agencies and private industry. The goal of Fire Loss Reduction is one of four technical research areas in BFRL. The intent of this research is to provide engineered fire safety for people, products, facilities and enhanced firefighter effectiveness. The goal is broken into the four component programs described below.

The objective of the first component program is to eliminate the risk of flashover cost-effectively by enabling 1) new/improved materials whose fire resistance does not negatively impact performance, cost, or the environment; 2) early and certain fire and environment sensing; and 3) automatic fire suppression technologies compatible with occupants and the environment. Flashover is the dramatic and sudden transition from a relatively small, slowly developing fire to a much larger and dangerous fire in which all flammable surfaces within the enclosure are involved. Flashover is generally accompanied by a significant increase in the heat release rate, extension of flames out open doors and windows, and a dramatic increase in the production of toxic fire products.

Fire statistics do not report directly the occurrence of flashover. Estimates based on the extent of fire damage indicate that roughly 30 % of reported fires transition to flashover and that these were responsible for 80 % of fires deaths and property damage in buildings in 1999. Reducing the risk of flashover offers an opportunity to significantly reduce the high human and property costs of fire. Means exist to prevent flashover: e.g., by having a fire fighter always on the scene, by installing sprinklers, or by limiting the contents of the room.

The problem is that these means of prevention lack public acceptance because they are not affordable, reliable, flexible, and/or predictable. Standard test methods are generally not applicable to new technologies, and models for fire growth on realistic objects do not yet exist. The lack of effective fire spread and growth models is recognized as a major obstacle to the implementation of performance-based codes. A major impediment to efforts to reduce the risk of flashover is insufficient understanding of fire growth and spread on room contents. The unavailability of appropriate fire growth and spread models is a serious roadblock to the implementation of performance-based fire standards. A substantial effort is being undertaken to improve the experimental and theoretical understanding of fire growth and spread within enclosures, with the goal of developing a modeling capability for real-world room contents that can be reliably used for fire safety engineering, product design, and materials assessment. BFRL has made significant progress in cost-effective approaches that reduce the flammability of polymers while improving or maintaining physical characteristics. Introduction of these materials into the market will accelerate fire safety. Active measures to limit fire growth require reliable early fire detection and effective suppression approaches. As an example, elimination of false alarms would allow detector systems to be wired directly to the fire fighting service, which, in turn, would reduce the response time to a fire. Directed research designed to enhance fire detector sensitivity while reducing the number of false alarms and to improve suppression effectiveness are being carried out. Component projects include:

- Real-scale specification and testing
- Flame radiation
- Early, fault-free detection
- Flammability measures for electronic equipment
- Micro-scale high throughput optimization of flame retarded polymers
- Bench-scale high throughput flame retardancy measures

The objective of the second component program is to enhance fire fighter safety and effectiveness through research and help achieve a 50% reduction in line-of-duty fatalities and burn injuries in the United States by 2012. Fire fighting operations proceed with very limited information about the extent of fire involvement, structure safety, hazards, and even the location of fire fighters. To be safer and more effective, incident commanders and fire fighters need access to reliable and timely information regarding fire conditions, developing hazards, and the location and condition of resources. Efforts are underway to explore new technology for protective clothing, wireless transfer of information from fire alarm systems, evaluation of performance of thermal imagers and exploring the use of thermal imagers for hazard sensing, acoustic sensing of weak roof structures, and capabilities of durable agents to protect structures from external fires. Component projects are:

- Developing a heat transfer model for fire fighter protective clothing under wet and dry conditions with associated material property database, which will be assembled into an effective training tool and software to assist in design.
- Working with a fire alarm manufacturers and the BFRL effort in Cybernetic Buildings, wireless means to deliver timely emergency information about conditions inside of buildings and predictions of developing hazards to first responders before they arrive at the scene is being demonstrated.
- The capabilities and limitations of the current generation of thermal imagers.
- A fundamentally based computational model is being developed to predict major features of the interaction of structures with wind-driven fires utilizing FDS.
- The capabilities of acoustic sensing to determine weakness in roof structures.
- Nano-particles added to polymer gels used to protect external structures against fire have been shown in laboratory scale experiments to greatly increase the durability of the gel. Based upon work completed last year in a grant, a standard method to determine the performance in full scale will be investigated to allow durable agents with different nano-particle formulations to be evaluated.
- To aid the fire services in keeping abreast of developments in research, information on fire service related research is being distributed electronically.

The objective of the third component program is to lead the world in fire measurement and predictive methods, enabling engineered fire safety for people, products, facilities, and first responders. Engineering correlations developed through fire testing over the past 25 years have improved fire codes and technologies in the U.S. and produced a slow decline in the number of deaths and injuries due to unwanted fires; however, the total economic burden of fire in the U.S. continues to rise. To counteract these losses, new fire safety technologies and performance-based codes are needed that can only be achieved by a higher level of understanding of the dynamics of fire, and more certain measurement methods. Component projects include:

- basic research on the physics of fire to improve our knowledge and capabilities in quantitative methods in heat release rate, heat flux (including spectral and total radiation), room flows, soot/smoke, and water sprays.
- advanced instrumentation with emphasis on measurement accuracy, precision, and interpretation of measurements through models and analysis
- mass and heat transport phenomena involving gas phase and condensed phase processes and their interaction
- gas phase model enhancement - radiation submodel, boundary layer submodel, water spray submodel, flow boundary sensitivity, experimental validation
- combustion submodel development - pyrolysis submodel, soot formation/destruction submodel, experimental validation
- building structure fire model enhancement - real-scale fire validating demonstrations, HVAC/smoke flows
- expanded numerical simulations and computational fluid dynamics models of transport processes to encompass higher accuracy radiation, droplet and sprays models and semi-empirical sub-models of phenomena at the fuel/flame interface
- a Large Fire Laboratory (LFL) with advanced measurement capabilities that promote the understanding of full and reduced-scale fire phenomena
- reference data for model input against which predictions can be compared and validated and made available electronically to the fire community
- tools and knowledge that enable the implementation of performance based fire codes, allow assessment of key test methods and address international barriers to standards and the role of uncertainty in regulations.
- transfer of BFRL research results to industry as well as to organizations that create fire standards and codes.
- guidance to U.S. fire testing laboratories to identify and address research needs.
- FRIS as the source of easily-accessible fire information and data.

The objective of the fourth component program is to investigate the building construction, the materials used, and the technical conditions that combined to cause the World Trade Center (WTC) disaster. This work is under planning and will serve as the basis for improvements in the way buildings are designed, constructed, and used; improved tools, guidance for industry and safety officials, revisions to codes and standards, and improved public safety.

Future Fire Research in IRSN

R. BERTRAND

Institut de Radioprotection et de Sûreté Nucléaire (IRSN)

This presentation indicates first the IRSN strategy related to the fire research. Then the dominant fire scenarios that can occur in the French NPP and that need data from research to be assessed are presented. At last, IRSN needs in fire research are indicated.

Strategy of IRSN in fire research: The axes of research are mainly defined according to the safety assessment issues. The tight connection between expertise and research inside IRSN as well as the dialogue between utilities (such as COGEMA) and IRSN allow to fix clearly the priorities and the purposes of the research programs.

The research is divided into two complementary parts : experimental tests and modelling. The strong connection between the experiments and the modelling allows to develop and to assess the computer codes used to realise fire safety assessment. Two modelling approaches are developed: a simplified and empirical approach for fast and global safety assessment and a more detailed approach for more precise assessments in specific complex configurations. The experimental work is also composed of two parts: rather global, full scale, representative tests for getting direct information on specific configurations or equipments (the knowledge gained from this applied research can be directly used for safety analysis and for the global assessment of computer codes); analytical tests designed to improve the basic knowledge of the fire and help in models development and qualification.

The main objective of fire modelling is to provide well-qualified computer codes essential for performing safety assessment. Actually for this purpose the FLAMME-S code is used. For the future, the SYLVIA code will provide a set of models for simulating the fire development (two zone and CFD approaches), the ventilation network components behaviour and the aerosols (soot, radioactive materials) deposition and transfer between the rooms and through the ventilation network. Furthermore, the SYLVIA code will be coupled to the IRSN statistical tool, named SUNSET [5], thus allowing uncertainty propagation and sensitivity studies on code input data and model parameters. The main objectives of this new code development are to perform the coupling between all the main phenomena involved during a fire in a nuclear plant (fire propagation, ventilation behaviour, radioactive aerosols and soot transfers) and to provide different modelling levels for various users (a simplified approach for fast-running calculations used for instance for PSA analyses; a detailed approach mainly for research activities).

Experimental programs in progress: IRSN is performing or is preparing 3 series of fire tests:

- FLIP test: these tests are related to TPB/TPH fire interacting with a wall in an confined and forced ventilated compartment,
- CARMELA test: these tests aim at providing knowledge of electrical cabinet fires. In a first test, analytical approach is implemented in order to understand the complex phenomena of electrical cabinet fires and notably the impact of some parameters (ventilation effect, spatial arrangement, cabinet filling, effect of the ignition location, quantity of combustible). In a second step, tests will be performed in a real electrical cabinet in order to study the consequences of such a fire notably on adjacent electrical cabinets and generation of inadvertent order,
- DIVA tests: this program firstly aims at studying all the consequences a fire, located in a room, has on neighbouring rooms and on the ventilation network: thermal propagation, smoke and fire spread, consequences of the fire on the ventilation and room equipments, management of the ventilation during a fire. For this program a new large-scale experimental facility has been built. It consists of three rooms (L=6m, l=5m, h=4m), a common corridor connecting these rooms, a room located above the third room and the neighbouring area of the corridor. The rooms are connected by a ventilation network and openings such as doors.

Fire scenarios selected: The fire scenarios that need research in order to improve the fire risk assessment have been identified by IRSN personal that is involved in safety assessment. These fire scenarios have been ranked to focus the fire research on dominant needs. For NPP, the fire scenarios selected are:

- an electrical cable fire induced by a fixed or transient combustible fire,
- a fire on a process control relay rack in a relay room,
- an electrical cabinet fire,
- a fire propagation to a compartment located above,

- a fire in a containment (unconfined fire),
- a fire in a benchboard of the control room.

IRSN fire research needs: Basic research topics are clearly identified by IRSN in order to improve the knowledge and modelling of the complex phenomena involved in fire scenarios.

For the fire study, the topics are:

- ✓ combustion parameters,
- ✓ soot production,
- ✓ improvement of the plume model in a confined and ventilated configuration,
- ✓ explosion hazards due to the non-burnt residues,
- ✓ fire propagation towards other fire sources,
- ✓ criteria for the failure of equipment and the electric cables.

A complementary research program is conducted for the transfer of radioactive aerosols inside a plant (including the ventilation network) and for the behaviour of the ventilation and confinement devices submitted to the thermo-mechanical stresses induced by a fire. The topics selected are, for example:

- ✓ Plugging of the filters by the aerosols of combustion,
- ✓ Setting up the suspension of radio-elements in the event of a fire,
- ✓ Mechanical resistance of the filters,
- ✓ Evolution of the aerosols of combustion outside the flame.

A first fire research program has been defined for the 3 first topics (combustion parameter, soot production, improvement of the plume model). This program that foresees to begin the research related to the combustion parameter in 2003 will be proposed in the frame of the next budget.

FIRST APPLICATIONS OF A QUANTITATIVE FIRE HAZARD ANALYSIS TOOL FOR INSPECTION IN THE U.S. COMMERCIAL NUCLEAR POWER PLANTS*

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ABSTRACT

Fires in a nuclear power plant (NPP) are a significant safety concern. The U.S. Nuclear Regulatory Commission's (NRC's) new Reactor Oversight Process (ROP) uses a risk-informed approach to evaluate the safety significance of inspection findings. As a part of this approach, the inspectors use a significance determination process (SDP) to evaluate the significance of fire risks to the operating reactor, as required by the new NRC inspection manual. A key step in the SDP is determining whether a credible fire scenario is possible. The paper titled "Development of a Quantitative Fire Scenario Estimating Tool for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program" ** introduced the new quantitative analytical tools for performing fire hazard analyses (FHAs) being developed by the NRC Office of Nuclear Reactor Regulation (NRR) fire protection engineering staff. These tools are designed for use by the regional fire protection inspectors. The paper notes that a FHA is intended to permit fire protection inspectors to quickly evaluate the potential for credible fire scenarios to cause critical damage to essential fire safe-shutdown (FSSD) systems, components, or equipment. It also discusses the process of creating an analytical quantitative tool based on the fire dynamics equations and pre-programmed correlations using Microsoft Excel® worksheets. These worksheets form the basis to be used to perform quick, easy, accurate calculations. The first paper discussed how to estimate burning characteristics of fire (heat release rate, flame height and burning duration), and hot gas layer temperature. Since then a second series of computational worksheets with different concepts of fire dynamics have been developed and taught to the regional inspectors. Applications which are discussed in this paper include: flame heat flux from a fire source to a target fuel using a point source and solid flame radiation model, centerline temperature of a buoyant fire plume, sprinkler actuation time and heat release rate (HRR) required to cause flashover in a compartment. The NRR fire protection engineering staff is in the process of developing additional worksheets to promote greater application of fire science engineering in the field during inspection.

Key words: fire hazards analysis, nuclear power plant, fire protection inspection finding, credible fire scenario, fire dynamics, correlations, worksheet, quantitative methods

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INTRODUCTION

One purpose of a fire hazard analysis (FHA) is to determine the effect of fires on the ability to operate the facility safely, that is, to protect the reactor and prevent the release of radiation to the environment. There are a variety of methods of performing a FHA. In this second paper we describe more analytical methods of quantitatively assessing fire hazards in NRC-licensed nuclear power plants (NPPs).

The NRC/NRR method uses simplified quantitative FHA calculation techniques to evaluate the potential for credible exposure fire sources to cause critical damage to essential fire safe-shutdown (FSSD) systems, components, or equipment, either directly or by igniting intervening combustibles, which in turn could cause critical damage. The NRC/NRR methods are based on material fire property data used in engineering and scientific calculations. The fire hazard calculations used in these worksheets are simple empirical correlations based on accepted fire dynamics principles.

REGULATORY BACKGROUND

The primary objective of the fire protection programs at U.S. NPPs is to minimize the probability and consequences of fires. Fire protection programs for operating NPPs are designed to provide reasonable assurance, through defense-in-depth (DID), that a fire will not prevent the performance of necessary safe-shutdown functions and that radioactive releases to the environment will be minimized. Regulatory Guide 1.189, "Fire Protection for Operating Nuclear Power Plants," April 2001, summarizes the multilevel approach to fire safety. The fire protection DID program has three objectives:

1. To prevent fires from starting.

2. To detect rapidly, control, and extinguish promptly those fires that do occur.

3. To provide protection for structures, systems, and components important to safety so that a fire that is not promptly extinguished by the fire suppression activities will not prevent the safe shutdown of the plant.

The NRC's regulatory framework for nuclear plant fire protection programs (FPPs) is described in a number of regulations and guidelines, including General Design Criterion 3 (GDC 3), 10 CFR 50.48, Appendix R to 10 CFR Part 50, Regulatory Guide 1.189, and other regulatory guides, generic communications (e.g., generic letters, bulletins, and information notices), NUREG reports, the Standard Review Plan (NUREG-0800) (SRP), and branch technical positions (BTPs).

FIRE HAZARD ANALYSIS FOR NPPs

NPPs achieve the required degree of DID for fire protection using echelons of administrative controls, fire protection systems and features, and safe-shutdown capabilities. A FHA should be performed to demonstrate that the plant will maintain the ability to perform safe-shutdown functions and minimize radioactive material releases to the environment in the event of a fire. Regulatory Guide 1.189 states that the objectives of a FHA are to,

1. Consider potential in-situ and transient fire hazards.

2. Determine the consequences of fire in any location in the plant according to the ability to safely shutdown the reactor and minimize and control the release of radioactivity to the environment.

3. Specify measures for fire prevention, fire detection, fire suppression, fire containment, and alternative shutdown capability for each fire area containing structure, systems, and components important to safety in accordance with NRC guidelines and regulations.

NPP FIRE SCENARIO DEVELOPMENT

A fire scenario can be thought of as a chain of events that begins with the ignition of combustibles and ends either with successful plant shutdown or core damage. A fire is postulated to occur at a specific location in a specific fuel package and to progress through various stages of growth. As the fire grows, it may damage plant equipment directly or indirectly (most often through electrical cables). For a given fire source, the FHA may postulate damage to different equipment, depending on how long the fire burns and the initial size of the fire. The postulated or predicted fire damage either directly or indirectly causes an initiating event such as a plant trip, or loss-of-offsite power.

When developing a fire scenario, the inspector should conservatively postulate a significant fire provided that the potential for a large fire is possible in the fire zone, area, or room. For example, in a large cabinet fire the initial fire damage extends beyond the cabinet where the fire started. A large cabinet fire in its initial stages may damage overhead cabling, an adjacent cabinet, or both. Assuming that electrical power is interrupted the initial size of a pump or motor fire may largely depend upon the size of the oil spill. If the configuration of the compartment, adjacent combustibles, etc., support the growth of a large fire, a large fire should be postulated. Since large-fire scenarios are normally expected to dominate the risk significance of an inspection finding, small-fires scenarios (for example a small electrical cabinet fire) are generally not analyzed when large-fire scenarios can be postulated. Suppression is not credited unless suppression could prevent the damage to the component. Automatic suppression, fire brigade, operator response, and fire frequencies are accounted for in other parts of the SDP.

FIRE PROTECTION INSPECTION FINDINGS

A fire protection inspection finding usually concerns a failure or partial failure in meeting one of the objectives of DID. If there are no DID-related findings against a fire protection feature or system, the fire protection feature and system is considered capable of performing its intended function and remaining in its normal (standby) operating state.

EFFECTS OF FIRE ON NPP OPERATIONS

Recent studies indicate that fires are a significant risk to the safe operation of an NPP (NUREG-1742). In addition to local damage, heat transfer and the spread of smoke may cause damage far from the burning object. A toxic mixture of combustion products in the smoke can hinder work in the area by reducing visibility and creating a potentially lethal environment for plant personnel. Furthermore, the probability of failures in electrical components increases as temperatures rise and smoke becomes more concentrated.

Empirical data indicates that a nuclear power facility experiences more event precursors (small fires that have little impact on nuclear safety) than actual fire events such as the Browns Ferry Nuclear Power Plant (BFN) Unit 1 fire (NRC Bulletin 75-04, March 1975). Many fire protection experts argue that no fire in an NPP is without nuclear safety implications because every fire is a threat to safety through its effects on equipment or operating personnel. Statistically however, a NPP is expected to experience a fire that affects nuclear safety equipment every 6 to 10 years (Ramsey and Modarres 1998). The NUREG-1742 review of individual plant examinations of external events [including some detailed fire probabilistic risk assessments (PRAs)] showed that fire can be a significant contributor to a given plant's core damage frequency because a single fire and its effects can result in the loss of an otherwise highly reliable redundant safety capability. The loss of a redundant safety capability reduces possible success paths and may lead to core melt damage accidents

FIRE DEVELOPMENT

Fire hazards to NPP equipment may result from thermal destruction, fouling, corrosivity, and other sources. Fire is essentially a rapid self-sustaining oxidation process, producing heat and light of varying intensities. The chemical and physical reactions that take place during a fire are very complex and difficult to describe completely.

A fire starts when in-situ or transient combustibles ignite and then release heat to the surroundings by conduction, convection, and/or radiation. The rise in temperature in the fire compartment increases the volume of gas and forces it out of the compartment. The flow of expanding gas out of the compartment continues as the temperature rises. The pressure differential of the expanding gas across the compartment boundary depends on a number of factors including (1) the leakage area (including the ventilation system if applicable), (2) the volume of the fire compartment, (3) the rate of temperature rise, and (4) the rate of gas generation from the combustion process. When the fire temperature reaches a steady-state value, the gases in the fire compartment cease to expand. A balance is established as smoke moves out of the compartment (primarily by buoyancy) and air moves in to replace the smoke.

DEVELOPMENT OF THE FIRE DYNAMICS WORKSHEETS

Our challenge was to develop a method that could be taught to regional inspectors and put to use in a short time. Regional inspectors have diverse backgrounds typically in electrical, mechanical, nuclear, chemical, and civil engineering. We had to present the fire dynamics correlations so they could be understood by engineers who had little or no formal education in the field of heat and mass transfer. We also had to present the fire dynamics equations and correlations in a user-friendly format. After discussions with the fire protection engineers from the U.S. Bureau of Alcohol, Tobacco and Firearms (ATF) we decided to develop a series of Microsoft Excel® worksheets similar to ATFs' with the equations and correlations pre-programmed and locked in. The worksheets would allow quick, easy, accurate calculations. The worksheets would also list the physical and thermal properties of materials commonly encountered in the NPP. To begin the process, we had to select a series of fire dynamics correlation methods. We decided to base our program on state-of-the-art methods from the SFPE Handbook of Fire Protection Engineering, NFPA Fire Protection Handbook, and if necessary to modify the equations for use in specific NPP application. The paper titled, "Development of a Quantitative Fire Scenario Estimating Tool for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program," presented at the Structural Mechanics in Reactor Technology (SMiRT) Post-Conference Seminar No.1, 2001, discussed the first set of worksheets that were put into use by the regional inspectors.

The following section describes the second addition of fire dynamics worksheets recently developed to complement the first series.

METHODS OF PREDICTING HEAT FLUX FROM FIRE TO A TARGET FUEL

Introduction

The McCaffrey, Quintiere, and Harkleroad (MQH) and Foote, Pagni, and Alvares (FPA) temperature correlations are not valid for analyzing a fire scenario in a large open compartment. Very large spaces such as the reactor building in a boiling-water reactor (BWR) or the turbine building have too large of a volume for a uniform hot gas layer to build up. In these scenarios, we must look at other forms of heat transfer such as radiation. This section addresses radiation heat transfer when the target is at floor level.

Thermal radiation can be the significant mode of heat transfer for situations where a target is located laterally from the exposure fire source. An example is a floor-based fire adjacent to an electrical cabinet or a vertical cable tray in a large compartment.

Fire normally grows and spreads by direct burning, which results from impingement of the flame on combustible materials or by heat transfer to other combustibles. The three modes of heat transfer are, conduction, convection, and radiation. All these modes may be significant in heat transfer from fires. For example, conduction is particularly important in allowing heat to pass through a metallic object in a solid barrier and ignite material on the other side. Most of the focus on heat transfer in fires involves convection and radiation. It is estimated that in most fires some 75% of the heat emanates by convection. The hot products of combustion rising from a fire typically have a temperature in the range of 800 -1200 °C (1472 -2192 °F) and a density a quarter that of air. However, in an open industrial facility much of the convective heat is dissipated into the atmosphere. Conversely, in a smaller building compartment the heat is contained by the ceiling and walls. Radiation usually accounts for a smaller proportion of the heat generated from the fire. Radiated heat is transferred directly to nearby objects. However, in large open spaces where a hot gas layer is not established, radiation may be the most significant mode of heat transfer to evaluate. Thermal radiation is electromagnetic radiation of wavelengths from 2 to 16 μm (infrared). It is the net result of radiation from substances such as H_2O, CO_2, and soot (often dominant in pool fires).

Critical Heat Flux to a Target

Radiation from a flame or any other hot gas, depends on the temperature and emissivity of the gas. Emissivity is a measure of how well the hot gas emits thermal radiation. Emissivity is a value between 0 to 1, where 1 is a perfect radiator. The radiation that an observer feels depends on the emissivity and height of the flame.

The incident heat flux required to raise the surface of a target to a critical temperature is termed the critical heat flux. Measured critical heat flux levels for representative electrical cable samples typically range from 15 to 25 kW/m^2 (1.32 to 2.2 Btu/ft^2-sec). To account for inaccuracies, critical heat fluxes should be established for screening purposes with values of 10 kW/m^2 (0.88 Btu/ft^2/sec) for IEEE-383 qualified cable and 5 kW/m^2 (0.44 Btu/ft^2/sec) for non-IEEE-383 qualified cable. These values are consistent with selected damage temperatures for both types of cables as referenced in EPRI's Fire-Induced Vulnerability Evaluation (FIVE) methodology.

Numerous methods have been developed to calculate the heat flux from a flame to a target located outside the flame. Flames have been represented as cylinders, cones, planes and point sources to evaluate the effective configuration factor or view factor between the flame and the target. The configuration or view factor is a purely geometric quantity. It gives the fraction of the radiation leaving one surface that strikes another surface directly. The predictive methods range from very simple to very complex methods. The more complex methods involve correlations and detailed solutions to the equations of radiative heat transfer and computational fluid mechanics. Routine FHAs are usually based on simple correlations because of the macroscopic goals of the analyses and the limited resources available for routine evaluation. As a result of the widespread use of these methods, a great deal of effort has gone into their development. Burning rates, flame heights, and radiative heat fluxes can be predicted by these methods.

POINT SOURCE RADIATION MODEL

A point source estimate of radiant heat flux is the simplest and the most widely used flame representation. To predict the thermal radiation field of a flame, the flame is modeled as a point source at the center of a flame. More realistic radiator shapes entail very complex configuration factor equations. With the point source model radiant heat flux varies as the inverse square of the distance to the target, R. With an actual point or spherical source of thermal radiation, the distance R is simply the distance from the point, or from the center of the sphere, to the target (Drysdale 1998 and SFPE Engineering Guide 1999).

The thermal radiation hazard of fires depends on the composition of the fuel, the size and the shape of the fire, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of the object exposed to the fire. A point source exposure fire may start from either fixed or transient combustibles (e.g., electrical cabinet, pump, liquid spill, switchgear or motor control center (MCC), or intervening combustible some distance above the floor). For example, the top of a electrical cabinet is the point source we use for a postulated switchgear fire. The point source of a transient combustible liquid spill or pump fire is located on the floor.

The point source model assumes that radiant energy is released from the center of the fire. The radiant heat flux is inversely related to the horizontal distance of the target from the fire. This is expressed mathematically, in the following equation:

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi R^2} \qquad (1)$$

where:

$\dot{q}''$ = radiative heat flux (kW/m^2 [Btu/sec/ft^2)]

$\dot{Q}$ = heat release rate of the fire [kW (Btu/sec)]

R = radial distance from the center of the flame from edge of source fire [m (ft)]

χ_r = fraction of total energy radiated

In general, χ_r depends on the fuel, flame height, and configuration. It varies from approximately 0.15 for low-sooting fuels, such as most alcohols, to 0.60 for high-sooting fuels. In very large fires (several meters in diameter), cold soot can envelop the luminous flames and reduce χ_r considerably. (See Figure 1.)

The heat release rate (HRR) of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire, $\dot{Q}$, is calculated by the following equation (Babrauskas 1995):

$$\dot{Q} = \dot{m}''\Delta H_{c,eff} A_f \qquad (2)$$

where:

$\dot{Q}$ = heat release rate (kW)

$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)

A_f = horizontal burning area of the fuel (m^2)

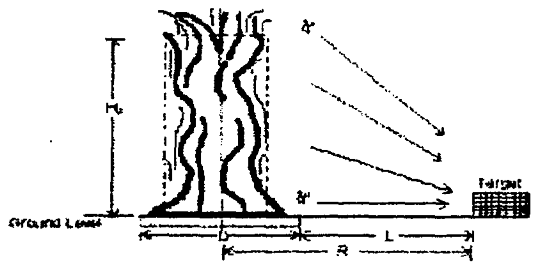

Figure 1 - Illustration of Radiant Heat Flux From a Point Source Fire to a Target Fuel

Appendix A gives an example of the use of a Microsoft Excel® worksheet to estimate flame heat flux to a target fuel using point source radiation model.

SOLID-FLAME RADIATION MODEL WITH TARGET LOCATED ABOVE GROUND LEVEL

This worksheet provides a method for assessing the impact of radiation from pool fires to potential targets using view or configuration factor algebra. The method included in this worksheet contains a range of detailed calculations. Some methods are most appropriate for first order, initial hazard assessments, while greater engineering effort is required for more detailed methods which are capable of better predictions.

The method presented in this section has been included in the Society of Fire Protection Engineering (SFPE) Engineering Guide on Thermal Radiation. The accuracy of this method has been examined in the SFPE Engineering Guide through comparisons of the method with available experimental data (SFPE Engineering Guide 1999).

The solid-flame model assumes that the fire can be represented by a solid body of a simple geometrical shape, with thermal radiation emitted from its surface, and that non-visible gases do not emit much radiation. (See Figure 2.) The geometries of the fire, target, and their relative positions must be taken into account since part of the fire may be obscured as viewed from the target thus changing the effective volume of the fire. The thermal radiation intensity to an element outside the flame envelope is calculate by the following equation:

$$\dot{q}'' = EF_{12} \qquad (3)$$

where:

$\dot{q}''$ = incident radiative heat flux (kW/m²)

E = average emissive power at flame surface (kW/m²)

$F_{1\to2}$ = configuration or view factor

Emissive Power

Emissive power is the total radiative power leaving the surface of the fire per unit area per unit time. Emissive power can be calculated by the use of Stefan's law, which gives the radiation of a black body in relation to its temperature. Because fire is not a perfect black body, the emissive power is a fraction (ε) of the black body radiation:

$$E = \varepsilon\sigma T^4 \qquad (4)$$

where:

E = flame emissive power (kW/m^2)
T = temperature of the fire (K)
ε = emissivity
σ = Stefan-Boltzmann constant = 5.67×10^{-11} (kW/m^2-K^4)

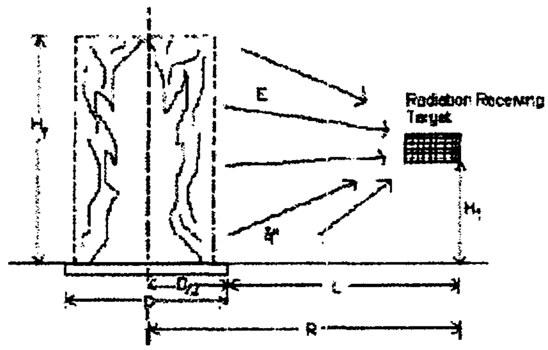

Figure 2 - Solid Flame Radiation Model With No Wind and Target Above Ground Level

To use Stefan-Boltzmann's law to calculate radiation the inspector must estimate the fire's temperature and emissivity. Turbulent mixing causes the fire temperature to vary. Therefore, it can be useful to calculate radiation from data on the fraction of heat liberated as radiation, or to rely on measured radiation values.

Shokri and Beyler (1989) correlated experimental data on flame radiation to external targets in terms of the "average emissive power" of the flame. The flame is assumed to be a cylindrical, black-body, homogeneous radiator with an average emissive power. The effective power of the pool fire in terms of effective diameter is given by the following correlation:

$$E = 58\left(10^{-0.00823D}\right) \qquad (5)$$

where:

E = flame emissive power (kW/m^2)
D = diameter of pool fire (m)

The effective power is the average emissive power over the whole flame and is significantly less than local emissive power level. The emissive power decreases with increasing pool diameter because black smoke outside the flame dims the radiation of the luminous flame.

For noncircular pools, the effective diameter is the diameter of a circular pool with an area equal to the actual pool area. The effective diameter is obtained by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (6)$$

where:

A_f = surface area of the noncircular pool
D = diameter of pool fire (m)

Configuration Factor, View Factor or Shape Factor, $F_{1\to2}$

The configuration factor is a purely geometric quantity. It is the fraction of the radiation leaving one surface that strikes another surface directly. In other words, it is the fraction of hemispherical surface area (or solid angle) viewed by the differential element when looking at another differential element on the hemisphere.

The configuration factor is a function of target location, flame height, and fire diameter. Its value is between 0 and 1. When the target is very close to the flame, the configuration factor approaches 1 since the target views only the flame. The flame is modeled as a cylinder with a diameter equal to the pool diameter, D, and a height equal to the flame height, H_f. If the pool has a length-to-width ratio near 1, a circular source of equivalent area can be used to determine the flame height, H_f for non-circular pools. (See Figure 3.)

The flame height of the pool fire is obtained by the following correlation (Heskestad 1995):

$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \qquad (7)$$

where:

H_f = flame height (m)
$\dot{Q}$ = heat release rate of the fire (kW)
D = diameter of the fire (m)

Figure 3 - Two-Cylinder Representation of the Configuration Factor for Target Located Above Ground Level

As previously discussed, HRR of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire, $\dot{Q}$, is estimated by Equation 2. The radiation exchange factor between a fire and an element outside the fire depends on the flame's shape, the distance between the fire and the receiving element, and the orientation of the element to the fire. The turbulent diffusion flame is approximated by a cylinder. Under wind-free conditions, the cylinder is vertical (Figure 2).

Given the diameter and height of the flame, Equations 9 is used to obtain the view or configuration factor, $F_{1\to2}$, for a cylindrical radiation source whose target is above the ground . Two cylinders are used to represent the flame for a target above the floor. One cylinder represents the flame below the height of the target, and the other represents the flame above the height of the target (Figure 3).

For targets above ground level, Equations 8 and 9 are used to estimate the two configuration factors for Equation 9:

$$F_{1\to 2,V_1} = \begin{pmatrix} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_1}{\sqrt{S^2-1}}\right) - \frac{h_1}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_1 h_1}{\pi S\sqrt{A_1^2-1}}.\tan^{-1}\sqrt{\frac{(A_1+1)(S-1)}{(A_1-1)(S+1)}} \end{pmatrix} \quad (8)$$

where:

$$h_1 = \frac{2H_{f_1}}{D}$$

$$S = \frac{2L}{D}$$

$$A_1 = \frac{h_1^2 + S^2 + 1}{2S}$$

$$F_{1\to 2,V_2} = \begin{pmatrix} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_2}{\sqrt{S^2-1}}\right) - \frac{h_2}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_2 h_2}{\pi S\sqrt{A_2^2-1}}.\tan^{-1}\sqrt{\frac{(A_2+1)(S-1)}{(A_2-1)(S+1)}} \end{pmatrix} \quad (9)$$

where:

$$h_2 = \frac{2H_{f_2}}{D}$$

$$S = \frac{2L}{D}$$

$$A_2 = \frac{h_2^2 + S^2 + 1}{2S}$$

and:

L = distance between the center of the cylinder (flame) and the target
H_f = height of the cylinder (flame)
D = diameter of cylinder (flame)

The total view or configuration factor at a point is the sum of two configuration factors:

$$F_{1\to 2,V} = F_{1\to 2,V1} + F_{1\to 2,V2} \quad (10)$$

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate flame heat flux to a target fuel above ground level using solid flame radiation model with no wind.

A METHOD FOR ESTIMATING THE CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Introduction

A fire plume is a buoyant rising column of combustion products, not-yet-burned fuel vapor, and entrained air. The plume of a fire in a building impinges on the ceiling unless the fire is very small or the ceiling very high. A fire plume usually contains smoke particles. Surrounding air mixes into the plume and dilutes the smoke which reduces the temperature. This mixing is called entrainment. To predict the course of a fire, it is necessary to know the rate at which air is entrainmed into the plume. There are correlations for calculating the rate of entrainment, but the results are not entirely reliable because small disturbances in the air near the plume can have large effects on the entrainment rate. If combustion occurs only in the lower part of the plume, there is approximately an order of magnitude more entrained air above the combustion zone than the stoichiometric requirement.

A fire plume has two zones: the flaming (reacting) zone and the nonflaming (nonreacting) zone. The flaming zone is just above the fire source; the fuel vapors released by the combustibles burn in this zone. The air for the reaction is entrained by the upward movement of the reactants. Above the flaming zone of the column of hot combustion products is called the nonflaming zone since no reactions take place there.

Fire Plume Characteristics

Fire plumes are characterized in various ways depending on the scenario. The most common plume for fire protection engineering applications is the point source thermal plume or buoyant axisymmetric plume, which is caused by a diffusion flame just above the burning fuel. An axis of symmetry is assumed along the vertical centerline of this plume. Another type of fire plume is the line plume. This is a diffusion flame formed above a long narrow burner. Air is entrained from both sides of the burner as the hot gases rise. Some examples of line fires are flames spreading over flammable wall linings, a balcony spill plume, a burning long-sofa, a burning row of townhouses, and the advancing front of a forest fire.

Plume Temperature

The highest temperature is at the plume centerline. The temperature decreases toward the edge of the plume, where more ambient air is entrained, thus cooling the plume. The centerline temperature, $T_{p(centerline)}$, varies with height. It is roughly constant in the continuous-flame region and represents the mean flame temperature. The temperature decreases sharply above the flames as more ambient air is entrained into the plume. The symbol $\Delta T_{p(centerline)}$ represents the difference between the centerline plume temperature and the ambient temperature, T_0. Thus $\Delta T_{p(centerline)} = T_{p(centerline)} - T_0$.

There are numerous ways of correlating the height above the fire source and HRR to estimate the plume centerline temperature. For example, consider a region of a ceiling jet at a radial distance from the fire axis equal to the vertical distance from the fire source to the ceiling. In this region, the maximum velocity in the jet drops to half the value near the fire axis, and the temperature (relative to the ambient temperature) drops about 60 percent near the fire axis. The maximum velocity and temperature occur at a distance below the ceiling equal to about 1 percent of the distance from the fire source to the ceiling. If the walls are very far away, the temperature and velocity of the ceiling jet decay to negligibly low values before the jet reflects when it reaches the wall. If the wall is close, the jet reaches the wall. The reflected jet goes back toward the fire axis, just under the original jet. Thus the hot layer under the ceiling becomes thicker.

If the compartment has an open door or window and fire continues, the hot layer ultimately becomes thick enough to reach the top of the opening, at which point the hot smoke-laden gases start to exit the compartment. If the fire is next to a wall (or a corner), the behavior of the ceiling jet can be predicted provided the fire is assumed to be twice (for wall) or four times (for corner) as large as the actual size.

Heskestad 1995, provided a simple correlation for estimating the maximum centerline temperature of a fire plume as a function of ceiling height and HRR:

$$T_{p(centerline)} - T_0 = \frac{9.1\left(\frac{T_0}{g c_p^2 \rho_0^2}\right)^{\frac{1}{3}} \dot{Q}_c^{\frac{2}{3}}}{(z - z_0)^{\frac{5}{3}}} \qquad (11)$$

where:

$T_{p(centerline)}$ = plume centerline temperature (K)
T_0 = ambient air temperature (K)
$\dot{Q}_c$ = convective HRR (kW)
g =acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/Kg-K)
ρ_0 = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

The virtual origin is the equivalent point source height of a finite area fire. The location of the virtual origin is needed to calculate the thermal plume temperature for fires that originate in an area heat source. The thermal plume calculations assume that the plume originates in a point heat source. Examples of area heat sources are pool fires and burning three-dimensional objects such as electrical cabinets and cable trays. A point heat source model is made for an area source by calculating the thermal plume parameters at the virtual point source elevation rather than the actual area source elevation.

The virtual origin, z_0, depends on the diameter of the fire source and the total energy released. The virtual origin is given by:

$$\frac{z_0}{D} = -1.02 + 0.083\frac{\dot{Q}^{\frac{2}{5}}}{D} \qquad (12)$$

where:

z_0 = virtual origin (m)
D = diameter of fuel source (m)
$\dot{Q}$ = total HRR (kW)

For noncircular pools, the effective diameter is the diameter of a circular pool with an area equal to the actual area (Equation 5).

Total HRR, $(\dot{Q})$, is used when calculating the mean flame height and the position of the virtual origin. In estimating other plume properties the convective HRR, $(\dot{Q}_c)$, is used since this is the part of the energy release rate that causes buoyancy. The energy losses due to radiation from the flame are generally about 20% to 40% of the total HRR, $(\dot{Q})$. Sootier and more luminous flames, often from fuels that burn inefficiently, will have higher energy losses. The convective HRR is therefore often in the range $\dot{Q}_c = 0.6$ to $0.8\dot{Q}$, where $\dot{Q}$ is the total HRR and $\dot{Q}_c$ is the convective heat release from the fire.

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate the centerline temperature of a buoyant fire plume.

A METHOD FOR ESTIMATING SPRINKLER ACTUATION TIME

Introduction

It is often useful for an inspector to be able to determine if, or when automatic suppression will activate for a postulated fire scenario.

Automatic sprinklers are thermosensitive devices designed to react at predetermined temperatures by automatically releasing streams of water and distributing them in specified patterns and quantities over designated areas. The automatic distribution of water is intended to extinguish a fire or control its spread. A closed-element sprinkler is only activated when it absorbs a sufficient quantity of heat.

The effectiveness of a sprinkler installation depends upon the characteristics of the system itself (e.g., the thermal rating and spacing of the sprinklers, how far the sprinklers are mounted below the ceiling, and their pressure/flow characteristics), the characteristics of the building in which the system is installed (e.g., the height of the ceiling, the volume of the compartment, the presence of openings, joists, or ventilation currents at ceiling level), which can affect the flow of hot gases from a fire to the sprinklers, the type of combustibles, and their closeness to the ceiling.

Sprinkler Activation

In a fire protection analysis, it is often important to estimate the burning characteristics of selected fuels and their effects in enclosures including when fire protection devices such as automatic sprinklers, and thermal and smoke detectors will activate for specific fire conditions. There are equations available based primarily on experimental correlations, for estimating these effects.

Sprinklers are primarily activated by the convective heat transfer from the fire. Convection transfers heat through a circulating medium, typically, air. The air heated by the fire rises in a plume, entraining additional room air. When the plume strikes the ceiling, it spreads to produce a ceiling jet, in a shallow layer beneath the ceiling surface, driven by the buoyancy of the hot combustion products. The thickness of the ceiling jet flow is 5 to 12 percent of the height of the ceiling above the fire source, with the highest temperature and velocity at 1 percent of the distance from the ceiling to the fire source. Heat-sensing elements of sprinklers and thermal detectors are activated by the ceiling jet.

Computer programs have been developed to calculate the response time of sprinklers installed below the ceilings of large compartments. These programs estimate the time to operation for a set-specified fire HRR history. They are convenient because they avoid the tedious repetitive calculations needed to analyze a growing fire. The same calculations can be easily done with a scientific hand calculator for stead-state fires that have a constant HRR. If cases where a more detailed analysis of a fire that has important changes in HRR over time is required, the fire may be represented as a series of steady-state fires one after another.

The following equation gives the time needed to heat the sensing element of a suppression device, from room temperature to operation temperature, in a steady-state fire:

$$t_{activation} = \frac{RTI}{u_{jet}} \ln\left(\frac{T_{jet} - T_0}{T_{jet} - T_{activation}}\right) \qquad (13)$$

where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = Response Time Index $(m\text{-}sec)^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_0 = ambient air temperature (°C)
$T_{activation}$= activation temperature of sprinkler head (°C)

RTI is the fundamental measure of the thermal sensitivity of sprinklers. The RTI is determined using plunge tests in which the sprinkler is exposed to a uniform gas flow of constant temperature and velocity. The test results can be used to predict the activation time of sprinklers in any fire environment. The RTI assumes that conductive heat exchange between the sensing element and supports is negligible. The RTI is a function of the time constant, τ, of the sprinkler head which is related to the mass and surface area of the sensing element. Faster sprinklers have lower RTI and smaller time constants. Sprinklers with low time constants typically have low ratios of mass to surface area. This is the basis of quick response sprinklers. The RTI concept was developed by Factory Mutual Research Corporation (FMRC). It is given by the following equation:

$$RTI = \frac{m_e c_{p(e)}}{h_e A_e} \sqrt{u_{jet}} \qquad (14)$$

where:

m_e = mass of element (kg)
$c_{p(e)}$ = specific heat of element (kJ/kg-K)
h_e = convective heat transfer coefficient (kW/m^2-K)
A_e = surface area of element (m^2)
u_{jet} = velocity of gas moving past the sprinkler (m/sec)

The expressions for estimating the maximum ceiling jet temperature and velocity as a function of ceiling height, radial position, and HRR were developed by analyzing of experimental data on large-scale fires having HRRs between 668 kW to 98,000 kW. The expressions are given for two regions: where the plume directly hits the ceiling and the surrounding region and, where the flow is horizontal.

The ceiling jet temperature and velocity correlations are given by the following equations (Alpert 1972, and Budnick et al.,1997):

$$T_{jet} - T_0 = \frac{16.9\dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \quad \text{for } \frac{r}{H} \le 0.18 \qquad (15)$$

$$T_{jet} - T_0 = \frac{5.38\left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \quad \text{for } \frac{r}{H} > 0.18 \qquad (16)$$

$$u_{jet} = 0.96\left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \quad \text{for } \frac{r}{H} \le 0.15 \qquad (17)$$

$$u_{jet} = \frac{0.195\dot{Q}^{\frac{1}{3}}H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \quad \text{for } \frac{r}{H} > 0.15 \qquad (18)$$

where:

T_{jet} = ceiling jet temperature (°C)
T_0 = ambient air temperature (°C)
$\dot{Q}$ = heat release rate of the fire (kW)
r = radial distance from the plume centerline to the sprinkler head (m)
H = distance from the top of the fuel package to the ceiling level (m)
u_{jet} = ceiling jet velocity (m/sec)

These correlations are widely used to calculate the maximum temperature and velocity in the ceiling jet at any distance, r, from the fire axis. Note, the regions where each expression is valid are given as a function of the ratio of the radial distance, r, to the ceiling height, H. As the ratio of r to H increases with distance from the centerline of the plume jet, r/H increases. For example, regions where r/H>18, use Equation 16. Equation 15 is used for a small radial distance where the hot gases have just begun to spread under the ceiling.

As with the temperatures there are two velocity regions in the ceiling jet flow, u_{jet}: (1) one close to the impingement point where velocities are nearly constant and (2) the other farther away where velocities vary with radial position.

The ceiling jet temperature is important in fire safety analysis because sprinklers are usually on the ceiling. Knowing the temperature and velocity of the ceiling jet as a function of radial distance enables inspectors to estimate the response times of sprinklers.

The temperature and velocity of a ceiling jet also vary with the depth of the jet. Near the ceiling, the temperature is at a maximum, then decreases downward. The temperature profile of a ceiling jet is not symmetric like the temperature profile of a plume, where the maximum temperature is along the plume centerline.

Knowing the ceiling jet temperature and velocity, the actuation time of a sprinkler can be estimated if the spacing of the sprinkler and the RTI is known.

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate the sprinkler actuation time.

A METHOD FOR PREDICTING COMPARTMENT FLASHOVER

Introduction

The likelihood of flashover can be estimated by determinating the temperature within a compartment during a fire. Flashover occurs when the surface temperatures of combustibles rise, producing pyrolysis gases, and the compartment heat flux ignites the gases. Flashover is assumed if the temperature of the smoke layer exceeds 450 °C (842 °F). Flashover generally occurs when the smoke layer reaches temperatures between 500 °C (932 °F) and 600 °C (1112 °F). The hot-smoke layer is considered almost a black-body radiator. At 450 °C (842 °F) the radiation from the smoke would be approximately 15 kW/m^2 (1.32 Btu/ft^2-sec). Fuel burning above 450 °C (842 °F) has a higher incident heat flux if the fire is in the open.

The International Standards Organization (ISO), defines flashover as "the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure and the relatively abrupt change from a localized fire to the complete involvement of all combustibles within a compartment" ("Glossary of Fire Terms and Definitions," ISO/CD 13943, International Standards Organization, Geneva, 1996).

NFPA 555 "Guide on Methods for Evaluating Potential for Room Flashover," defines room flashover in terms of temperature rise and heat flux at floor level. The NFPA guide gives a gas temperature rise at flashover of 600 °C (1112 °F) and a floor-level heat flux at flashover of 20 kW/m^2.

Heat Release Required to Cause Flashover

The minimum HRR necessary to cause flashover in a compartment has been widely studied. The minimum rate increases with the size of the compartment, and depends, on the ventilation in the compartment. If there is too little ventilation, flashover cannot occur. If there is too much excess air flow, it dilutes and cools the smoke, requiring a higher HRR to reach the critical temperature for flashover. The materials of construction and the thickness of the ceiling and upper walls are also important factors in determining whether flashover will occur and, if so, how soon.

There are several methods of estimating the onset of flashover in a compartment. The methods are usually based on simplified mass and energy balances for single-compartment fires and correlations with experimental data on fires.

Observations from full-scale fire tests and fire fighter experience describe flashover as a discrete event. Numerous variables affect the transition of a compartment fire to flashover. Thermal influences are clearly important when radiative and convective heat flux are assumed to be predominate. Ventilation, compartment volume, and the chemistry of the hot-gas layer can also influence the occurrence of flashover. Although the speed of the transition to flashover increases the uncertainties, the onset of flashover can still be estimated by correlating with the considerable body of full-scale test data on flashover.

Thomas (1981), developed a semi-empirical correlation of the HRR necessary to cause flashover in a compartment. He used a simple model of flashover in a compartment to study the effect of wall-lining materials and thermal feed-back to the burning objects. He predicted a temperature rise of 520 °C (968 °F) and a black-body radiation of 22 kW/m² to a surface distant from burning wood fuel at the predicted critical HRR necessary to cause flashover. According to the NFPA 555, room flashover potential is best estimated by using Thomas's flashover correlation (Equation 18).

Thomas' flashover correlation simplifies the energy balance of a compartment fire. The correlation gives the minimum HRR for flashover (Thomas 1981, Walton, and Thomas 1995, and NFPA 555 2000 Edition):

$$\dot{Q}_{FO} = 7.8A_T + 378A_v\sqrt{H_v} \qquad (19)$$

where:

$\dot{Q}_{FO}$ = heat release rate to cause flashovber (kW)
A_T = total area of the enclosing compartment surfaces (m²), excluding the area of the vent opening(s)
A_v = area of the ventilation opening(s) (m²)
H_v = height of the ventilation opening(s) (m)

The constants in Equation 18 represent values correlated to experiments producing flashover.

This equation requires that the duration of the fire be known or that the fire has been burning for a long period of time and the heat conduction has become steady-state.

Typically a few minutes up to around 30 minutes is a reasonable range of time for estimating the likelihood of flashover. Firefighter response time is also usually within this range (Karlsson and Quintiere 2000).

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate the HRR necessary to cause flashover.

SUMMARY

The additional fire scenario estimating tools described in this paper will advance the NRC risk-informed inspection process in several ways:

1. The use of simple fire dynamics correlations will enable regional fire protection inspectors to transition from purely qualitative fire risk evaluations to evaluations based on both qualitative and quantitative methods. The correlations will decrease the reliance on opinion and reduce the uncertainties in fire risk evaluations.

2. The worksheets with locked-in equations and correlations will allow regional inspectors to more easily perform fire hazard analyses, reduce the potential for mathematical errors and the misapplication of the SFPE Handbook of Fire Protection Engineering and NFPA Fire Protection Handbook equations.

3. Regional inspectors gain insights into the fire risk scenarios by having tools that can rapidly be changed to calculate potential fire dynamics effects.

LESSONS LEARNED AND IMPROVEMENTS

Lessons learned and improvements have come about primarily during training of the inspectors in the quarterly NRC regional fire protection inspectors workshops and the inspector's applications of the worksheets in actual NPP inspections. There are three major areas where lessons learned/improvements have been made to date.

1. One advantage of worksheets is the tabular listing of material fire property data. Collecting the input to the fire dynamics equations and correlations for this is a project in itself. There were three lessons learned identified. First, when there are several values in the literature for the same material, which value should be used? This was a problem with HRRs for cable jackets. The solution was to pick the "best" value and use only that value in the worksheet. If the licensee has a more precise value the inspector can input that value. The second problem is unavailable or incomplete data. This problem was discussed in training workshop sessions. Much of the HRR data currently available was funded and developed for a specific end-user. For example, the General Services Administration (GSA) (which deal mostly with office environments) HRR values may not be applicable to NPPs. At times inspectors have to correlate the scenario they are developing with known data that may not, at first, seem applicable to NPPs. Third, some of the existing data does not fully describe the potential hazard. A good example of this is the HRR for electrical cabinets. The published data focus on combustibles in the cabinet (typically cable insulation) and neglect possible large energy release [amperes squared multiplied by time (I^2t)]. The fire at San Onofre Nuclear Generating Station, Unit 3, on February 3, 2001, showed that heat from an electrical fault in a cabinet can vaporize copper conductors and destroy surrounding metal cabinets. For medium- and high-voltage applications, preliminary NRC research indicates that these HRR values may be under predicting by a factor of 1000. Inspectors are aware of this and are instructed to use higher values to include the electrical energy when they can justify the higher values. Additionally, the inspector are trained in the fundamentals of fire dynamics and the use of the engineering correlations to recognize those configurations where the correlations are appropriate and where they should not be used. The NRC/NRR staff fire protection engineers are always available for inspector consultation to ensure the proper application of these analysis tools.

2. Most of the equations and correlations in the worksheets are simple mathematical expressions. The mathematical expressions are not limited and sometimes give physically impossible values. To prevent such errors, the worksheets have red warning flags added. If a value exceeds known limits, a red flag appears. For example a red flag appears when an equation increases room temperature values well beyond those physically possible.

3. For convenience the new worksheets use pull-down menus and dialog boxes. This enhancement will allow the users to select the single input, instead of entering all the parameters associated with the input. For example, an inspector can simply click on "concrete" in the menu and the correct parameters appear in the equation. This enhancement will also eliminate manual errors in entering the table values in the equations.

CONCLUSION

Using commercial available spreadsheet software (like Microsoft Excel®) to create a series of computational worksheets, the techniques of fire dynamics analysis can be taught to and reliably applied by inspectors. The worksheets also reduce mathematical complexities and errors.

The NRR fire protection staff is continuing to develop additional worksheets for regional inspector application in the area of fire risk evaluation. The worksheets discussed in this paper are the second set completed and put into use. The NRC/NRR fire protection engineering staff expects to complete the full suite of fire dynamics worksheets in about 3 years.

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APPENDIX A

SAMPLE PROBLEM

This is an example of how to do an engineering FHA using the NRC/NRR fire dynamics Microsoft Excel® worksheets.

STATEMENT OF PROBLEM

During a routine fire protection inspection, a NRC inspector discovers a significant oil leak in a station air compressor. It is important to determine whether a fire involving 20 gallon spill of lubricating oil from a compressor could damage the safety-related cable tray and electrical cabinet in an access corridor in the fuel building. The compressor is on a pedestal approximately 1.0 foot above floor level and has a 12 ft^2 (1.12 m^2) oil retention dike. The safety-related cable trays are located 8 ft (2.45 m) above the corridor floor with a horizontal distance of 4 ft (1.2 m) from edge of the compressor's dike. The horizontal distance between the compressor dike and the electrical cabinet is 5 ft (1.52 m).

The access corridor has a floor area of 20 x 15 ft (6 x 4.6 m), a ceiling height of 10 ft (3 m), and has a single unprotected vent opening (door) of 4 x 6 ft (1.22 x 1.4 m). The compartment has no forced ventilation. The compartment construction is 1 ft thick concrete. The corridor has a detection system and a wet pipe sprinkler system. The nearest sprinkler is rated at 165 °F (74 °C) with a RTI of 235 $(m\text{-}sec)^{1/2}$) and located 9.8 ft (2.98 m) from the center of the dike. Determine if there is a credible fire hazard to the safety-related cable trays and electrical cabinet.

Use the following worksheets to evaluate fire scenario.

1. Heat flux to the target (electrical cabinet) using point source model, $\dot{q}''_{cabinet}$
2. Heat flux to the target (cable trays) using the solid-flame radiation model, $\dot{q}''_{cable}$
3. Centerline plume temperature, $T_{P(centerline)}$
4. Sprinkler activation time, $t_{activation}$
5. HRR necessary to cause flashover, $\dot{Q}_{FO}$

ANALYSIS

Accidental spills of flammable and combustible liquid fuels and resulting fires depend on the composition of the fuel, the size and shape of the fire, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of the object exposed to the fire. Liquids with relatively high flash points (like lube oil or diesel fuel) require localized heating to ignite. However, once started, a pool fire spreads rapidly over the surface of the liquid spill. To perform a conservative FHA, it will be assumed that the 20 gallons of lubricating oil will be spilled into the diked area and the over heated compressor ignites the oil.

The summary results of the calculations are given in table. See Microsoft Excel® worksheets for details of the calculations.

Fire Hazard Calculation for Compressor Lubricating Oil Spill in Access Corridor

Heat flux to target (electrical cabinet) $\dot{q}''$ (kW/m²)	Heat flux to target (cable trays) $\dot{q}''$ (kW/m²)	Centerline plume temperature $T_{P(centerline)}$ [°C (°F)]	Sprinkler activation time $t_{activation}$ (min)	HRR necessary to cause flashover $\dot{Q}_{FO}$ (kW)
12.50	17	689 (1272)	2	2100

It should be noted that exposure to high plume temperatures could potentially cause the unprotected safety-related cable trays to fail. The flame heat fluxes to the electrical cabinet and the cable trays are high enough to damage them.

The results of the calculation demonstrate that a pool fire with a 12 ft² dike area in an access corridor could damage unprotected safety-related cable trays and electrical cabinets. The analysis also suggests that for the postulated oil fire, the sprinkler system, if operable, should activate and should provide some protection to the safety-related cables and equipment.

METHOD OF ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET LIQUID FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

[illegible]

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

[illegible]

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")	0.039	kg/m²-sec
Net Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg
Fuel Spill Area or Dike Area (A_{dike})	12.00	ft²
Distance between Pool Fire and Target (L)	5.00	feet
Radiative Fraction (χ_r)	0.35	

1.11
1.52

Lube Oil

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m²-sec)	Effective Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m³)
Methanol	0.017	20,000	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
Benzene	0.085	40,100	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	0.018	26,200	1035
Diethy Ether	0.085	34,200	714
Benzine	0.048	44,700	740
Gasoline	0.055	43,700	740
Kerosine	0.039	43,200	820
Diesel	0.045	44,400	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810
Transformer Oil, Hydroc	0.039	46,000	760
Fuel Oil, Heavy	0.035	39,700	970
Crude Oil	0.0335	42,600	855
Lube Oil	0.039	46,000	760

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-2)

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-206)

POINT SOURCE RADIATION MODEL

$q" = Q\chi_r/4\pi R^2$

Where
- $q"$ = incident radiative heat flux on the target (kW/m²)
- Q = pool fire heat release rate (kW)
- χ_r = radiative fraction
- R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} =$ $\pi D^2/4$

$D =$ $(4\ A_{dike}/\pi)^{1/2}$

$D =$ **1.19** m

Heat Release Rate Calculation

$Q = m''\Delta H_c A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ΔH_c = net heat of combustion of fuel (kJ/kg)

A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)

$Q =$ **2000.02** kW

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L+D/2$

Where R = distance from center of the pool fire to edge of the target (m)

L = distance between pool fire and target (m)

D = pool fire diameter (m)

$R =$ **2.12** m

Radiative Heat Flux Calculation

$q'' = Q\chi_r/4\pi R^2$

$q'' =$ 12.40 kW/m^2 1.09 BTU/ft^2-sec ANSWER

FAILURE CRITICAL HEAT FLUX FOR CABLES

Cable Type	Damage Threshold Damage Threshold Heat Flux (kW/m^2)
IEEE-383 qualified	10
IEEE-383 unqualified	5

Reference Fire-Induced Vulnerability Evaluation (FIVE), page 6-14

NOTE

[redacted]

METHOD OF ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET LIQUID FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

[illegible]

Parameters should be specified ONLY IN THE RED INPUT PARAMETER BOXES.

[illegible]

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec		
Net Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg		
Fuel Spill Area or Dike Area (A_{dike})	12.00	ft^2	1.11	m^2
Distance between Pool Fire and Target (L)	4.00	feet	1.219	m
Vertical Distance of Target from Ground ($H_1 = H_{f1}$)	7.00	feet	2.134	m

THERMAL PROPERTIES FOR Lube Oil

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Effective Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)
Methanol	0.017	20,000	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
Benzene	0.085	40,100	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	0.018	26,200	1035
Diethy Ether	0.085	34,200	714
Benzine	0.048	44,700	740
Gasoline	0.055	43,700	740
Kerosine	0.039	43,200	820
Diesel	0.045	44,400	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810
Transformer Oil, Hydroc	0.039	46,000	760
Fuel Oil, Heavy	0.035	39,700	970
Crude Oil	0.0335	42,600	855
Lube Oil	0.039	46,000	760

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-2)

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: SFPE Handbook of Fire Protection Engineering 3rd Edition (Page 3-272)

SOLID FLAME RADIATION MODEL

$q" = EF_{12}$

Where $q"$ = incident radiative heat flux on the target (kW/m^2)

E = emissive power of the pool fire flame (kW/m^2)

F_{12} = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = (4\ A_{dike}/\pi)^{1/2}$

D = **1.19** m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

E = **56.71** (kW/m^2)

View Factor Calculation

$F_{12,V1}$ = $1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2})-(h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{12,V2}$ = $1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2})-(h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{12,V} = F_{12,V1} + F_{12,V2}$

Where $F_{12,V}$ = total vertical view factor
R = distance from center of the pool fire to edge of the target (m)
H_f = height of the pool fire flame (m)
D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

R = L+D/2 = **1.815 m**

Heat Release Rate Calculation

$Q = m''\Delta H_c A_f$

Q = **2000.02** kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

H_f = **3.699** m

S = 2R/D = **3.047**

$h_1 = 2H_{f1}/D$ = **3.582**

$h_2 = 2H_{f2}/D$ = $2(H_f-H_{f1})/D$ = **2.628**

$A_1 = (h_1^2+S^2+1)/2S$ = **3.793**

$A_2 = (h_2^2+S^2+1)/2S$ = **2.821**

$B = (1+S^2)/2S$ = **1.687**

$F_{12,H}$ =	**0.153**	0.093	0.231	0.388	0.750	0.153	$F_{12,V1}$
$F_{12,V}$ =	**0.143**	0.077	0.170	0.294	0.800	0.143	$F_{12,V2}$
$F_{12,V}$ =	**0.296**						

Radiative Heat Flux Calculation

$q'' = EF_{12}$

q" = 16.76 kW/m² 1.48 BTU/ft²-sec ANSWER

FAILURE CRITICAL HEAT FLUX FOR CABLES

Cable Type	Damage Threshold Damage Threshold Heat Flux (kW/m²)
IEEE-383 qualified	11.4
IEEE-383 unqualified	5.7

Reference Fire-Induced Vulnerability Evaluation (FIVE), page 6-14

NOTE

[redacted]

METHOD OF ESTIMATING TEMPERATURE OF A BUOYANT FIRE PLUME

[redacted]

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

[redacted]

INPUT PARAMETERS

Heat Riease Rate of the Fire (Q)	2000.00	(kW)	
Distance from the Top of the Fuel to the Ceiling (z)	9.00	ft	2.74 m
Area of Combustible Fuel (A_c)	12.00	ft²	1.11 m²

AMBIENT CONDITIONS

Ambient Air Temperature (T_0)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_0)	1.20	kg/m³	
Acceleration of Gravity (g)	9.81	m/sec²	
Convective Heat Release Fraction (χ_c)	0.50		

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 2-9).

$T_{p(centerline)} - T_0 = 9.1\,(T_0/g\,c_p^2\,\rho_0^2)^{1/3}\,Q_c^{2/3}\,(z - z_0)^{-5/3}$

Where Q_c = Convective portion of the heat release rate (kW)
T_0 = ambient air temperature (K)
g = acceleration of gravity (m/sec²)
c_p = specific heat of air (kJ/kg-K)
ρ_0 = ambient air density (kg/m³)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\,Q$

Where Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction

Q_c = 1000 kW

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = (4\,A_{dike}/\pi)^{1/2}$

D = 1.19 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083\,(Q^{2/5})/D$

Where z_0 = virtual origin of the fire (m)
Q = heat release rate of fire (kW)
D = diameter of pool fire (m)

z_0/D = 0.44

z_0 = 0.52 m

Centerline Plume Temperature Calculation

$T_{p(centerline)} - T_0 = 9.1\,(T_0/g\,c_p^2\,\rho_0^2)^{1/3}\,Q_c^{2/3}\,(z - z_0)^{-5/3}$

$T_{p(centerline)} - T_0$ = 664.22

$T_{p(centerline)}$ = 962.22 K

$T_{p(centerline)}$ = 689.22 °C 1272.59 °F **ANSWER**

NOTE

[redacted]

METHOD OF ESTIMATING SPRINKLER RESPONSE TIME

[redacted]

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

[redacted]

INPUT PARAMETERS

Heat Release Rate of the Fire (Q)	2000.00	(kW)	
Sprinkler Response Time Index (RTI)	235	$(m\text{-}sec)^{1/2}$	
Activation Temperature of the Sprinkler Head ($T_{activation}$)	165	(°F)	73.89 °C
Distance from the Top of the Fuel Package to the Ceiling Level (H)	9.00	(ft)	2.74 m
Radial Distance from the Plume Centerline to nearest Sprinkler Head (r)	9.80	(ft)	2.99 m
Ambient Air Temperature (T_0)	68.00	(°F)	20.00 °C
			293.00 K

Convective Heat Release Fraction (χ_c) 0.70

r/H = 1.09

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)* FOR Standard response bulb

Common Sprinkler Type	Generic Response Time Index RTI $(m\text{-}sec)^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34

Reference Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)* FOR Ordinary

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550

Reference Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, p. 67.

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference NFPA Fire Protection Handbook 18th Edition (Page 11-97)

$t_{activation} = (RTI)/u_{jet}^{1/2} \ln (T_{jet} - T_0)/T_{jet} - T_{activation})$

Where $t_{activation}$ = sprinkler activation response time (sec)

RTI = sprinkler Response Time Index $(m\text{-}sec)^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_0 = ambient air temperature (°C)

$T_{activation}$ = activation temperature of sprinkler head (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_0 = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_0 = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where
- T_{jet} = ceiling jet temperature (°C)
- T_0 = ambient air temperature (°C)
- Q_c = convective portion of the heat release rate (kW)
- H = distance from the top of the fuel package to the ceiling level (m)
- r = radial distance from the plume centerline to the sprinkler head (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where
- Q = heat release rate of the fire (kW)
- χ_c = convective heat release fraction

Q_c = 1400 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.09 r/H > 0.18

$T_{jet} - T_0 = 5.38\,(Q_c/r)^{2/3}/H$

$T_{jet} - T_0$ = 118.34

T_{jet} = 138.34 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\,(Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$ for r/H > 0.15

- u_{jet} = ceiling jet velocity (m/sec)
- Q = heat release rate of the fire (kW)
- H = distance from the top of the fuel package to the ceiling level (m)
- r = radial distance from the plume centerline to the sprinkler head (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.09 r/H > 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$

u_{jet} = 1.635 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI)/u_{jet}^{1/2}\ \ln\,(T_{jet} - T_0)/T_{jet} - T_{activation})$

$t_{activation}$ = 111.69 sec

The sprinkler will respond in approximately 1.86 minutes ANSWER

NOTE: If $t_{activation}$ = "NUM" Sprinkler is not activate

NOTE

[redacted]

METHOD OF PREDICTING VENTED COMPARTMENT FLASHOVER
NO FORCED VENTILATION

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	feet	6.096 m
Compartment Length (l_c)	15.00	feet	4.572 m
Compartment Height (h_c)	10.00	feet	3.048 m
Vent Width (W_v)	4.00	feet	1.219 m
Vent Height (H_v)	6.00	feet	1.829 m

METHOD OF THOMAS

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-140)

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (H_v)^{1/2}$

Where Q_{FO} = heat release rate of the fire (kW)
A_T = total area of the compartment enclosing surface boundaries (m^2)
A_v = area of ventilation opening (m^2)
H_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

$A_v = (W_v)(H_v)$

$A_v =$ 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times dc)] - A_v$

$A_T =$ 118.54 m^2

Minimum Rate of Heat Release for Flashover

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (H_v)^{1/2}$

$Q_{FO} =$ 2064.41 kW **ANSWER**

NOTE

[illegible]

INSTITUT DE RADIOPROTECTION ET DE SURETE NUCLEAIRE
DEPARTEMENT DE RECHERCHES EN SECURITE

	RÉDACTION	VÉRIFICATION	QUALITÉ	APPROBATION
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DATE	14/05/2002	18/06/2002	21/06/02	25/06/02
VISA				
REV. A				
REV. B				

Titre	Overview of the FLAMME_S code validation matrix
Auteur(s)	**E. Bouton**
Type : NT	Numéro : SESHP/GME/IPS/FLS/C40/NT/02.337

Service d'Essais de Sûreté Hors Pile
Groupe Modélisation et Etudes des Feux

IRSN/DRS/SESHP/GMEF Cadarache, le 25/06/2002

SESHP/GME/IPS/FLS/C40/NT/02.337

Overview of the FLAMME_S code validation matrix

E. Bouton

SERVICE D'ESSAIS DE SURETE HORS PILE Groupe Modélisation et Etudes des Feux		
Nat. Document	NT	
TITRE	**Overview of the FLAMME_S code validation matrix**	
Auteur(s)	E. Bouton	
Type de diffusion : Normale	"Mots clés" :	Nbre de pages : 199 Nbre de figures : 3

RESUME :
Ce document présente une vue d'ensemble de la matrice de qualification du code FLAMME_S.

ABSTRACT :
This document is an overview of the validation matrix of the FLAMME_S code.

Repère bureautique : SESHP/GME/IPS/FLS/C40/NT/02.337

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1 INTRODUCTION

This note has been written in the framework of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications organized by the NRC. Its aim is to give to the participants or the FLAMME_S users an overview of the validation matrix of the code. Therefore, in this document, only the FLAMME_S major features and the test conditions are described. More detailed information can be found in the references, mostly written in French and not open to release.

2 OVERVIEW OF THE FLAMME_S CODE

The FLAMME_S code was developed to compute the consequences of a fire in nuclear power plants or in industrial facilities. This code is based upon a classical two zones model and it can be applied to a single or a multi-room configuration. The main characteristics of the FLAMME_S code are :

- The flame and the plume above the fire pool are described with the empirical correlations set by Heskestad. The Mac Caffrey's plume model is currently under development.
- The calculation of the radiative exchanges inside the room (on walls and on targets) due to the flame relies on a classical point source approach.
- The heat loss of the gases through the walls by conduction is taken into account and can induce the heating of the gases of a target room near the fire room.
- The rooms of the facility can be connected with a ventilation system (at a constant or variable flow rate) or with vertical vents like doors.
- No ceiling jet or horizontal vent models are available.

FLAMME_S can be used autonomously or coupled with the SIMEVENT code devoted to the calculation of flow rates in complex ventilation networks. But the description of this ventilation code is beyond the scope of this paper.

3 VALIDATION DOMAIN

The objective of the validation process of the FLAMME_S code is to evaluate the calculation results for several different configurations, in terms of :

- the room's number of the facility (up to 3 rooms),
- the location of the pool fire (in the middle of the room or against a wall),
- the ventilation conditions (forced or natural),
- the kind of fuels used.

All the tests series considered in the validation matrix are listed in the following table :

Configuration	Location of the pool fire	Test series	Number of tests
Single room	In the middle of the room	LIC, LPI, PEPSI	13
Single room	Against a wall	FLIP	5
Multi rooms	In the middle of the room	Cooper	19
Multi rooms	Against a wall	Peacock	7

Table 1 : List of the test series considered in the validation matrix

Additional information about the test conditions is indicated below or may be found in the references. Furthermore a "rough" criteria, the relative error, has been used to evaluate the quality of the agreement between calculations and test results. When the relative error is less than 20 %, FLAMME_S can be used with confidence for similar calculation conditions. All the tests listed in this document satisfy this condition, except some Peacock's test (See § 3.3.2).

3.1 Fuel used during the test

The different kind of fuel used during the tests are indicated in the following table.

Fuel	Chemical formula	Test
TPH	$C_{12}H_{26}$	LIC2.CB
70% TPH - 30% TBP	70% ($C_{12}H_{26}$) – 30% ($C_{12}H_{27}O_4P$)	LIC/FLIP
Ethanol	$C_2H_6O_1$	LIC1.14/FLIP
Mineral Oil (DTE medium)	$C_{31,34}H_{63,9}$	LPI
Domestic fuel	$C_{15,55}H_{29,3}$	LPI13
Methane	CH_4	Cooper
Methane/acetylene		Peacock

Table 2 : List of fuels

TPH : Hydrogened Tetra Propylen

TBP : Tri Butyl Phosphat

More detailed characteristics of the fuel are given in annexe.

3.2 Single room tests performed at IRSN

3.2.1 Centred fire pool

The different tests achieved with the fire pool in the middle of the room [5], [6] are indicated in the table below.

Area of the pool (m^2)	Fuel	Facility (Volume m^3) (L×l×H) ou (S×H) (wall material)	Ventilation conditions	Test
0,0314	Mineral oil (DTE medium)	4,35 m^3 (0,856 m^2×5,35 m) (steel wall)	confined	LPI 7
0,0314	Mineral oil (DTE medium)	4,5 m^3 (2,011 m^2×2,24 m) (steel wall)	confined	LPI 9bis

0,0629	Mineral oil (DTE medium)	4,5 m^3 (2,011 m^2×2,24 m) (steel wall)	confined	LPI 10
1	70% TPH - 30% TBP	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (3 V/H)[1]	LIC 2.3
1	70% TPH - 30% TBP	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LIC 2.8.1
1	70% TPH - 30% TBP	3600 m^3 (20 m×15 m×12 m) (concrete wall)	confined	LIC 2.CA
1	TPH	3600 m^3 (20 m×15 m×12 m) (concrete wall)	confined	LIC 2.CB
1	Mineral oil (DTE medium)	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (5 V/H)	LPI 11A LPI 11 PEPSI 1
1	ethanol	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (5 V/H)	LIC 1.14
2	Mineral oil (DTE medium)	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (5 V/H)	LPI 12
5	70% TPH - 30% TBP	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LIC 2.8.5
5	Mineral oil (DTE medium)	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LPI 13
5	Domestic fuel	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LPI 19

Table 3 : List of IRSN tests (centred fire)

3.2.2 Fire pool against a wall

In the FLIP tests [1], [8], the fire pool was located against the south wall of the PLUTON facility (V = 400 m^3, l×w×h 9 m×6 m×7,6 m). In this facility, all the walls are made of concrete except the south wall which was covered with a thermal insulating material made of thermipan. Whatever the test considered, the steady ventilation flow rate before the onset of the fire was 3 volume changes per hour. The squared inlet (0.5 x 0.6 m^2) is located in the bottom and in the middle of the north wall ; the squared outlet (0.5 x 0.8 m^2) is in the top and in the middle of the west wall (cf. Figure 1).

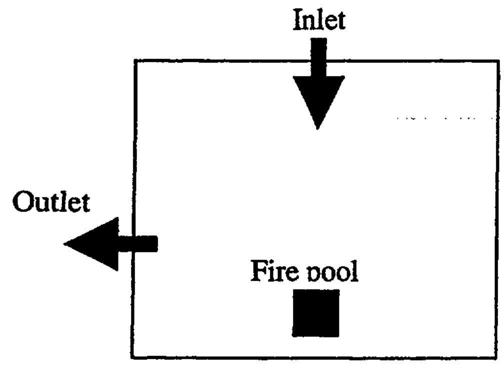

Figure 1: overview of the PLUTON facility

Additional information about the FLIP test is listed below :

Area of the pool (m^2)	Kind of fuel	Q (kW)	Test
0.4	TBP/TPH	360	FLIP1
0.4	Ethanol	215	FLIP1A
1.0	TBP/TPH	645	FLIP2
1.0	Ethanol	510	FLIP2A
1.5	TBP/TPH	910	FLIP7

Table 4 : List of IRSN FLIP test (fire pool against a wall)

Remark : Q is the average heat release rate (kW)

3.3 Multi-room tests

The FLAMME_S code was validated in multi-room configurations by using the tests performed by Cooper [4], [9], [10] and Peacock [7], [2], [3].

3.3.1 Cooper tests

The facility used by Cooper has 2 or 3 rooms, with a variable length for the corridor. The surface of the total floor is in the range of 40.6 m^2 to 89.6 m^2.

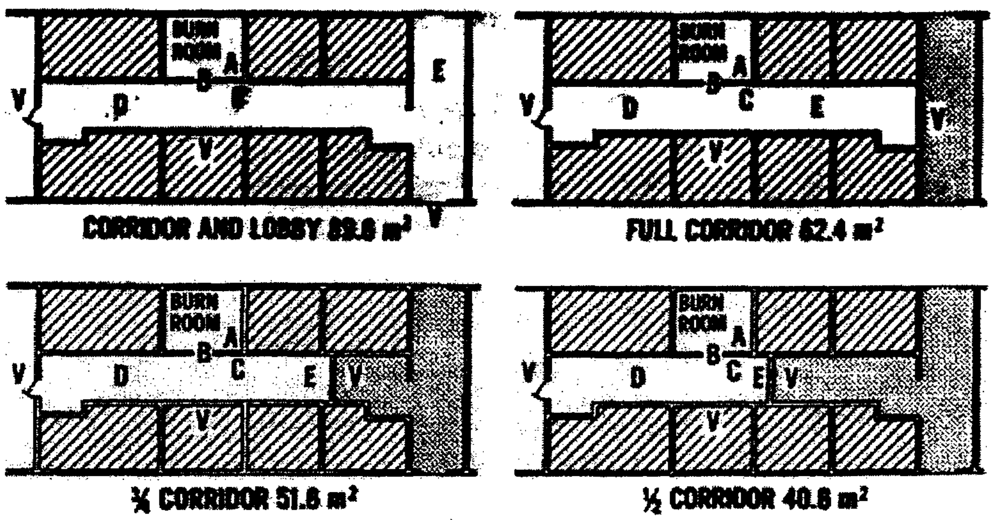

Figure 2 : Overview of the Cooper facility

A square gas burner (0.3 x 0.3 m^2) is set in the middle of a room and is supplied with methane. In the tests, the fire duration does not exceed 10 mn. The steady heat release rate of the fire (Q) is 25, 100 or 250 kW. The growth of the fire is modeled as :

$$Q(t) = 30\,t \quad \text{with} \quad 0 < t < 10 \text{ mn} \quad (Q \text{ in kW})$$

The other test conditions are listed in the following table :

Q (kW)	½ corridor	¾ corridor	corridor	Corridor and lobby	Corridor 1/2 door	Corridor 1/4 door	Corridor 1/8 door
25	x	x	x	x			
100	x	x	x	x	x	x	x
225	x	x	x	x			
Ramp fire	x	x	x	x			

Table 5 : List of Cooper tests

3.3.2 Peacock tests

An overview of the facility used by Peacock is displayed on the following scheme. It is composed of two or three rooms connected by doors.

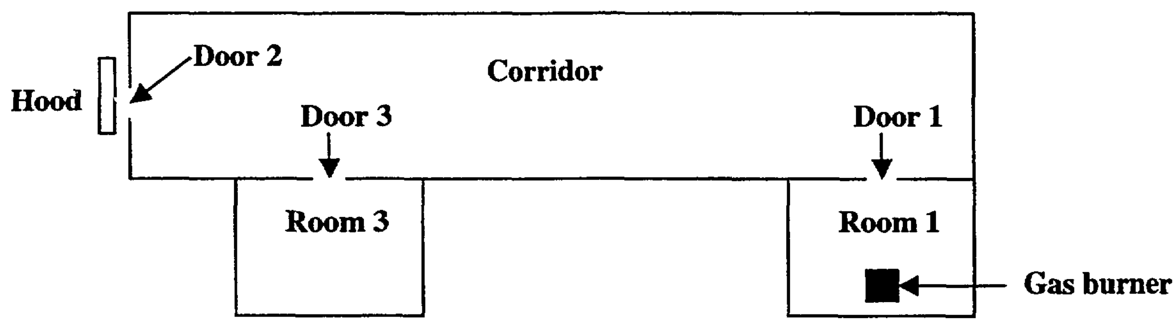

Figure 3 : Overview of the Peacock facility

The burn room walls are made of ceramic fiber and those of the second and third room are covered by gypsum board. Furthermore, the room dimensions are indicated in the following table :

Room	Length (m) x width (m) x height (m) Volume (m^3)
1	2.34 x 2.34 x 2.16 (11.83 m^3)
2	12.19 x 2.44 x 2.44 (72.6 m^3)
3	2.22 x 2.24 x 2.43 (12.1 m^3)

Table 6 : Room dimensions of Peacock's facility

A gas burner is set against a wall of the first room. The fuel is a gas mixture made of methane and acetylene. The heat release rate of the fire (HRR) is varied in the range of 100 to 500 kW. The combustion products are collected by a hood located just behind the second door. By using the O_2 consumption method, the HRR of the fire is deduced from hood measurements and not directly recorded with a weight device. This is the main difference with the other tests performed and listed in the validation matrix.

The conditions of the Peacock's tests are summed up in the table below :

Test number	Q (kW)	Door (corridor)	Third room
1	100	Open	No
4	100	Open	Yes
5	300	Open	No
6	300	Closed	Yes
7	300	Open	Yes
8	500	Open	No
9	500	Open	Yes

Table 7 : List of Peacock's tests

Concerning these tests, some restrictions about the agreement between calculations and test results must be made. Whatever the test considered, the average room temperature is well estimated ; the maximum value reached in the fire room in the case of the 500 kW heat released rate is very high around 550 °C. The flow rates through the door connecting the fire room to the corridor is also in good agreement with measurements. This is not true for the other doors of the facility probably due to the uncertainty on measurements. Furthermore, the upper layer temperature is enough over-estimated and the lower layer temperature under-estimated ; for these variables the relative error is beyond 20 % criteria.

4 CONCLUSION

Some general remarks can be drawn from the validation process about the limitations and the validation domain of the code. The upper layer temperature (resp. the lower layer temperature) is generally over-estimated (resp. under-estimated) even if the agreement between calculations and measurements is good. Given a facility and a forced ventilation flow rate before the start of the fire, the accuracy of the calculation decreases as a function of the heat release rate of the fire. These results are in agreement with the literature and not limited to the FLAMME_S code. They are likely link to the two zone approach.

Given the previous limitations, the FLAMME_S code is well validated over a large range of test conditions derived from the literature or from experiments performed at IRSN (more details of the tests used are given below). The main results of the comparison between the calculations and the experiments are the following :

1/ The relative error is less than 20 percents for the main thermodynamical parameters like the pressure in the room, the oxygen concentration and temperature in each layer, the average temperature of the wall and the ventilation flow rate, except in some Peacock tests (See § 3.3.2).

2/ The FLAMME_S code is validated for single room configurations (18 IRSN tests) and for multi-room configuration (19 tests performed by Cooper and 7 experiments achieved by Peacock).

Therefore the FLAMME_S code can be used with confidence in the following conditions :

- The room walls are made of concrete or of steel.
- The height of the room is equal or greater than the smallest horizontal dimension of the room.
- The room is sealed or connected to the outside with vertical openings or with a ventilation network (the flow rate is in the range of 3 to 5 volume changes per hour before the start of the fire).
- The fire pool is set in the middle of the room or against a wall.
- The fuel is a gas or made of mineral oil or of an organic liquid.
- The ratio of the pool area to the area of the floor of the facility is less than 5 percents.

- The pyrolysis rate of the fuel is an input data.
- The ratio of the heat release rate to the volume of the facility is less than $5kW/m^3$.

In the next future, new validation exercises are planned. FLAMME_S will be used to simulate the results obtained in a multi-room configurations with natural and mechanical ventilation (DIVA tests).

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Remark :

Reports written in French are the IRSN's property and not open to release.

ANNEXE1 : CHARACTERISTICS OF THE FUELS

Legend :

M : molar mass

PCI : standard heat of combustion (MJ/kg)

χ_r : heat fraction released by the flame as radiation

ρ : density

Kind of fuel	M (g/mol)	PCI (MJ/kg)	χ_r	ρ (kg/m³)	Test
Ethanol	46	25.6	0.25	794	FLIP
	46	26.78	0.25	794	LIC1.14
TBP/TPH	195.25	36	0.35	836	FLIP
	195.25	40	0.35	816.8	LIC2.3 LIC2CA
	195.25	32	0.35	816.8	LIC2.8.1 LIC2.8.5
Mineral Oil	439.98	41.86	0.35	870	LPI PEPSI
Domestic fuel	215.9	40	0.35	840	LPI19
TPH	170	40	0.35	749	LIC2CB
Methane	16	55	0.24	/	Cooper
Methane/actetylene	20.96	46.54	0.25	/	Peacock

ANNEXE 2 : CHEMICAL REACTIONS

In the validation process, the combustion products are composed by H_2O, O_5P_2, CO_2, C and the chemical reaction is written in the following way :

$$C_aH_bO_cP_d + \delta[O_2 + 3.7742 N_2] -> b/2 H_2O + d/2 O_5P_2 + \alpha CO_2 + \beta C$$

It is possible to compute the mole number of each product with the following assumptions :

- Every hydrogen atom is combined with oxygen to product water,
- Phosphor atoms in the fuel form O_5P_2,
- The mass fraction of soot to mass of burnt fuel is p.

Given these assumptions, the different mole numbers are written as :

$\alpha = a - (p/100)M_{fuel}/M_{soot}$ $\beta = (p/100)M_{fuel}/M_{soot}$ $\delta = 0.5\,[b/2 + (5/2)d + 2\alpha - c]$

TBP/TPH

Test	O_2	CO_2	C	p (%)
LIC23	18.298	11.929	0.071	10*
LIC2.8.1	16.02	9.651	2.349	24*
LIC2.c.a	16.107	9.738	2.262	13.9
LIC2.8.5	16.042	9.673	2.327	14.3
FLIP	16.091	9.722	2.278	14

$*\beta = (p/100)\,M_{fuel}/M_{soot} - (d/2)\,M_{O5P2}/M_{soot}$

Mineral oil

Test	O_2	CO_2	C	p (%)
LPI7	43.905	27.93	3.41	9.3
LPI9bis	43.282	27.307	4.033	11
LPI10	44.125	28.15	3.19	8.7
LPI11A LPI11 LPI12 LPI13	45.738	29.763	1.577	4.3
PEPSI	44.525	28.55	2.79	7.62

Other fuels

Fuel	O_2	CO_2	C	p (%)
Domestic fuel	20.356	13.031	2.519	14
TPH	17.083	10.583	1.417	10
Methane	2	1	0	0
Methane/acetylene	2.428	1.329	0.046	2.63

ZONE MODEL VALIDATION OF ROOM FIRE SCENARIOS

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ABSTRACT

Part of tre results of the Scenario B of the CIB W14 Round Robin for computer fire code assessment are presented. The scenario consisted of three subscenarios. Each of them was a single room with natural ventilation and a wood material fire source. Sixteen participants from ten countries using eleven different computer codes demonstrated the calculation of scenario B. The participants used two CFD-codes and nine two-zone models from 1997 to 1998. In this short report calculation results using codes developed at NIST are compared with measurements and discussed in general.

INTRODUCTION

Zone and field models describing fire development and smoke movement are commonly used as a part of advanced design or fire safety evaluation of buildings. Although numerous efforts to compare fire models with experiments have been published, systematic validation of the plethora of existing fire codes is lacking. This deficiency has become critical due to the introduction of performance based building codes, which often encourage the use of numerical simulations. Designers and authorities, which may not be knowledgeable about fire simulation, should be given guidance on which codes to use and on the limits of the models. VTT organized a round robin of fire simulation within the auspices of CIB W14. Two rounds of calculations were arranged. In the first, scenario A, users, programs, and their technology were studied simultaneously. The main result was, that the user is the most critical component. No further details are given here on scenario A. In scenario B the major objective was to test the performance of the technology although also it revealed a lot from the user contribution. This presentation summarizes the most important findings from that round concentrating on technology contained in CFAST and FIRST model codes originating from NIST.

OVERVIEW OF SCENARIO B

Scenario B consisted of three subscenarios B1, B2 and B3. The experiments corresponding to the subscenarios were conducted during the years 1983, 1985 and 1986 in the VTT testing hall, shown in Figure 1, jointly by VTT and Technische Universität Braunschweig (Hagen & Haksever 1985). Originally, the aim of the test series was to study full compartment fires. Subscenarios B1 and B2 shown in Figures 2 and 3, consisted of a single room with a door/window open to ambient. The names of the tests during the test programme and the room sizes are shown in Table 1.

Table 1 - The subscenarios. Test times were actually longer than the times mentioned here, but the given times were chosen for the Round Robin.

	Test label	Room size (m^3)	Fire load (kg)	Fire load density (MJ/m^2)	Peak RHR (MW)	Test time (min)
B1	SF83-3	$15 \times 7.2 \times 3.5$	1989	330	11	100
B2	SF85-10	$20 \times 7.2 \times 3.6$	1815	220	14	180
B3	SF86-10	$7.4 \times 7.2 \times 3.6$	2×500	330	5.2	120

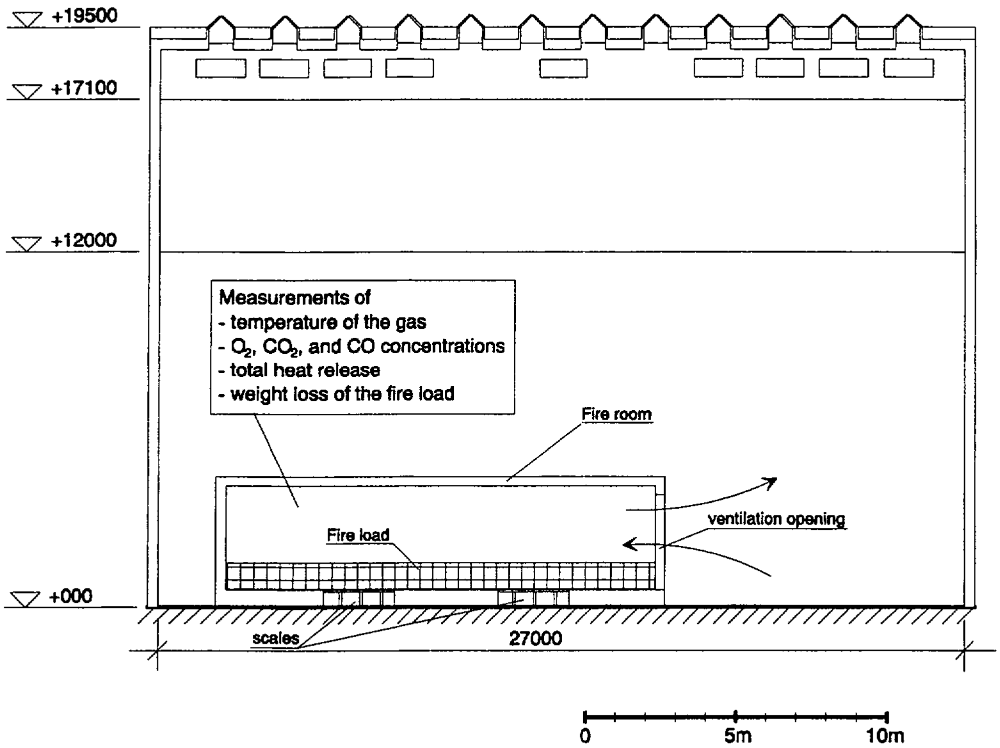

Figure 1. Schematic longitudinal cut of the testing hall. Dimensions are in mm.

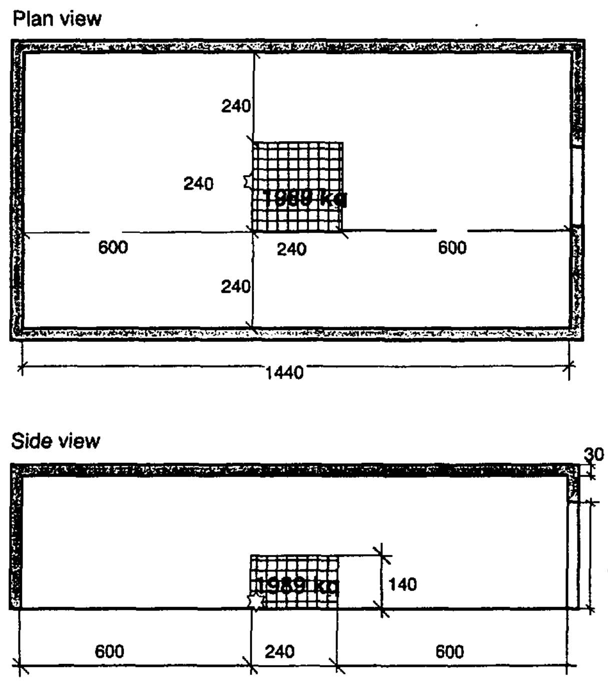

Figure 2. Subscenario B1.

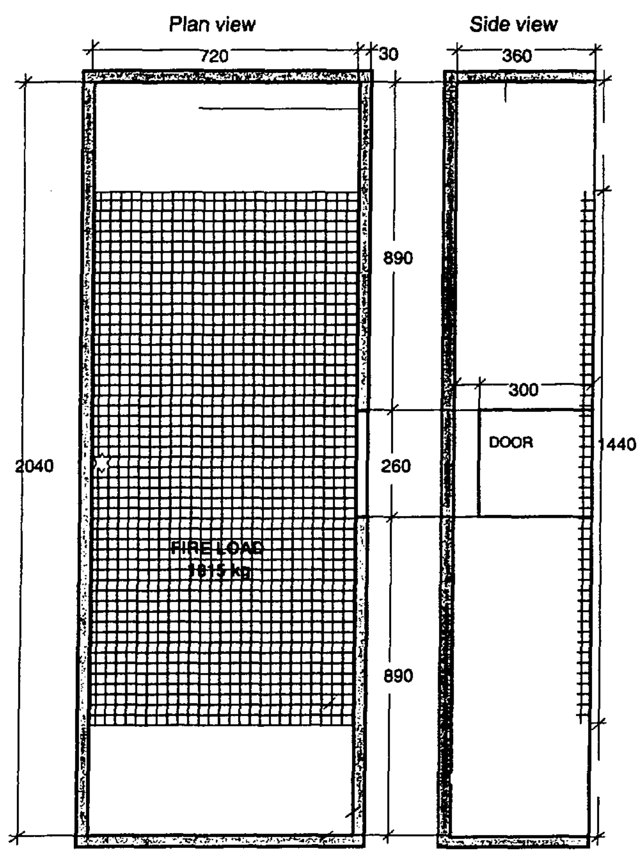

Figure 3. Subscenario B2.

EXPERIMENTAL DATA REDUCTION FOR FIRE MODEL VALIDATION

Here only data reduction of calculation of interface height and layer temperatures is treated. The height of the smoke layer interface is one of the key variables studied during the fire safety analysis of the buildings. It is a natural output variable for two zone model fire codes where the assumed existence of the interface is part of the model. However, when the question is about experimental or CFD data, where temperature is measured/calculated in discrete number of points, there is no general consensus about the correct calculation method for the interface height.

Kawagoe (1958) presented a one-zone model for a post flashover fire with ventilation to ambient and discovered that the flow rate was proportional to the vent factor $A\sqrt{H}$. The two-layer concept was introduced by Thomas *et al.* (1963) who presented the relationships of the layer heights, temperatures and the flow rates. Prahl and Emmons (1975) and Rockett (1976) further studied the hydrodynamic vent flows and presented the relationships between the interface and neutral plane heights and the mass flows in/out of the vent. A careful presentation of the flow equations in the vent has been given by Tanaka (1978), later included in zone model code BRI2 (Tanaka & Nakamura 1989). More recent reviews about the subject have been given by Thomas (1992) and Cox (1995).

In principle, when the fire is sufficiently small compared to the size of the compartment two layers will form. The height of the layer interface can be found by determing the inflection point of the vertical temperature profile. However, in the case of a relatively strong fire, as is the situation in the present scenarios, a single layer may form, with very small vertical temperature gradients. This is demonstrated in Figure 4 showing the development of the vertical temperature profiles inside the compartment in B3. Each line represents one time point. The absolute level of the temperature has been removed for linear presentation by transformation using:

$$T(z_i,t) = T(z_{\min},t) + t, \qquad (1)$$

where T is in °C and t in minutes. It can be seen that the development of the hot layer is clear up to the 20 minutes or flashover, after which the difference between the uppermost and lowest measurement is small and no large gradient exists, not to mention a true discontinuity assumed in the papers of Thomas et al. (1963) and Rockett (1976).

One of the most common methods to determine the interface height is to use the so-called *N* percent rule, suggested by Cooper *et al.* (1982). The interface height at time *t* is defined to be the elevation z_i at which the temperature first satisfies

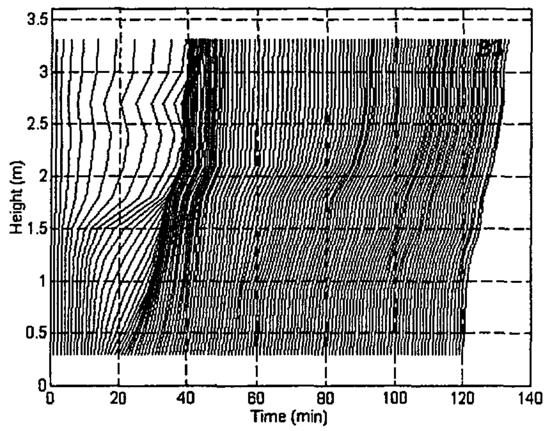

Figure 4 . Mean temperature profiles during the experiment B3.

$$\frac{T(z_i,t)-T_{amb}}{T(z_{top},t)-T_{amb}}=\frac{N}{100}. \tag{2}$$

In the literature the values suggested for *N* range from 10 to 20. The method was applied to the current scenarios with a value of *N* = 15. The average temperatures in the upper and lower layers were then calculated as mean values of the measurements in the upper and lower sides of z_i, respectively. In cases where $z_i = 0$ the lower layer temperatures are meaningless.

Mathematically the question is: "How to calculate three unknown variables, z_i, T_U and T_L, from the series of temperature measurements at discrete number of heights?" Quintiere *et al.* (1984) introduced a method to calculate the upper layer temperature T_U as an arithmetic average of the upper thermocouple readings. One then solves z_i and T_L from integral equations

$$\int_0^H T(z)dz = (H-z_i)T_U + z_i T_L, \tag{3}$$

$$\int_0^H \frac{dz}{T(z)} = (H-z_i)\frac{1}{T_U} + z_i\frac{1}{T_L}. \tag{4}$$

where *H* is the ceiling height. Equation (3) describes the mathematical averaging procedure of the zone model, but has no physical meaning, although it is quite close to the requirement for enthalpy equivalency. Equation (4) is a requirement for mass equivalency.

The goal of this experimental data reduction is to produce data that can be directly compared with the zone model results. The applied calculation method should therefore be able to give interface height and average temperatures that produce the same hydraulic flows as the zone models. Janssens and Tran (1992) introduced a method that combined the mass flow equations of Prahl and Emmons (1975) and Rockett (1976) with the mass integral (4). The problem of this method was that at high temperatures, the mass flow out of the vent is very insensitive to small changes of temperature and the mathematical solution of the system became difficult. They also presented an alternative method where the interface height was taken from the inflection point of the temperature profile. As their example cases had clear layer structures they had good results but here this method can not be applied.

For the round robin comparison the following procedure was used:

1. The lower layer temperature T_L is taken to be the average of the thermocouple readings of the lowest measurement points.
2. The interface height and upper layer temperature were solved from the integral equations (3) and (4). Combining these equations gave expression for the interface height
3.

$$z_i = \frac{T_L\left(I_1 \cdot I_2 - H^2\right)}{I_1 + I_2 T_L^2 - 2T_L H} \qquad (5)$$

where

$$I_1 = \int_0^H T(z)dz \text{ and } I_2 = \int_0^H \frac{dz}{T(z)} \qquad (6)$$

The problem of this method is the calculation of integrals (6) using relatively few measurement points. Interface heights calculated by this method will be presented together with those calculated with the N-percent rule with $N = 15$.

Shortly after these analyses were made He at al. (1998) treated the problem in a through way. They also concluded the N-percent rule results deviated from the two, methods to define the layer height: integral ratio method (given by equations (3) and (4)) and a more refined least squares method. The algorithm of CFAST produced data close to integral ratio and least squares methods.

PARTICIPANTS

CFAST

The model code CFAST comes from the package HAZARD I, developed at NIST (Peacock et al. 1997). CFAST was used by Jason D. Averill from NIST, Petra Büttner from Hosser, Hass & Partner (HHP) and Daniel Joyeux from Centre Technique Industriel de la Construction Metallique (CTI).
Version: 2.21 (HHP and CTI) and 3.1 (NIST)
Physical models:

- Multi-room two layer model
- McCaffrey entrainment law
- Pyrolysis / Heat release rate given by user
- Maintained carbon-hydrogen-oxygen balance
- Ceiling-floor and inter compartment heat transfer

FIRST

The model code FIRST (FIRe Simulation Technique) was developed at the National Bureau of Standards (NBS), (Mitler & Rockett 1987). During the round robin it was used by Daniel Joyeux from CTI.
Version: September 1987
Physical models:

- One compartment two zone model

Several plume models: Morton-Taylor-Turner (virtual and fire base source points), McCaffrey, Zukoski, Delichatsios and Kawagoe

RESULTS

For shortness in this paper only subscenario B1 is presented. Results are similar from other scenarios described in the full paper (Hostikka & Keski-Rahkonen 2002).

Comparisons of the measured and calculated interface heights are shown in Figure 5. Calculation results for two different methods are presented: the 15 %-rule in Equation (3) and the density integral method in Equation (5). The quality of the agreement between the measurements and the calculations depends on the method used. As mentioned before, in this subscenario, the existence of an interface is questionable due to the very small vertical temperature gradients. The following observations can be made:

There is a lot of deviation between both the different CFAST curves and between the CFAST simulations and the measurements. Only NIST and HHP's open round simulations are close to each other during the first 60 minutes.

CFAST show very high interface heights where the height of the base of the flame was assumed by the modellers to be 1.4 m.

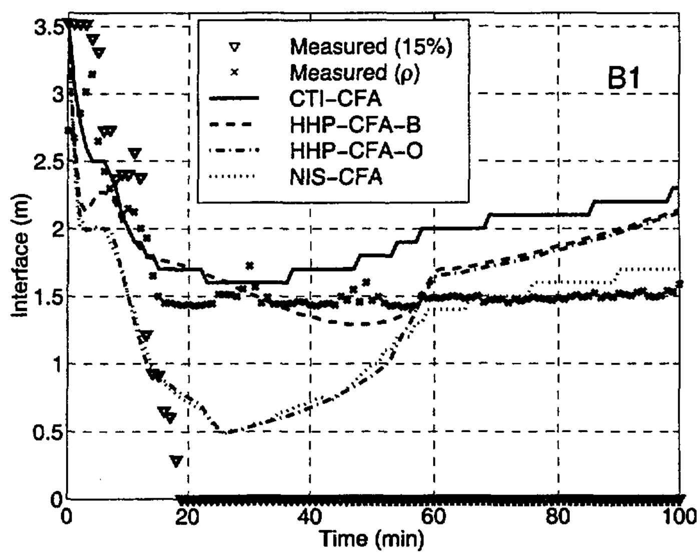

Figure5. Comparison of interface heights given by CFAST zone model and measurements in subscenario B1. The major change in the HHP-simulations was the different base of the flame height.

CFAST

CTI

The comparison between calculations with CFAST and experimental results indicates in a first approach rather bad calculations results. This is the results of the fact that a lower (cold) zone has to exist during calculations while the experimental data do not imply that. The calculation results of the upper layer temperature are always higher than the measured, with 300 or 400 °C. According to author, this result is a good result because such codes have to be used for fire safety calculations, their results have to be in a safe side. According to the author a more convenient comparison could be made by calculating a mean temperature of the whole compartment, ie. by using a one zone model. However, a two zone model as CFAST can also be used and can give good temperature results as an envelop of the experimental results.

HHP

There is a great deviation between experimental and measured data especially concerning the interface height and the species concentrations. While the experiments show a room which remains nearly completely filled with the smoke layer, the code calculates an increasing interface height after the burning peaks. In B1 the interface height calculation results were enhanced when the height of the flame basis was decreased. The deviation may also be caused by the 15%-rule used for the experimental determination of the interface height.

The maximum temperatures of the upper layer show a good agreement with the measured values. In this field the code shows a sufficient accuracy. The calculated upper layer temperatures are somewhat higher than the measured ones but this is consistent to the fact, that, according to the calculations, a part of the room (the lower layer) has only temperatures between 200 and 400 °C.

The measured O_2 concentration is well approximated by the calculation, whereas there are some differences concerning the concentrations of CO and CO_2. Especially the CO production is strongly depending of the course of the fire and difficult to predict.

FIRST

Simulation of the scenario B was not possible with the Delitchatsios and Kawagoe air entrainment models. The run with Zukoski model did not converge. The Morton-Taylor models and the McCaffrey models gave results and converged all along the simulations. The results obtained with the three models were rather similar. The reported results were given using the McCaffrey model.

The comparison between calculations with FIRST (Figure 6) and experimental results indicated very bad results as the scenarios were not very good applications for a two zone model. In terms of interface height, as the two zone model needs a lower zone, the lower zone had to exits in all three subscenarios. The upper layer temperatures were always lower than the experimental ones. A difference of about 200°C between measured and calculated temperature was generally obtained in the upper layer temperature comparison.
The oxygen concentration calculations are rather closed to experiments but the carbon dioxide calculations under-estimate the experimental results. This happened partially because the calculation results were given in mass fractions but the experimental data in mole (volume) fractions.

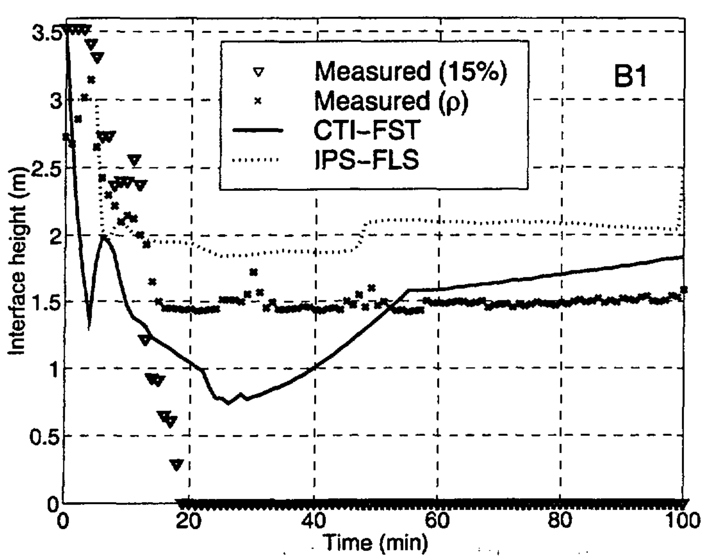

Figure 6. Comparison of interface heights given by FIRST and FLAMME-S zone models and measurements in subscenario B1.

Comparison of the measured and calculated upper layer temperatures are shown in Figures 7 and 8. The limits of the temperature averaging are based on the interface heights calculated by the 15%-rule. However, the method used for the interface calculation had very little effect on the averaged temperatures. Effects of the radiation on the operation of thermocouples were not considered. Below are listed the visual observations concerning the comparison.

CFAST calculations by HHP show a very good agreement with the measured temperature during the first 50 minutes. CTI and NIST in turn achieved considerable over- and underestimations of the maximum temperatures, respectively.
FIRST show good agreement during the first 25 minutes. After that FIRST starts to underpredict.

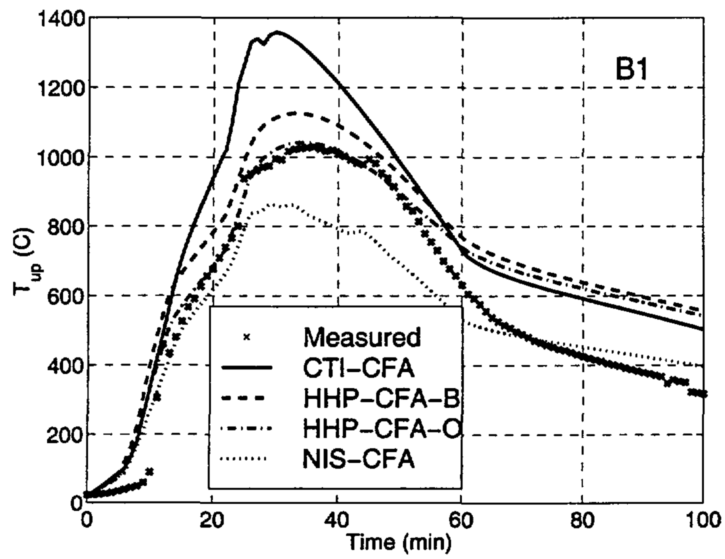

Figure 7. Comparison of upper layer temperatures given by CFAST zone model and measurements in subscenario B1.

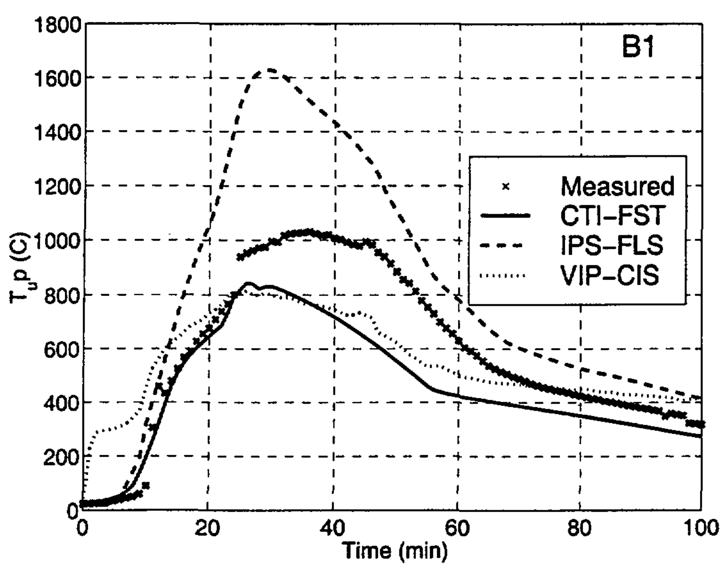

Figure 8. Comparison of upper layer temperatures given by FIRST, FLAMME_S and CISNV zone models and measurements in subscenario B1.

GODNESS DETERMINATION OF THE RESULTS

Based on the previous sections one can say, that each of the codes reproduces the qualitative behaviour of the layer height and upper layer gas temperature. It is not easy to see from the tens of plots, which of the codes performed better than the other ones. A summary of the calculation results of the two-zone models is here given to facilitate making conclusions. The purpose of the summary is not to judge or rank the codes, but to estimate the state of the art of the technology. Since the user seems to be the biggest source of error, it is reasonable to try to decouple the effects due to the user and due to the code itself. Therefore, only the simulation, that seemed to have the best overall agreement with the measurements, was selected for the summary. Here no distinction was made between the blind and open calculations. The summary cannot be complete, because some of the codes were used by only one participant. In these cases the comments of the participants should be taken into account to decide whether the simulation is representative or not.

Goodness of fit by formal methods like least squares analysis of multivariable functional relationships or any alternative test is not yet worthwhile. Pearson has shown (Cramér 1946) squares of differences in the form

$$\sum_i c_i (f_i - g_i)^2 \qquad (7)$$

where f is the normalized function in points i to be compared against function g in the corresponding points, become χ^2-distributed with N-1 degrees of freedom, if the weights are chosen as inverse square roots of functions g

$$\chi^2 = \sum_{i=1}^{N} \frac{(f_i - g_i)^2}{g_i} \qquad (8)$$

Formula (8) is a starting point for nonlinear curve fitting by χ^2 minimum method (Abramowitz & Stegun 1972). A successful application of this method in a noisy environment is described in Routti & Prussin (1969).

If we cannot be sure, that the difference f_i -g_i is not totally random and normally distributes, there is not much point of using χ^2-distributions for comparison. To get a simple quantitative measure for the goodness of predictions in ad hoc manner, relative error indicators were calculated. For the upper layer temperature the variable to consider is the temperature rise from the initial value $\theta(t) = T(t) - T(0)$. The thickness of the smoke layer h_{smoke} and the depletion in the oxygen concentration ΔO_2 were used to measure the goodness of the interface height and species predictions, respectively. Interface height was here calculated using the density integral method.

The simplest way would be to calculate the average of the relative value of absolute deviation

$$\mathrm{E} = \frac{100\%}{t_0} \cdot \int_0^{t_0} \frac{|\theta_s(t) - \theta_m(t)|}{\theta_m(t)} dt \qquad (9)$$

where t_o is the simulation time, θ_s is the simulation result and θ_m is the measured value. For applications in fire safety engineering this indicator alone would be rather misleading, since errors at irrelevant times would gain much weight. For evaluating the suitability of the technology for design purposes indicators are needed which give weight for those values indicative for dimensioning. As for the selected variables the large values are important, a weighted average E_{max} is defined, where the relative error weighted by the measured value.

$$E_{max} = 100\% \cdot \frac{\frac{1}{t_0}\int_0^{t_0} \frac{|\theta_s(t)-\theta_m(t)|}{\theta_m(t)} \cdot \theta_m(t)dt}{\frac{1}{t_0}\int_0^{t_0}\theta_m(t)dt} = 100\% \cdot \frac{\int_0^{t_0}|\theta_s(t)-\theta_m(t)|dt}{\int_0^{t_0}\theta_m(t)dt} \qquad (10)$$

If low values are important for design, then the weighting by small values, like the inverse of the measured value, would be appropriate.

The results are given in Table 2 for each code-scenario combination calculated. The accuracy of the upper layer temperature predictions ranges from 17 to 42 %. Smoke layer heights vary from 20 to 65%, and oxygen depletion from 7 to 76%. It is possible to make some conclusions of the mutual order of the codes, but the order of best codes varies from scenario to scenario. Based on the experience from these simulations we could conclude that two-zone models predict e.g. heating of structures for these types of fire scenarios at best at 20 % level of accuracy, if used properly. The technology on smoke layer height and oxygen depletion prediction is, on the average, slightly more inaccurate than for temperatures. CFAST and FIRST performe better than average.

Table 2. Mean relative errors E_{max} (%) of the two-zone model results. ARG = Argos, CFA = CFAST, MRF = MRFC, FIG = FIGARO, FW = FIREWIND, FST = FIRST, FLS = FLAMME-S, FIS = FISBA.

Code Variable	ARG	CFA	MRF	FIG	FW	FST	FLS	FIS	Average
T_{up} B1	25	13	14	14	21	21	48	26	23
T_{up} B2	27	27	25	26	NA	15	36	33	27
T_{up} B3	32	10	20	12	NA	NA	41	35	25
Average	28	17	20	17	21	18	42	32	24
h_{smoke} B1	72	23	14	27	20	19	25	19	27
h_{smoke} B2	69	62	81	88	NA	86	70	65	74
h_{smoke} B3	54	36	10	28	NA	NA	51	32	35
Average	65	40	35	48	20	52	49	39	43
ΔO_2 B1 [a]	3.3	2.7	2.0	3.0	7.4	1.7	1.1	1.8	3
ΔO_2 B2	37	38	36	31	NA	54	53	38	41
ΔO_2 B3	31	34	42	43	NA	NA	175	67	65
Average	24	25	27	26	7	28	76	36	31

[a] Only the first 20 minutes are taken into account.

CONCLUSIONS

A group of fire models was evaluated in the compartment fire scenario by comparing the simulations against the experimental results. The main limitations of the evaluation are due to the type of the fires, that were not well suited for the zone models, and due to the limited resources of both the participants and the organisers of the round robin. This report should not be considered as a thorough validation or ranking of the codes or the users.

All of the codes had features that indicated a discrepancy with the experimental data in the blind simulations, but which could be improved during the open round by choosing alternate submodels and/or changing some optional parameters. According to the summary of the quantitative error estimates the deviations from the experimental data range from ±10 % up to a factor of 2. These deviations are of the same order with the uncertainties related to the experimental measurements and input data, especially the burning rate. The conclusion is that, for this kind of fire scenarios, the expected uncertainty of the zone models is about 25 % in temperature and smoke layer height predictions, if the codes are used properly. Where several persons used the same code, the dependence of the results on the user was demonstrated (not detailed here). It was indicated very clearly, that the user is the most critical link in the chain of using computer fire simulation models for fire safety engineering. This was true even though this group represented code developers, and other well educated fire science and engineering practitioners. The effect is expected to be much more pronounced when the whole group of computer fire code users is considered.

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Fire zone model MAGIC :

The validation and verification principles

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Abstract

This paper present the principles used in the validation and verification of MAGIC (EDF Zone Model for simulation of fire in multi-compartment building). The general problem of validation of zone model is discussed: validation of the sub-model (classic laws, empirical correlation,..) and validation of the global model. Then a short presentation of MAGIC validation is provided: principles, list of references, examples and future prospects.

Zone model approach of fire

A zone model results from the association of various sub-models :

- Integration of classical laws of physics
- energy and mass balance on different layers (homogeneous temperature and concentrations, hydrostatic pressure, Perfect Gas assumption , etc..).
- simplified conduction in walls (1, 2 or 3D) or in some targets
- simplified radiation (semi-transparent assumptions in concave rooms)
- Semi-empirical models which can be found in fire source , plume, ceiling jet, convection heat exchange coefficient, openings and vent, detection, suppression etc..

Due to this nature, we must first say a few words about sub-model validation.

Validation of the sub-models

The General laws are accepted by the scientific community. Empirical models have most of the time been directly obtained from specific experiment, and have been qualified according to it. Both have shown a certain accuracy and validity domain. *(ex: Alpert correlation for ceiling-jet was studied for r/H<3).* The control of the right use of it must be done inside the code (for instance : produce "warnings" when getting out of a validity domain).
So, the sub-model validation has to be considered during the zone-model conception.
Nevertheless, a sub-model used outside of its validity domain does not necessarily mean that the global code results will not be acceptable. Moreover it is not possible to deduce the accuracy of a code from its component ones. <u>For those reasons, a global validation process remains always necessary to validate the zone model itself.</u>

Validation of the global zone-model

The objectives of the zone model validation are the accuracy of the calculation data and the validity domain. Both are linked : the acceptable accuracy domain is the validity domain. Accuracy of the code seems impossible to determine theoretically, but it can be displayed by confrontation to experimental fire, and estimated by this means. The criterion of "sufficient" accuracy themselves, can be discussed.
The accuracy of a fire model, observed by comparison to experimental fires, remains quite rough because too many parameters are involved in the fire process, and some complex phenomena (combustion, mass flow, etc..) cannot be completely described. Furthermore, when using the model in a real life risk study, the input control will be much worse and will interfere with the calculation relevance.

Consequently, it is not crucial to get a very high level of accuracy when confronting experimental and numerical results. The most important issues are to show that the code provides realistic quantitative results in its current application field and respects the qualitative tendencies in the fire dynamics and the significant effect of input variations.

In fact, the validation process is mainly demonstrative : it has to prove that, when the input parameters are efficiently controlled, the code results are sufficiently realistic, in the range of the code current application field. To make the demonstration efficient, the way of using the code in this process must be similar to the way it is used for typical fire risk studies.

Validation "code of ethic"

If we had to list the most important issues of a "good" validation process, we would retain :
a- The quality of the reference tests :
To be demonstrative, the tests must be well known, approved and accepted by the scientist community. Of course, the quality of the experiment is the main factor of this acceptance, and has been discussed a lot (ex: ASTM E603)
b- The conditions of the code use:
To enhance the confidence and decrease the user effect, the input of the code during the test must be clearly identified.
Any user modeling choice (fixed exchange coefficient., plume model, etc..) specific to the calculation must be identified, or, as much as possible, avoided.
c - The Field covered by the tests :
The tests should cover the field of application of the code. First building configuration : mall to medium scale compartment configuration, multi-compartment and large scale tests, opened or confined condition for instance. Also, fire parameters: kinds of combustible, heat release rates, etc..

The validation File of MAGIC

MAGIC is EDF code for determinist fire risk studies in NPP. The validation process of the code is based on comparison to real scale fires : about 60 real scale fire tests are available in the base. The file is used to define the validation domain of the code. This includes volumes from 10 to 1300 m^3 (a 200 000 m^3 case is at work), heat release from 100 kW to 2.5 MW (a 60 MW case is at work) , ventilated and post-flashover fires, Mono-compartment and multi-compartment varied configurations, gas burner, liquid pool or solid fires, linear or axisymetrical fire source.

MAGIC has a large validation file, including among others the following references :
- Semi-natural fires in a room: Hognon B. CSTB/ DGRST-CSTE 1980 and Carmier, Curtat, Hognon, Bertin - CNRS - CSTB 1984
- Semi-natural fire in a commercial hall corridor : N. C. Markatox, M.R. Malin "Int J Heat transfer" Vol. 25 n° 1 p. 63-75 BRE/FRS 1986
- Fires in ventilated room: (Alvares N.J., Hasegawa H.K., Lipska.Quin A.E.) Report UCRL-53179, LLNL, Univ. of California, Livermore 1982
- Fire in a compartimented building (Cooper L.Y& al.) J. of Heat Transfer vol. 104 pp 714-749 NBS (1982)
- Real-size tests in multi-compartimented buildings : R.D Peacock, S. Davis, V. Babraukas "Data for room Model Comparisons", Journal of research of the NIST, vol 96, N°4, 1991.
- Control-room tests FM/SNL : S. Nowlen NUREG/CR-4681 1987
- 20-foot separation tests UL/SNL : NUREG/CR-3192 1983
- Large cable fire tests (2 compartiments) EDF-CNPP : CNPP TR 96 5045 P1 -1997
- CTICM Hotel-room : H. Lebotgne Test reprt 96S511 (1996) Linen-room (2 compartments, post-flashover): H. Leborgne TR 97S031 (97) Large hall tests : TR 98-x-406 (97) ; TR 94-R-242 (94)

MAGIC Code quality assurance

In accordance with the code Quality Assurance process, a selection of about 20 tests from the validation file is used systematically to guarantee no regression of new versions. Any difference between versions must be justified in the validation report. The code is always in standard conditions when launching the reference tests. The validation process report is part of the documentation and the tests can be easily re-played by the user.
At this point it is important to underline the differences between verification and validation of the code : the verification of the code specification consists in controlling the respect of sub-model specifications, the different parts (user interface functionalities, calculation options, etc..). It is a different task than validation, also done through the MAGIC code Assurance Quality process. This aspect must not be neglected because the validation tests are not necessary covering all the code possibilities.

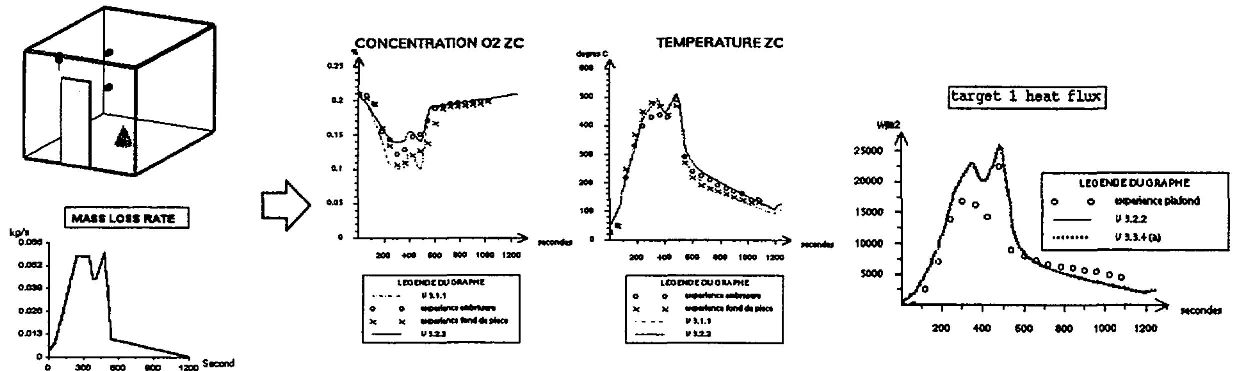
Direct comparison of numerical and experimental data

The model necessary input for comparison are : the building materials and configuration, boundary conditions, the combustible properties and location and the mass loss rate scenario.

The commonly available data for comparison are (in decreasing frequency) : local temperatures, average temperatures, heat exchanges on targets obtained on fluxmeters, interface height (which estimation may follow different point of view) gas velocities, species concentrations (O_2, CO_2, CO, C_nH_m NOx, SOx,..), pressure, mass flow through openings.

The first comparison is generally done on gas temperature and fluxes, considering at less the range and delay of the peaks. Those variables represent the thermal boundary condition for the

materials to protect. Nevertheless, they are not easy to obtain, being very unstable, linked to mass flows and radiation. In some cases it seems that internal temperature of targets could be an interesting alternative to develop. The other measurements are less frequent, some like pressure or mass flows are rarely provided.
The comparison is first a "visual" analysis of differences. Numerical analysis can be done, based on relative difference *(ex: (Tmes-Tcalc)/ (Tmes-To) as a error percentage).* Sensitivity to input variation has been done in the process of qualifying the physic model adjustments.



Mono-compartment test (CSTB 84)

figure 1: comparison of numerical and experimental data

Future prospects

The validation process of code MAGIC is in constant progress. The file is to be reinforced by tests focusing targets temperature. Those variables fluctuate less than gas temperature and are more relevant for risk studies (dysfunction, ignition). Tests are to be done in 2002. Pressure measurement and interaction with ventilation system will be studied through specific tests, also programmed in 2002. The next field of investigation should concern fire suppression effect and complex multi-room configurations : horizontal openings and duck-board.

Conclusion of EDF experience

The validation file is the key of code acceptance. Comparison to real-size and a large field of experiment data is the only way to guarantee an efficient demonstration of the code efficiency. The experimental tests and measurement must be of good quality, available to and accepted by the scientific community. At last, the process of code validation must be independent of modeling choices and available to the final user.
The results obtained with MAGIC on a selection of experimental data has allowed us to get confident for its use in a large range of volumes, heat release and configurations.

CFD SIMULATION OF A3.5MW OIL POOL FIRE IN A NUCLEAR POWER PLANT CONTAINMENT BUILDING USING MULTI-BLOCK LARGE EDDY SIMULATION

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Introduction

Implementing performance-based regulations require the presence of analytical tools and analytical methods [1]. In the case of fire safety regulation, there are three categories of tools available for demonstrating the performance of a structure and its fire protection systems [2]. These categories include hand calculations, lumped-parameter models, and field models. For most scenarios, one of the first two methods should be all that is required to demonstrate performance. However, there will be instances where neither of the first two methods will be enough. Situations, for example, with highly complex geometry or where detailed knowledge of spatial effects are needed may require the use of field models. In some sense, this is unfortunate, since the use of field models requires a much large expenditure in terms of both time and computational resources [3]. However, the time required to use a field model can be greatly reduced by the use of a multi-block solution scheme. To demonstrate the potential of a multi-block field model for fire simulation, a multi-block version of FDS was used to simulate a portion of an oil pool fire experiment that took place in the HDR facility in Germany [4].

HDR Facility

The HDR test facility [slide 7] was the containment building from a decommissioned nuclear reactor in Germany. The facility was a cylinder 20 m in diameter and 50 m in height and was topped by a 10 m radius hemispherical dome. The facility had eight levels and over 60 compartments. Multiple vertical flowpaths were present in the form of two axially located sets of equipment hatches, two staircases, and an elevator shaft. The total free air volume in the facility was 11,000 m^3 of which the dome contained 4,800 m^3 [5].

The test simulated for this work is test T52.14 [slides 8-11] an oil pool fire test done in 1987 that occurred on the level below the dome. The T52.14 test used a 2 m^2 pool of Shellsol-T, a liquid hydrocarbon, placed on a weighing platform in a firebrick lined compartment beneath the dome. This compartment was connected to a second firebrick lined compartment beneath one of the equipment hatches. The hatches both above, leading to the dome, and below this compartment were open. The test started by igniting 50 liters of oil followed by adding additional oil at a rate of 5.6 L/min once the initial volume nearly depleted as determined by the weighing platform. The entire facility was instrumented with 56 velocity sensors, 155 thermocouples, and 43 gas sampling lines [5].

Multi-block FDS

FDS, Fire Dynamics Simulator [slide 3] has recently been released as version 2 by the National Institute of Standards and Technology [6]. FDS is a CFD model that solves the low-Mach number form of the Navier Stokes equations using a Smagorinski turbulence model. The FDS uses a simple mixture fraction combustion model [7] where the user can define basic parameters of the fuel chemistry. The FDS radiation model is a finite volume method radiation solver for the gray gas radiation transport equation [8]. RADCAL [9], a narrow band radiation model, is used to determine absorption coefficients based on the local mixture fraction and temperature. In both version 1 and version 2 of FDS, a single-block solver was implemented.

Single-block solvers [slide 4], common in many field models, use one computational grid that spans the entire domain of interest. For many fire problems, this is an efficient method of defining the computation. In fire simulation, a lower grid resolution is needed to track smoke movement than is required to adequately simulate the region of active combustion. Thus, with one grid being used, the requirement to finely node the fire means that many more cells than necessary are located in regions where only smoke transport is occurring [slide 5]. Also, if more than one compartment is being simulated, than there is the potential for many grid cells to be defined as dead space in order to encompass the compartments [slide 6]. Both situations, large numbers of dead cells or higher than needed resolution, increase both the time required for a computation and the computational resources needed.

In a multi-block solver, the user may define more than one computational grid. Thus a fine grid could be defined for the region of combustion and a coarser grid defined for non-combusting regions. Also each compartment could have a separate grid defined for it, eliminating the need to carry a large number of dead cells. However, as with many numerical schemes, while multi-block solvers remove some computational effort by eliminating grid cells, they do increase the overall computational overhead for a problem. This is because the solver must expend effort to share information between grids at their shared boundaries. This extra effort, however, can be easily outweighed by the time saved be reducing the number of nodes. As part of the development effort for the next release of FDS, a multi-block solver has been added.

Multi-block FDS Model of HDR Test T52.14

The T52.14 test was simulated using a multi-block version of FDS. The region modeled included the entire dome and the two firebrick lined compartments on the level beneath the dome, slides 17 and 18. An open vent located beneath the room adjacent to the fire room and in the dome floor opposite the fire room simulate the connections to the remainder of the HDR facility. A reasonable nodding of the fire room entails using grid cells on the order of 10 cm in size. Since the computational domain is 20 m x 20 m x 26 m, this would require over 1.2 million grid cells. However, this would result in many dead cells as only a small fraction of the space beneath the dome is being simulated, the fire room and its adjacent space. Also, in the dome there is no combustion occurring. Thus, the dome does not need to be as densely noded as the other two compartments. Instead three grids were used: one for the fire room, one for the room adjacent to the fire room, and one for the dome. The first two grids had a 10 cm resolution and the dome grid had a 25 cm resolution. This resulted in the use of 600,000 grid cells, a savings of 50%. A second FDS run was performed with a grid at ¾ the linear resolution. [slides 13,14]

The FDS simulation was done for the steady-state portion of the test and was run until temperatures at the upper dome measurement grid were observed to reach a quasi-steady state solution. Both cases were run on a 2.2 GHz, Pentium IV, Linux machine. The full resolution case required 7.5 minutes of CPU time to one second of realtime, and the ¾ resolution case required 2.5 minutes/s. [slide 15]

Results

Computational results of the two models show that the multi-block version of FDS performs well for a number of parameters. FDS results for the fire room [slide 16] compared to both the collected data and some hand calculations show that FDS is accurately predicting the major conditions of the fire room. One great advantage of a field model, the ability to generate 3D data for visualization can be seen in the image showing the calculated flame sheet superimposed on a temperature contour centered over the pool of oil [slide 17]. This image shows that the flame sheet is entirely within the room; however, with the fire size being simulated one would expect that external burning would be occurring. FDS would appear to be under predicting the flame lengths. In the door way, FDS matches well the measured velocity profiles; however, temperatures are not as well predicted in this location [slide 18]. The measured data shows flame temperatures, which would suggest external burning. Since FDS is not predicting external burning, its doorway temperatures are low. An animation of the entire plume structure shows how the velocity is smoothly continuous across all three grids [slide 19]. An indication that the multi-block solver is handling the grid transition well.

Comparisons of temperatures in the hatch leading to the dome show that FDS is underpredicting temperatures at this location by 100 K [slides 20,21] and that FDS is predicting the plume in a slightly different location in the hatch. The velocities, however, appear to be reasonably well predicted by FDS [slide 22]. Some of these differences are probably due to the external boundary conditions. FDS simulates these as open boundaries, whereas in the HDR facility the two external openings were actually hydrodynamically coupled. In the dome, comparisons of temperatures [slides 23,24] show that FDS is now over predicting the bulk temperature by 30-40 K, but matching well the plume center temperature. This may be due to FDS not transferring enough heat to the dome structures as compared to the test. The predicted velocities [slides 25,26] indicate that FDS is predicting a somewhat narrower plume, which could result from the numerical grid and a slightly different location of the plume centerline. However, this measurement location is close to 20 m from the fire, and the FDS plume center is <2 m from the position given by the data. An animation of the plume in the dome is shown. [slide 27]

Concluding Remarks

A multi-block version of FDS clearly has tremendous potential as a tool for simulating fires in large, multi-compartmented structures. The current prototype version maintains well flows across grid boundaries, even for grids of varying mesh sizes. Energy fluxes across the boundary also appear to be well maintained. Lastly, FDS was able to accurately predict the location of the plume after 20 m of travel from the fuel source.

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NIST Large Fire Laboratory

George W. Mulholland and David Stroup

The purpose of the NIST Large Fire Laboratory (LFL) is to apply quantified measurements, real-time analysis, and large area diagnostics to validate models for fire phenomenon including fire dynamics, detection, and suppression. The LFL is also used for obtaining product yield data and HRR data for model input for fire models and for carrying out large scale tests requiring specialized instrumentation and data interpretation. An overview of the LFL development, recent experiments and planned enhancements will be described below.

Capabilities of the Renovated Exhaust System

In 2000, the exhaust facility for our large scale facility was upgraded to remove smoke particulate using a baghouse and acid gases with a scrubber. In addition, the exhaust capacity of the facility was increased more than 20 fold to a flow of 42 m^3/s. The increased flow allows fire experiments to be carried out with heat release rate (HRR) as large as 10 MW for the 9 m × 12 m hood. This is near the peak HRR for a small house. A 6 m × 6 m hood is available for fire tests as large as 3 MW. In addition there are two smaller hood assemblies with dimensions of 2.5 m × 2.5 m and 1.2 m × 1.2 m that in the future will allow smaller burns when connected to the exhaust system. The full suite of hoods/exhaust capabilities will allow fire experiments ranging in size from about 5 kW to transient peak HRRs as large as 15 MW. The total high bay floor space for enclosure assemblies is 9 m × 30 m. The height of the base of the 9 × 12 m hood is 6.4 m allowing fire tests for a two story structure.

Quantitative HRR Calorimetry

The heat release rate (HRR) is the single most important quantity characterizing the hazard resulting from the burning of a given fuel package. It will determine the temperature within the enclosure, and the concentration of the combustion products including the smoke particulates and the toxic gases (CO and HCN) will be proportional to the HRR. A major focus of the LFL for the past two years has been the accurate measurement of HRR including a quantitative uncertainty assessment.

Our method is based on oxygen consumption calorimetry. The scientific basis of the method is that the HRR is proportional to the oxygen consumption together with the finding that for most materials found in buildings the heat of combustion per kg of oxygen consumed, H_c, is 13.1 MJ. The equation for the HRR is given by[1]:

$$\dot{Q} = (X^0(O_2) - X(O_2)H_C\rho(O_2)\dot{V}$$

where $X(O_2)$ is the oxygen mole fraction, $\rho(O_2)$ the density of oxygen, is the volumetric flow of ambient air into the combustion zone. There are a number of complications in performing quantitative measurements. First, the value of H_c is affected by incomplete products of combustion such as CO. Secondly, the exhaust flow is measured rather than the inlet ambient flow and the flow must be corrected to account for the changes in stoichiometry as oxygen is consumed and CO, CO_2, and H_2O are produced. Thirdly, the uncertainty in the measurement increases for small fire sizes because of the small change in the oxygen concentration.

Our methodology for performing the measurements is to collect all the combustion products in the 6 m square hood, pass the flow through a flow straightener, measure the duct flow velocity at eight locations using bi-directional probes, and sample the smoke at multiple locations using a sampling probe cross. A high flow diaphragm pump rapidly directs the smoke flow to the O_2, CO_2, and CO analyzers from the sampling location on the roof of the Laboratory through a heated line about 20 m to the instrumentation room on the first floor. The moisture is removed with a dry-ice trap before the gas enters the analyzers. There is approximately a 15 s delay from the time the smoke leaves the flame until the gas sample is detected by the gas analyzers and this delay time is compensated for in the data analysis. During the upcoming year a helium tracer gas method will be use for accurately characterizing the duct flow.

Three additional capabilities critical to enhancing the accuracy and usefulness of our heat release measurements are a calibration burner, a data acquisition/control system capable of providing nearly real-time output, and a natural gas heat of combustion "meter."

Calibration Burner

The burner consists of 11 tubes in a 1.6 m × 1.2 m planar array with holes spaced approximately every 2.5 cm along the tubes Valves control the fuel flow to various sections of the burner so that the flame dimensions will be similar to that of a buoyancy dominated diffusion flame as the flow is increased. The Fire Dynamics Simulation Code was used in designing the burner. The heat of combustion of the natural gas used by burner is measured by an accurate gas calorimeter. Other important design features are the use of industrial control devices for monitoring and controlling the flow rate and for shutting off the flow if the flame extinguishes. The flow monitoring device is calibrated at the NIST flow metering facility. The burner has been successfully tested over the heat release range from 50 kW to 6 MW.

Data Acquisition System

A dual processor workstation computer with National Instruments[1] hardware has been assembled with a LabVIEW program designed to compensate for different measurement times to achieve near real-time analysis and display of processed data. In typical use, 1 second averages for 60 channels are scanned at 200 Hz during a one hour test. In addition, the system can be used to control the fuel flow to have step changes or quadratic time dependence to simulate the typical growth rate for fires. The controlled burner and the heat release apparatus has been used for assessing the repeatability of the HRR calorimeter for fire sizes of 50 kW, 700 kW, to 3 MW. The hood was operated at two exhaust flow rates and 3 repeat measurements were made for each condition. For the larger two HRRs, the measured value agreed with the calibration burner to within 2 % and the measurement repeatability was within 6 %. The variation in the smallest

[1] Certain commercial equipment or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the national institute of Standards and Technology , nor does it imply that the materials or equipment are necessarily the best available for the purpose.

HRR was over 20 % and found to be a result of drift in the output of the oxygen meter. Efforts are underway to correct for the background drift of the analyzer and to purchase a lower drift oxygen meter.

Recent Large Scale Tests

The following major studies have been carried out in the LFL since its renovation: bed fires, smoke detector study, and sub-lethal toxicity measurements. These studies illustrate the range of capabilities in the LFL.

Bed Fires

The objective of the bed fires, sponsored by the Sleep Products Safety Council, was to quantify the relation between the heat release rate from a burning bed and the distribution of heat flux to the space around it[2]. Such heat fluxes might ignite other objects, leading toward room flashover. The information was in turn used to infer the largest tolerable bed fire that would both preclude other item ignition and minimize casualties due to heat and toxic gas exposures. The LFL six meter hood provided a unique capability to measure a very diverse range of bed fires which varied 100 kW to 5 MW.

Smoke Detector Study

In co-operation with the United States Fire Administration (USFA), other sponsors, and U.S. Consumer Product Safety Commission (CPSC), NIST coordinated the evaluation of current and emerging smoke alarm technology responses to common residential fire scenarios and nuisance alarm sources. The measurements were all carried out in a manufactured home contained within the LFL. Unique capabilities provided by NIST include the detailed characterization of the environment near the detector including the temperature, flow, gas concentrations, smoke particle concentration, particle size and optical density. The quality of the data was greatly enhanced by fully characterizing the response of the 150 gas and particle detectors used in the study with the unique Fire Emulator/Detector Evaluator developed at NIST.

Sub-lethal Effects Experiments

This study funded by the Fire Protection Research Foundation of National Fire Protection Administration is focused on characterizing the yields of toxic gases and smoke particulate produced by both pre-flashover and post-flashover fires. The room contents included electric cables, sofa mockups, or bookcases with and without a sheet of PVC. The test required characterization of the environment at two sampling locations with sensors for temperature (bare and aspirated thermocouples), velocity (bi-directional probes). Standard gas analysis included CO, CO_2, and O_2. An innovative feature of the experiments was the use of multiple FTIRs monitor the concentration of additional gases, such as HCl, HBr, HCN, and acrolein. In addition, for the first time at NIST, smoke was sampled in the upper layer leaving the doorway during flashover conditions. The smoke sampling included a temperature controlled filter assembly and a quantitative method for removing smoke deposited on the walls of the sampling tube.

Measurements at upstream and downstream locations enable estimation of the loss of smoke components to the walls.

Future Capabilities

We plan to develop the following challenging capabilities during the next year: soot volume fraction in the hot upper layer, heat transfer measurements to steel elements, to cable trays, and to the walls, and surface temperatures for metals, insulating materials, and cables.

There is also great interest in the application of large area imaging optical diagnostics to large scale fires. The current status of projects for measuring water spray and doorway flows are briefly described below.

Water Spray

An advanced measurement method is under development, with the goal of providing simultaneous measurement of sprinkler spray drop size and velocity. The method illuminates a 0.5 m by 0.5 meter area of the spray field with laser pulses, and uses laser induced fluorescence to image the droplets. Velocity is determined by analysis of the distance between two-color droplet pairs, and droplet size is determined from the size of the droplet images. Droplet sizes over the range of approximately 200 μm to 3000 μm can be measured, with low levels of uncertainty. Droplet velocities are accurately measured over the range 0.5 m/s to 50 m/s.. Data has been collected and analyzed data for 27 different parameter sets for an axially–symmetric sprinkler. The long term plan is to characterize the droplet size and velocity in the LFL for a sprinkler interacting with a fire plume.

Particle Imaging Velocimetry

Particle Image Velocimetry (PIV), a non-intrusive laser-based measurement technique, is being applied to measure two-dimensional fields of velocity vectors in the lower layer of a fire-induced doorway flow. The technique significantly improves upon the spatial and temporal resolution of traditional bi-directional probe measurements. Two-dimensional images of gas velocity vectors were recorded last year using the PIV technique for a 26cm x 26cm region along the axis of a surface opening for ambient conditions. The data included instantaneous velocity field, instantaneous vorticity field, and mean flow streamlines, respectively. This year The PIV system was upgraded to 3D so that all three components of the velocity vector can be measured in a single acquisition. A reduced scale buoyant He plume and enclosure were designed and fabricated. It is anticipated that measurements will be completed this fall and the measurement of doorway flows for a full scale experiment are planned for 2004.

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[1] Parker, W.J., "Calculations of the Heat Release by Oxygen Consumption for Various Applications," *J. Fire Sciences*, 2, 380-395 (1984).
[2] Ohlemiller, T.J. and Gann, R.G., "Estimating Reduced Fire Risk from an Improved Mattress Flammability Standard," NIST Technical Note 1446, 2002.

COCOSYS

Technical Note

TN – KLH 2/2002

Fire Benchmark #2

Part 1:

Fire in a large Hall

CFX and COCOSYS

Preliminary Results

- DRAFT VERSION-

W. Klein-Heßling

April 2002, Draft Version

Content

List of figures

1 Introduction

In the frame of the "International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications" a second benchmark exercise have been performed. In this exercise different pool fire experiments in a large hall have been investigated. In this technical note first results of performed COCOSYS calculations and some CFX preliminary results are discussed.

COCOSYS is a so-called lumped-parameter code. To simulate the local conditions (natural convection, temperature stratification) the fire hall is divided into a quite high number of control volumes. The main idea is to have for each temperature measurement a separate control volume and to have separate control volumes around the fire plume, the ventilation system and the doors.

CFX is a CFD program. The k-ε model has been used for the simulation of turbulence. For the reaction the eddy-break-up model has been used. CFX has a separate radiation model RAD3D to consider the heat distribution of the flame.

The CFX calculations have been performed by M. Heitsch. The results of COCOSYS and CFX are preliminary.

2 Nodalisation and used Models

For COCOSYS a detailed subdivision of the fire hall has been used. Fig. 2-1 to Fig. 2-3 show the nodalisation of the fire hall. With this subdivision nearly all temperature measurements have a separate control volume. There a direct comparison between experimental measurements and calculated results is possible. The total number of control volumes is 543.

The control volumes above the pool have an area of 6 m^2. This leads to some averaging of the temperatures in the fire plume. COCOSYS itself has no specific plume model.

The flow between the control volumes is mainly buoyancy driven. A momentum balance is not calculated.

For the calculations the given pyrolysis rates are used. In the first calculation the calculated temperature has been calculated to high. Therefore the reaction rate above the pool has been reduced by an additional factor FEFF of 60%. The remaining unburned heptan may be burned in upward direction. 20% of the reaction heat is distributed by radiation to the wall structures. The view factors used have been calculated by the new grid generator for COCOSYS. For the heat exchange between the walls and atmosphere the specified heat transfer coefficient and the COCOSYS heat transfer models for free convection have been used, respectively.

In the CFX calculations following standard models have been used:

- for the simulation of combustion the eddy-break-up model (for each cell)
- k-e model for turbulence
- the radiation is simulated by RAD3D
- the Magnussen-Model for the simulation of soot behavior

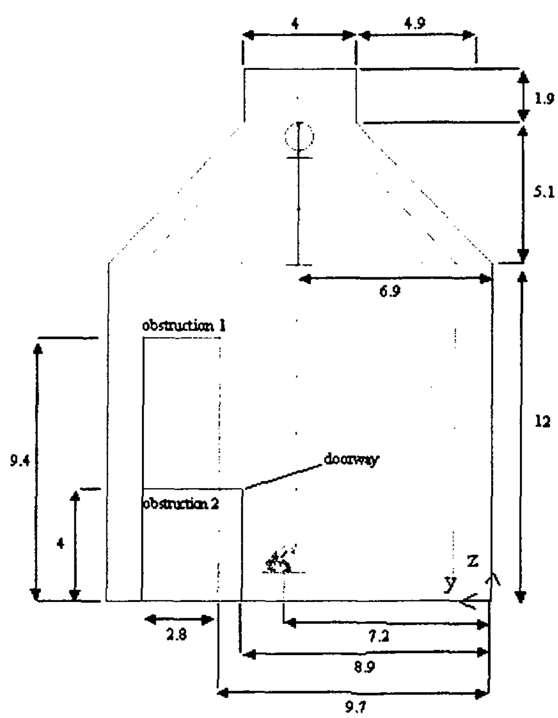

Fig. 2-1 COCOSYS Nodalisation: side view

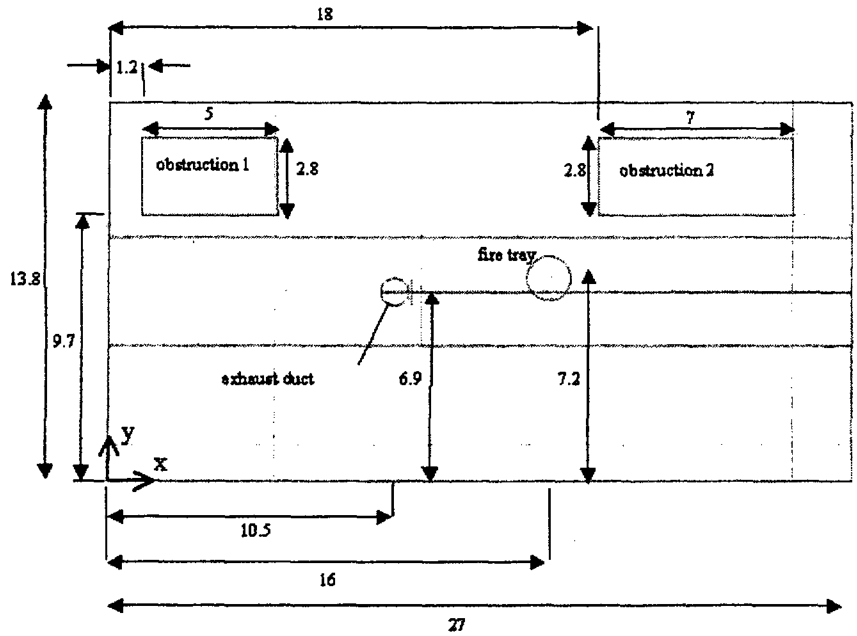

Fig. 2-2 COCOSYS Nodalisation: top view

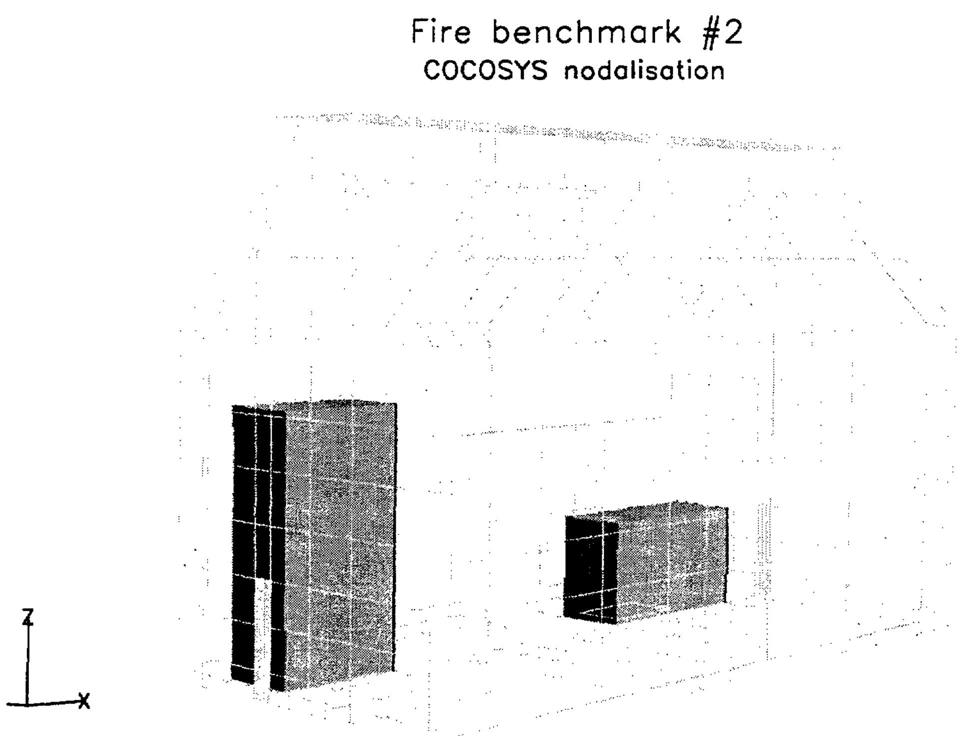

Fig. 2-3 COCOSYS Nodalisation

3 Preliminary results

In the following sections the preliminary results will be discussed. The figures show the actual status of the COCOSYS results for the three specified cases of part 1 and some CFX results for comparison reason.

3.1 Case 1

Fig. 3-1 to Fig. 3-6 show the comparison between the optimal COCOSYS calculation and the measurements at the 3 temperature trees. The quality of the results is quite well. The stratification of the temperatures at the upper measurement points is calculated somewhat too high. The main reason is the missing momentum balance in the COCOSYS calculation. The mass flow between the control volumes is mainly induced by the buoyancy leading to stratified results.

It has be pointed out, that the reaction efficiency is adjusted to the temperatures. Unfortunately there is no additional possibility to check this modeling assumption, like concentration measurements or measurement data of the temperature decrease after the burning process.

Fig. 3-7 shows the temperatures at T1.6 and T1.10 for the different variations of COCOSYS calculations and the CFX results. The CFX result is similar to the *COCfull* case of COCOSYS. Both calculation assume a full reaction of the heptan. The differences between the green (COCbase) and red (COCopt) curve results from the different assumptions for the heat transfer to the boundary and the infiltration. In the COCopt case the COCOSYS heat transfer models for free convection are used, the walls are handled non-adiabatic on the outer side and a the half of the infiltration from the upper position are shifted to the top of the roof. Assuming the full reaction the calculated temperatures are about 50 K too high. The influence of the different assumptions for heat transfer and infiltration leads to a temperature decreasing of about 15 to 20 K. Therefore the main effect results from the decreasing of the reaction efficiency.

The beginning of the temperature decrease after the burning process shows the right behavior. But the time period is too short, to conclude that the calculated heat loss into the walls and through the infiltration is simulated correctly.

Fig. 3-8 presents the comparison of the plume temperatures TG1 and TG2. COCOSYS has no specific plume model. As already mentioned the plume is simulated of a column of control volumes above the pool. The area of these volumes is 6 m^2. This lead to an averaging of the calculated temperatures. In the CFX calculation the temperatures are much higher and the behavior seems to be more realistic, also the temperature level is somewhat to high. A three-dimensional impression of the fire plume can be drawn from Fig. 3-9 for COCOSYS and Fig. 3-10 for CFX. Both figures show the temperature distribution in the middle yz-plane.

In the following figures the average values are presented. These have been calculated according the formulas specified in the benchmark description. Although the correspondence between the measured and calculated temperatures are quite well, the calculated interface height is too low (red curve).

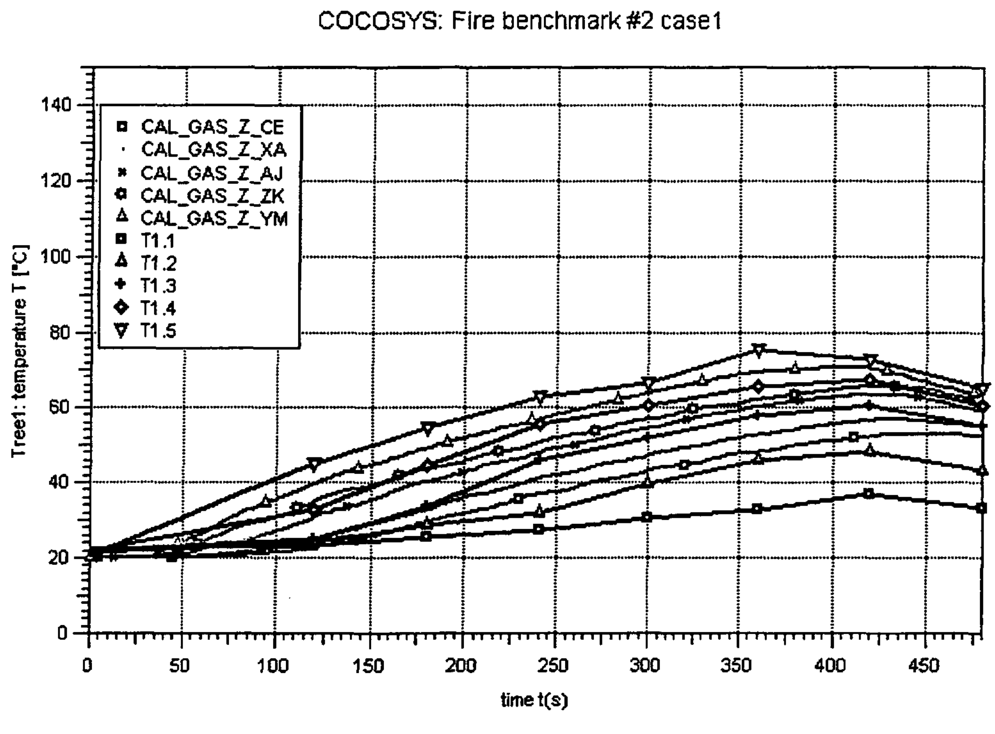

Fig. 3-1 Case1: temperatures at lower part of tree 1

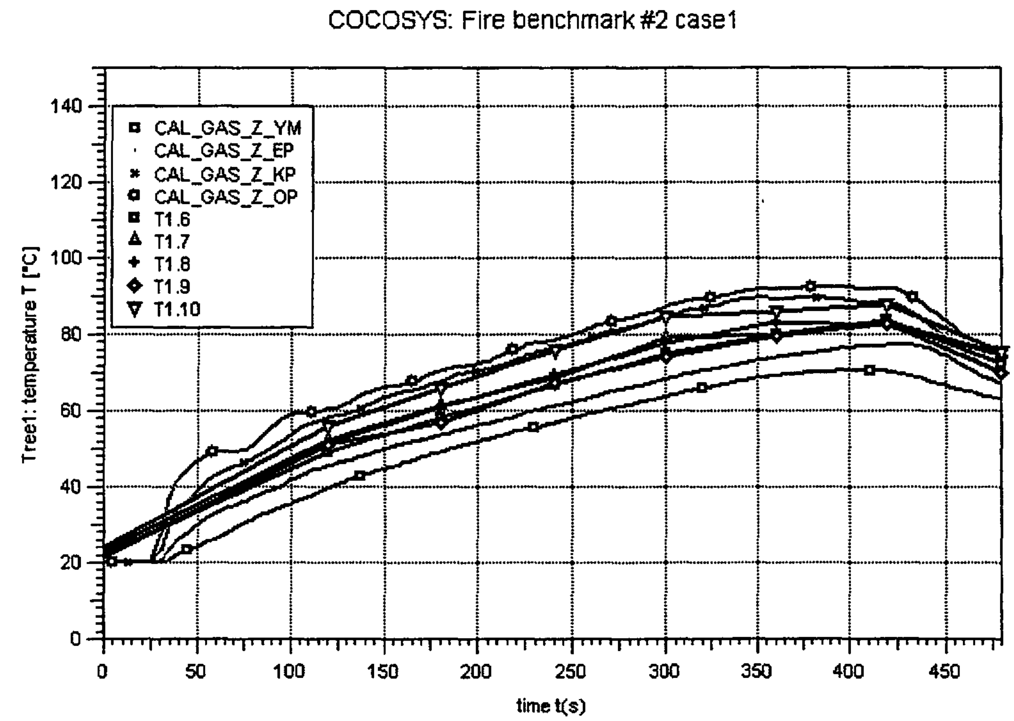

Fig. 3-2 Case1 : tempertures at upper part of tree 1

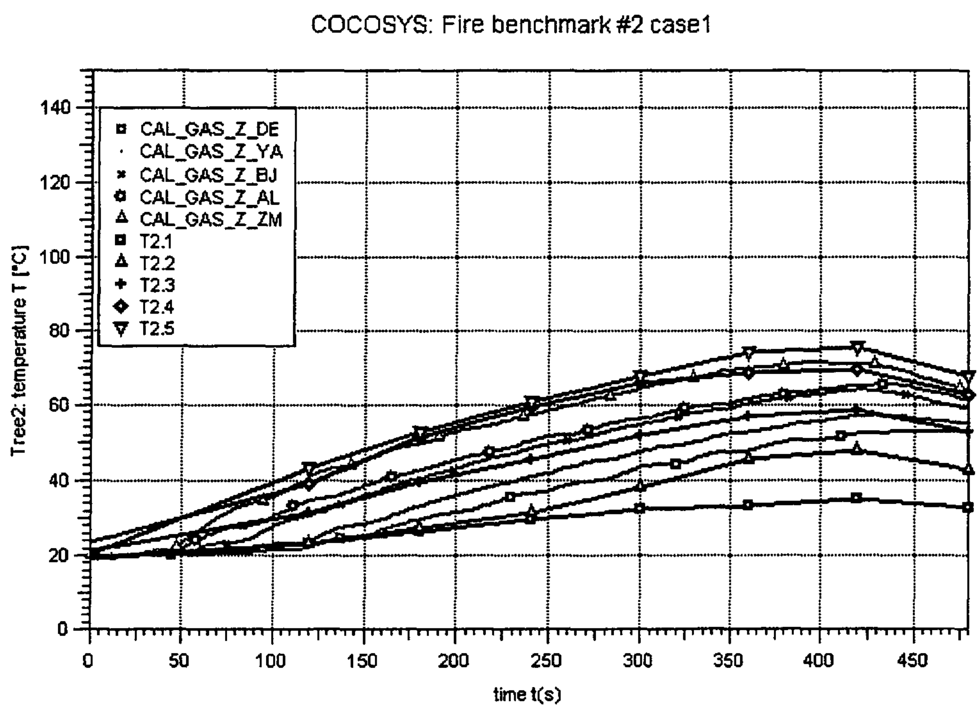

Fig. 3-3 Case1: temperatures at lower part of tree 2

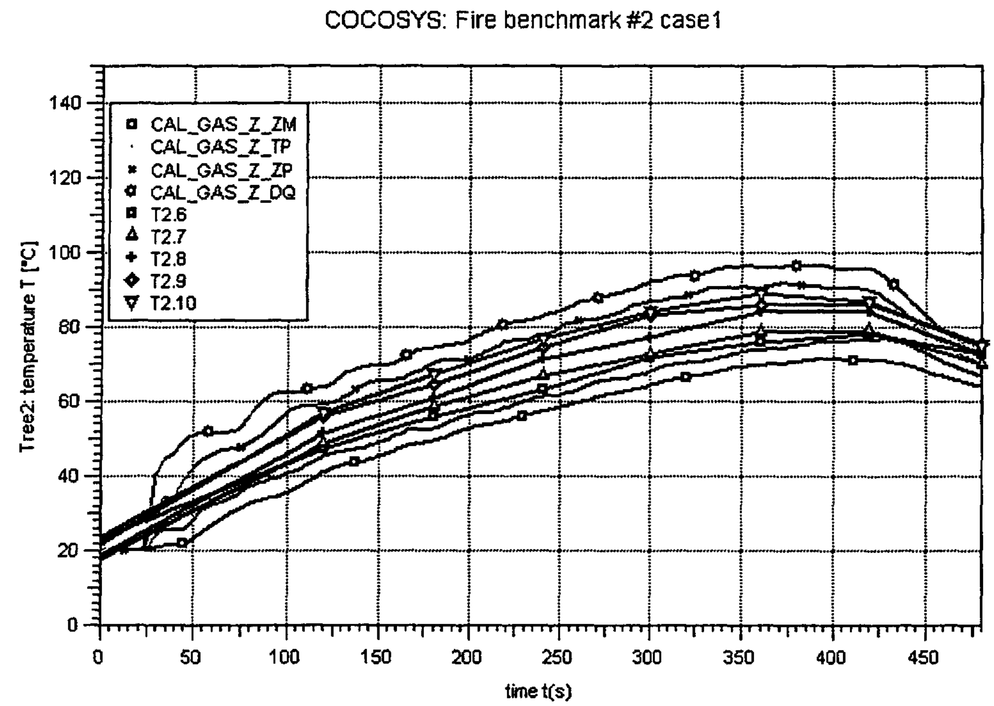

Fig. 3-4 Case1: temperatures at upper part of tree 2

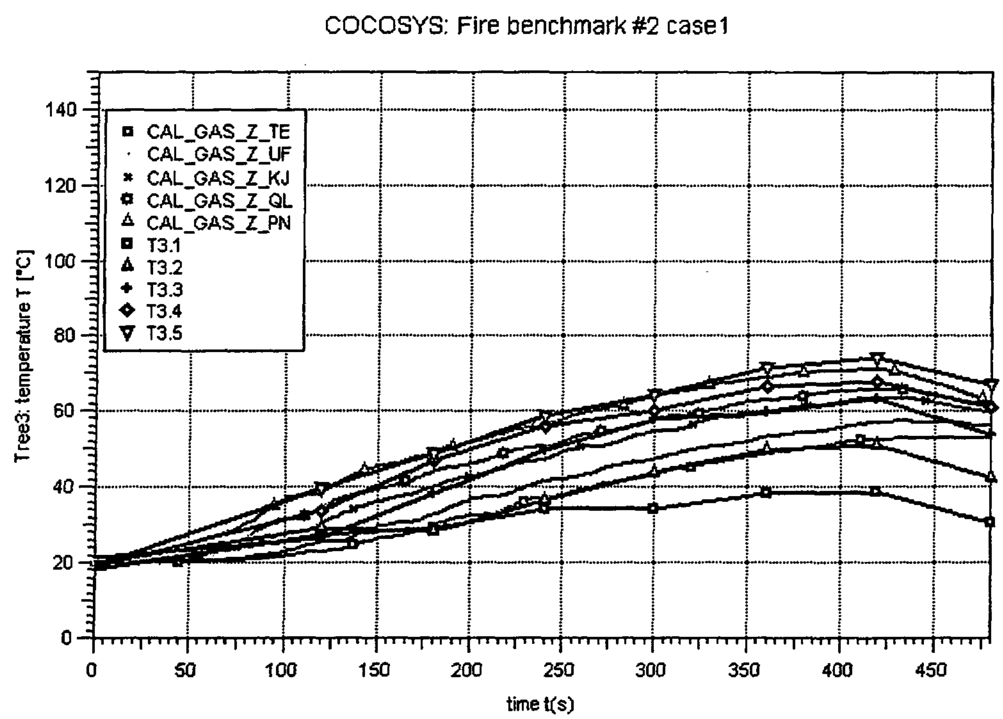

Fig. 3-5 Case1: Temperatures at lower part of tree 3

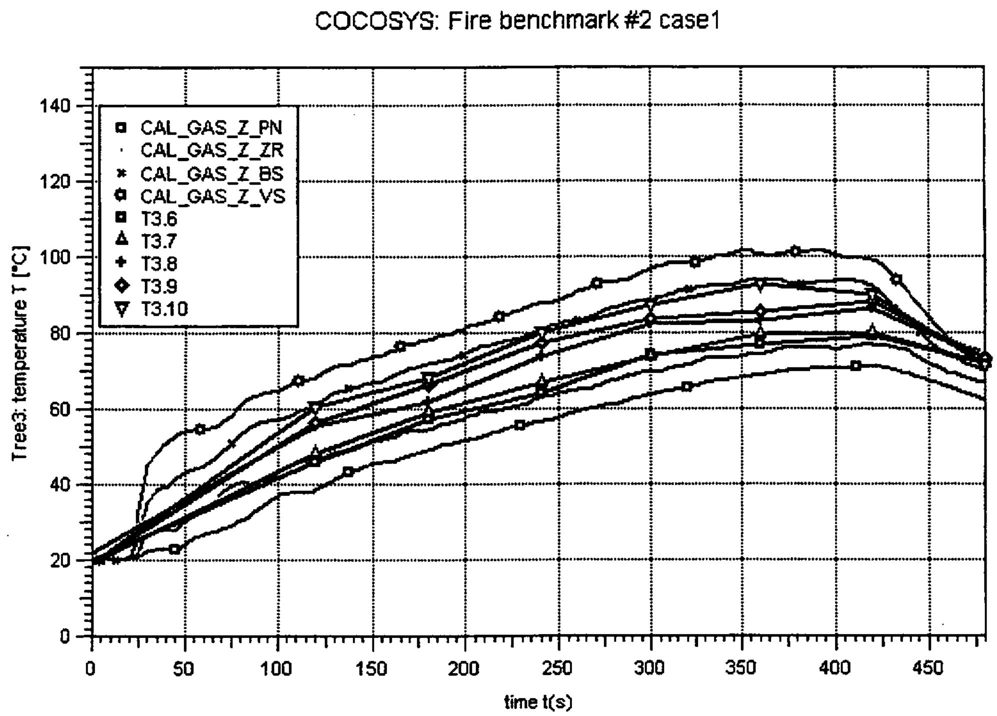

Fig. 3-6 Case1: Temperatures at upper part of tree 3

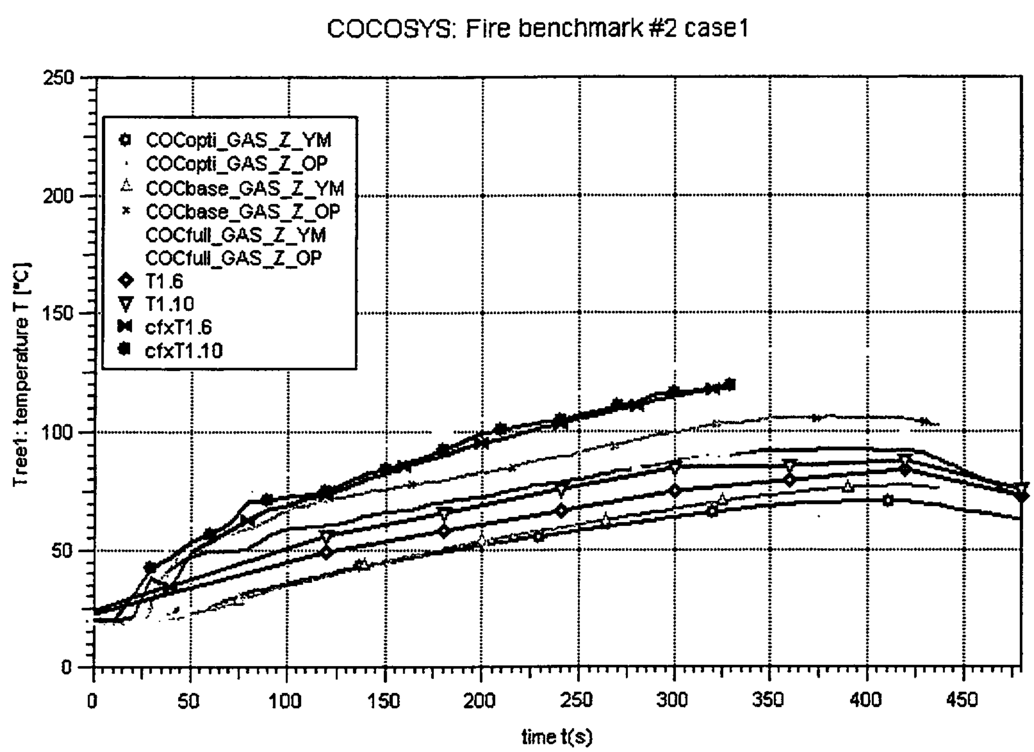

Fig. 3-7 Case1: Comparison between the different variations of calculation

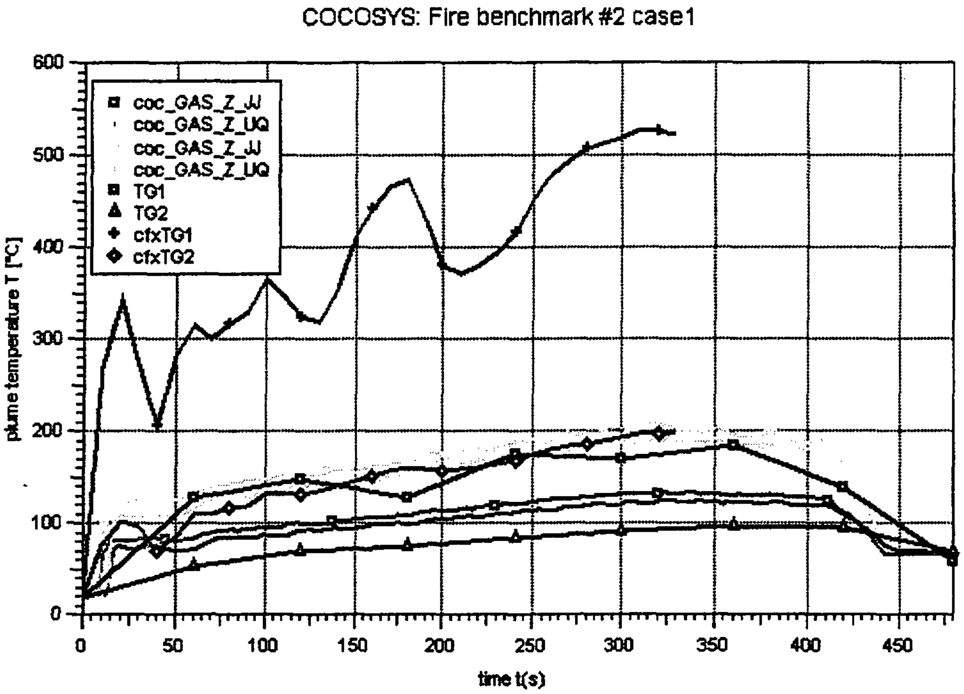

Fig. 3-8 Case1: Plume temperatures

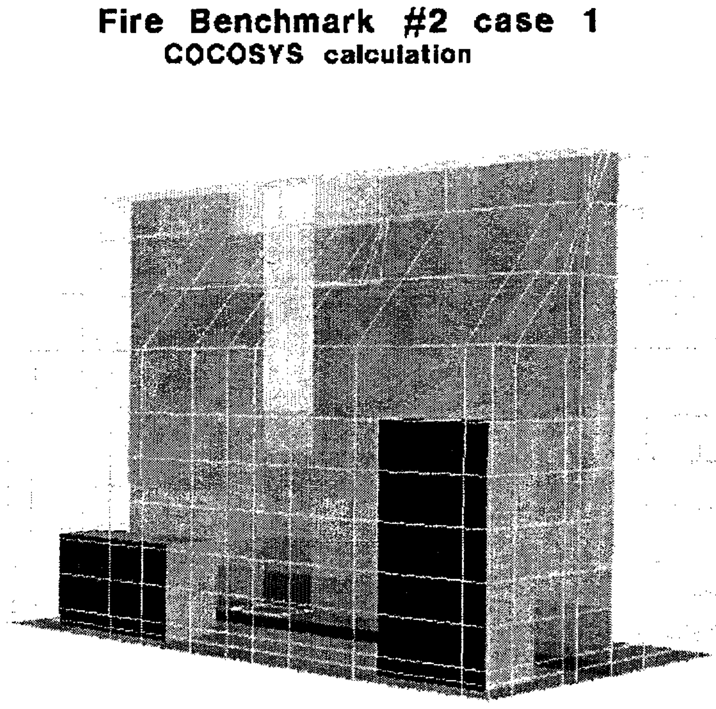

Fig. 3-9 Visualisation of the fire plume (temperature) in COCOSYS

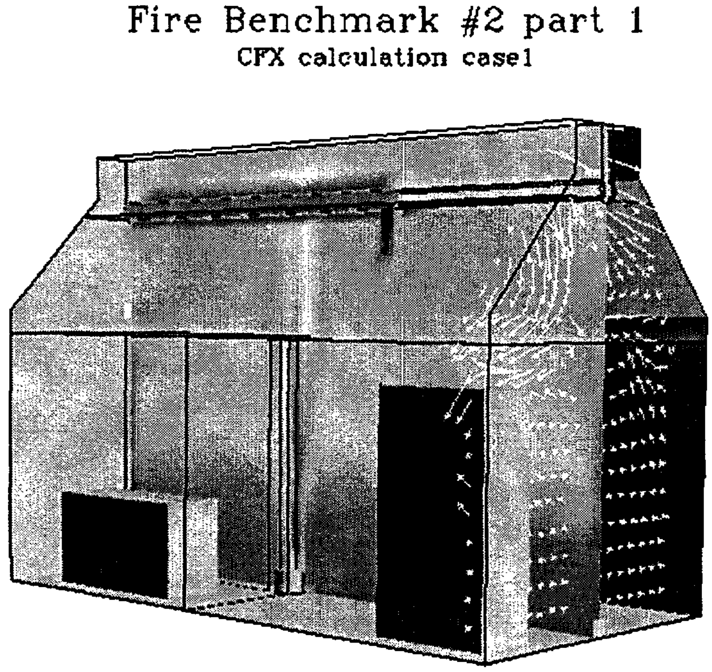

Fig. 3-10 Visualisation of the fire plume (temperature) in CFX

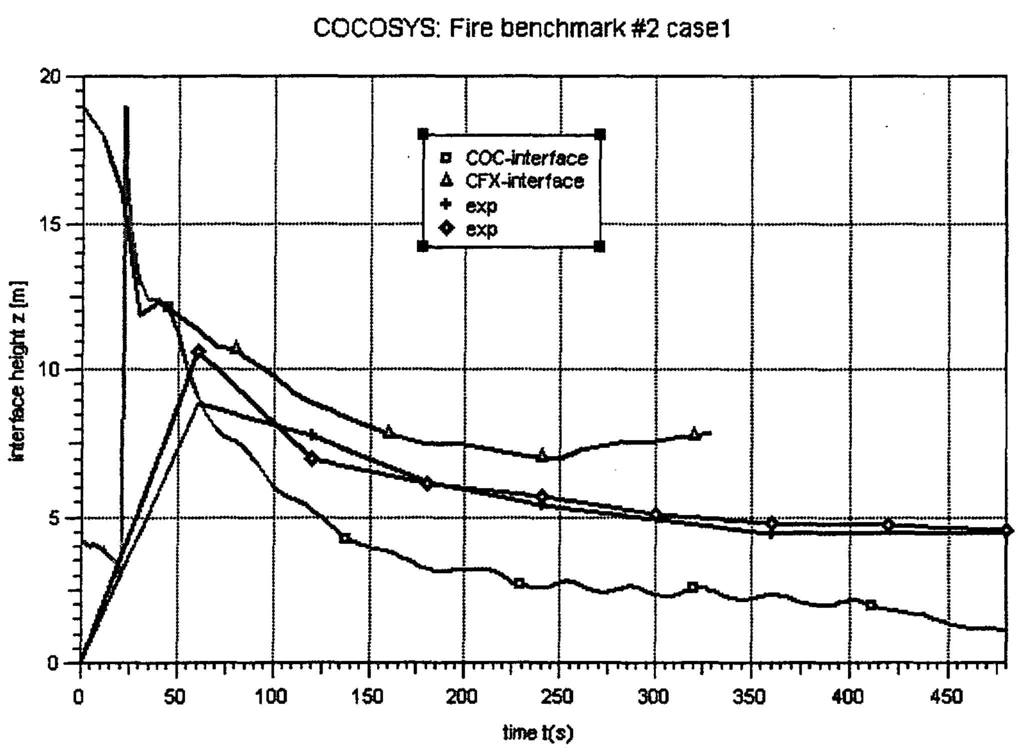

Fig. 3-11 Case1: Interface height

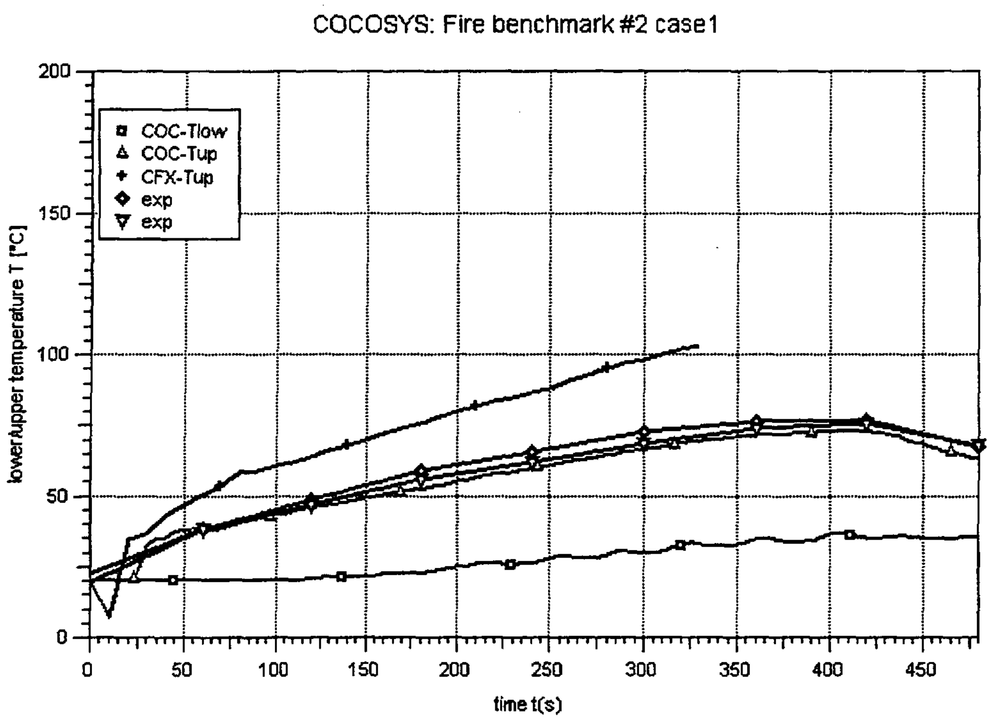

Fig. 3-12 Case1: Upper layer temperature

3.2 Case 2

Similar to case 1 COCOSYS simulates the temperatures quite well. The Fig. 3-13 to Fig. 3-18 show the comparison between the calculation and the measurement for the 3 measurement trees. As for the case 1 the calculated temperature stratification is calculated somewhat to strong. A similar behavior is also found for the calculated plume temperatures. Fig. 3-19 shows the different values of plume temperature for a calculation with a complete reaction of heptan over the pool surface (*COCfull*) and the optimal case with a 60% reaction efficiency. Because only the temperatures can be compared, an additional consistency check is not possible (for example for CO_2 concentration).

Fig. 3-20 presents the comparison of the heat loss to the wall structures for different calculated variations. The red curve corresponds to the optimal COCOSYS case. In the base calculation of COCOSYS (*COCbase*) the infiltration, heat transfer conditions are set according the benchmark specification. The heat loss calculated in the CFX calculations is lower. This is a reason for the higher calculated temperatures too.

The mass flow rate through the infiltration depends strongly on the specified boundary conditions. Fig. 3-21 presents the comparison between the three COCOSYS calculations. In the first calculation (*COCfull*) all environmental control volumes are started with a total pressure of 1.013 bar. Because the total pressure in the roof part of the fire hall is smaller a convection loop in the wrong direction (from upper to the lower infiltration) starts. In the calculations *COCbase* and *COCopt* all mass flows are positive (from inside to outside) during the heat up phase. Later at about 150s a convection loop in the right direction starts. The differences between the red and green curves show the effect of the moved upper infiltration to the top of the hall roof.

Fig. 3-22 and Fig. 3-23 show the average values for the interface height and upper layer temperature. Also the correspondence between calculated and measured temperatures looks quite well, the calculated interface layer height is somewhat lower.

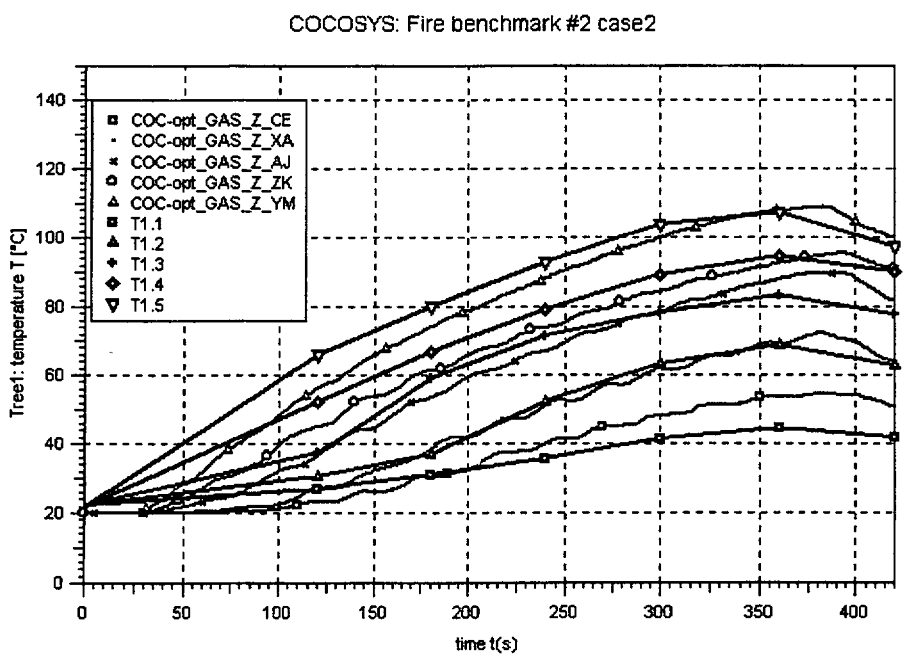

Fig. 3-13 Case2: Temperatures at the lower part of tree 1

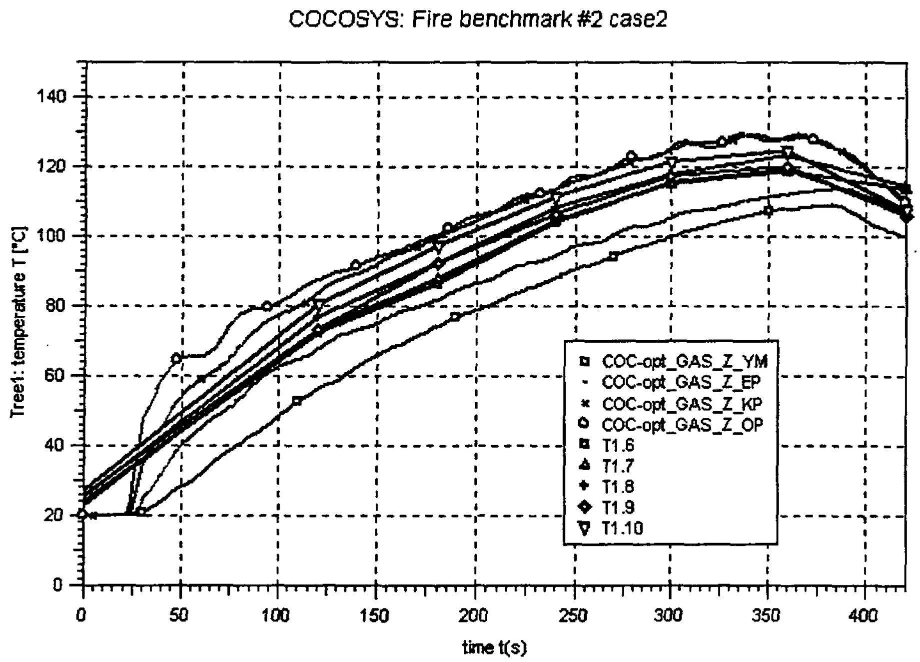

Fig. 3-14 Case2: Temperatures at the upper part of tree 1

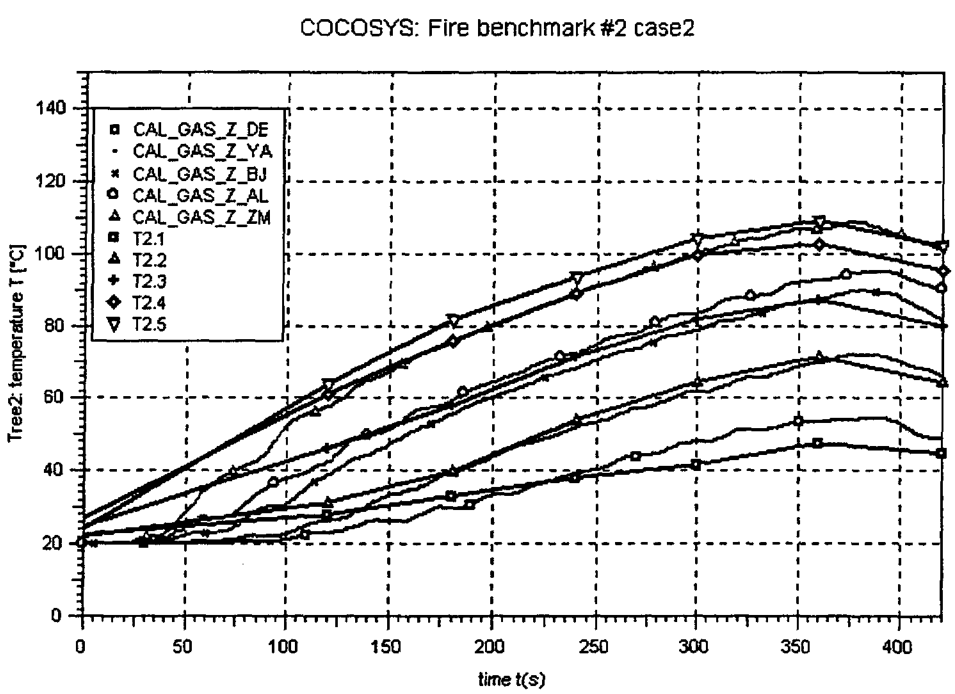

Fig. 3-15 Case2: Temperatures at the lower part of tree 2

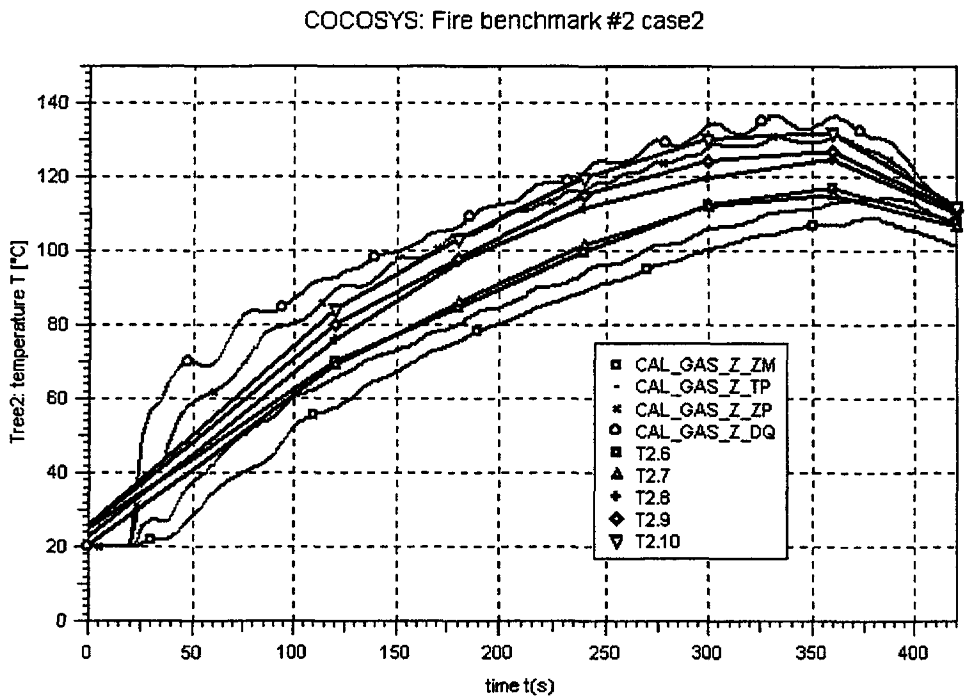

Fig. 3-16 Case2: Temperatures at the upper part of tree 2

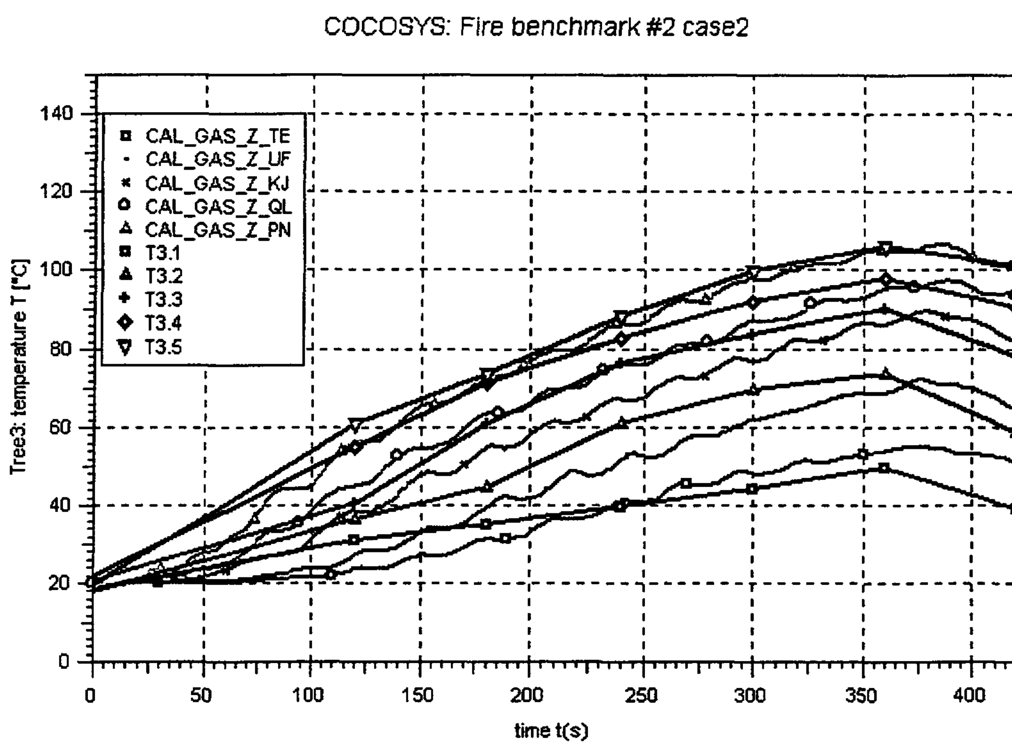

Fig. 3-17 Case2: Temperatures at the lower part of tree 3

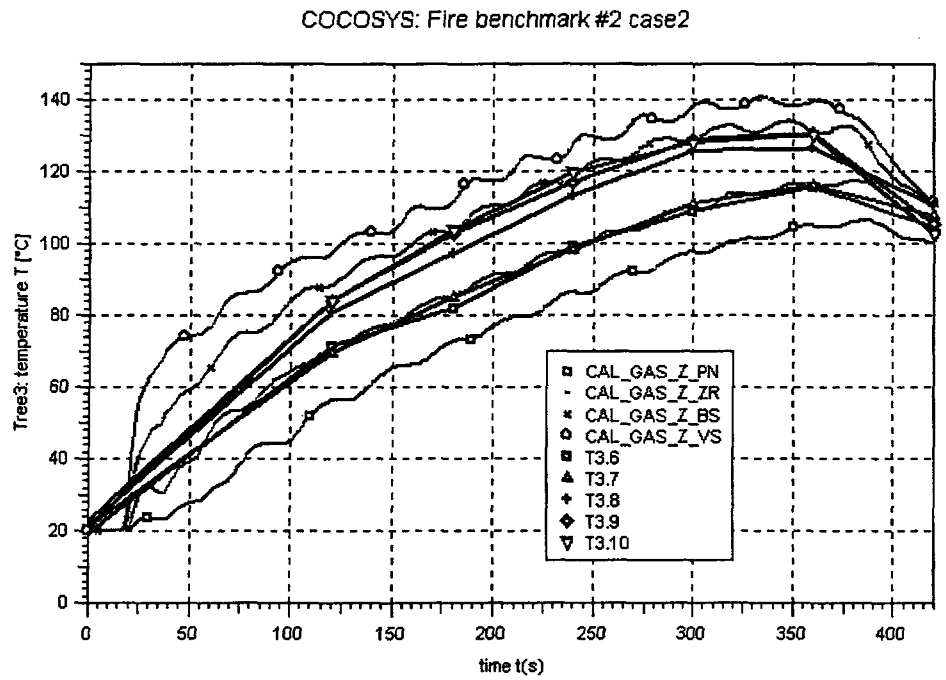

Fig. 3-18 *Case2: Temperatures at the upper part of tree 3*

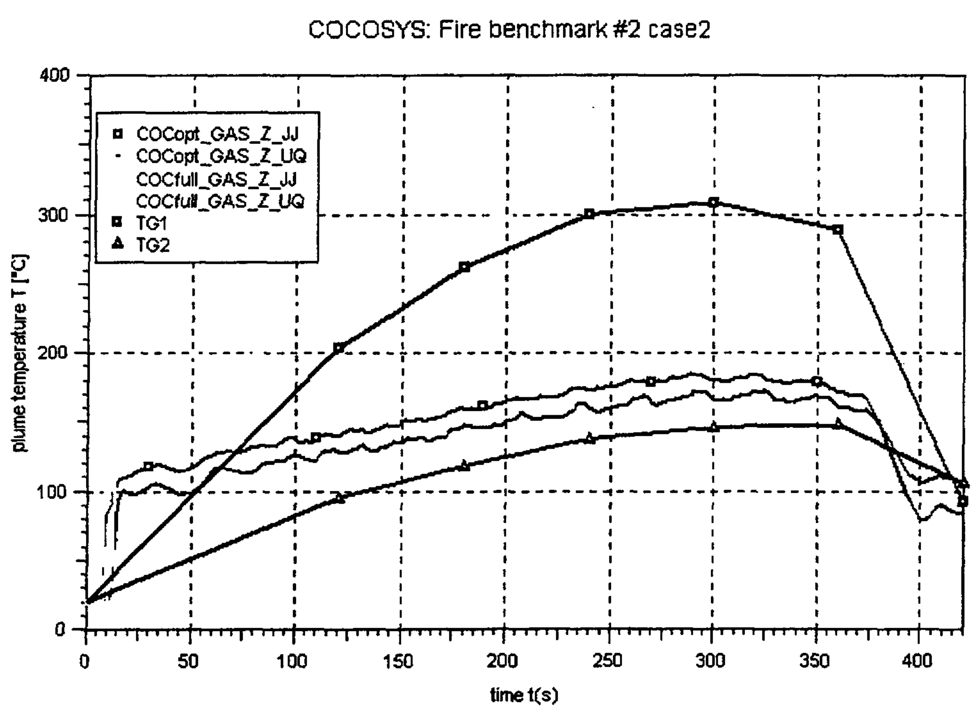

Fig. 3-19 Case2: Temperatures inside the plume

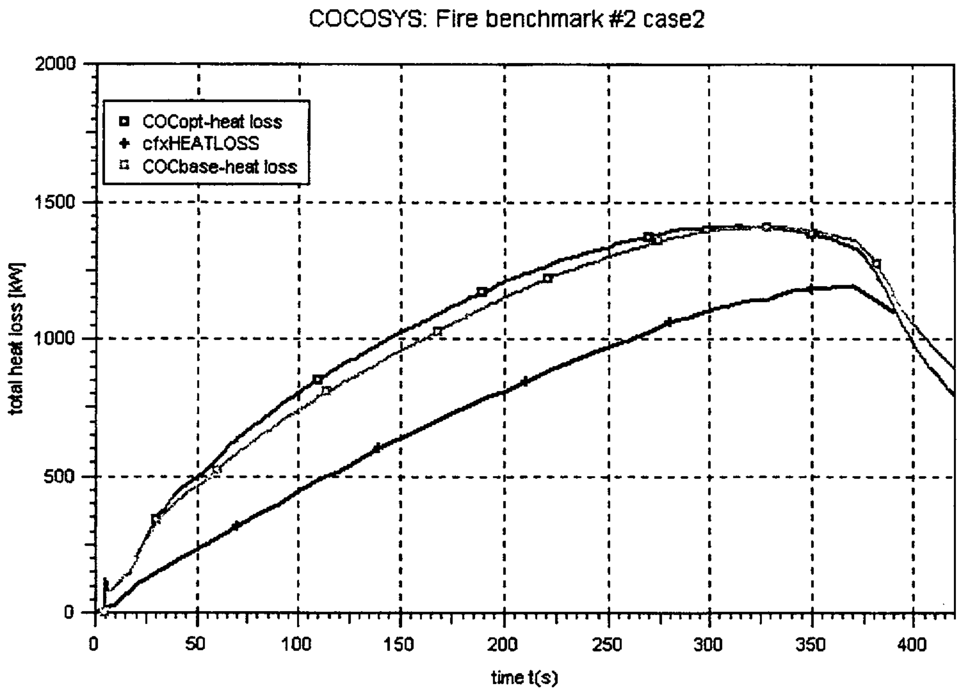

Fig. 3-20 Case2: Heat flow to the wall structures

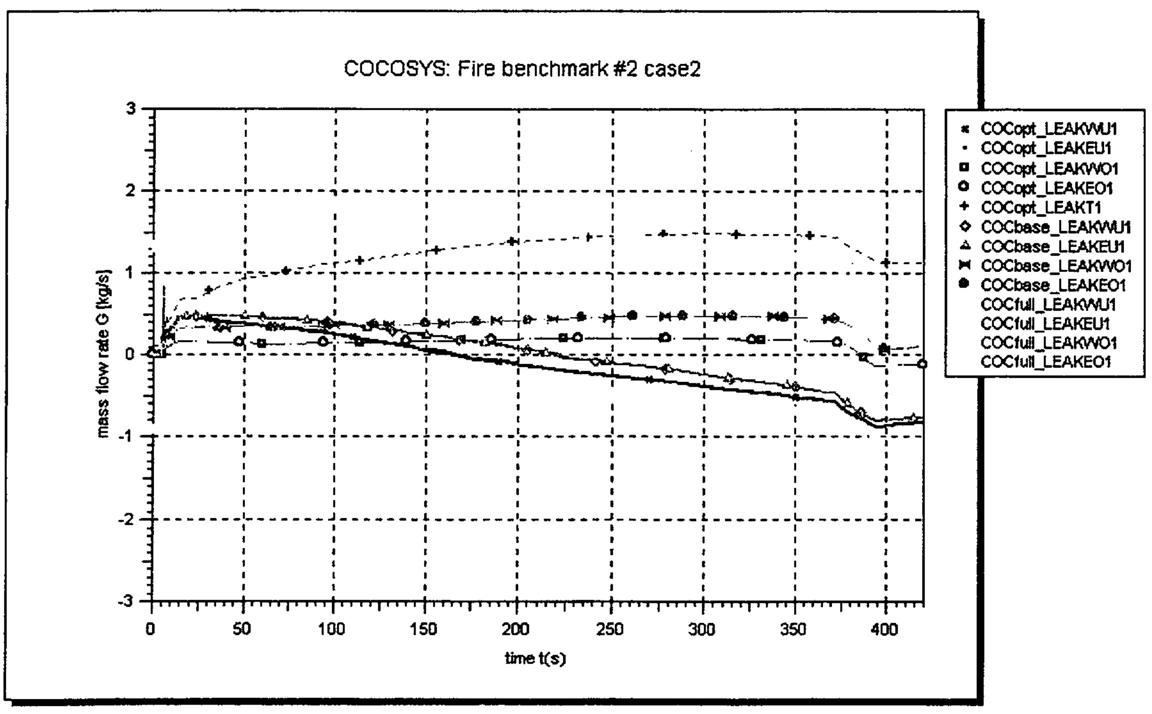

Fig. 3-21 Case2: Calculated mass flow rates through the infiltrations

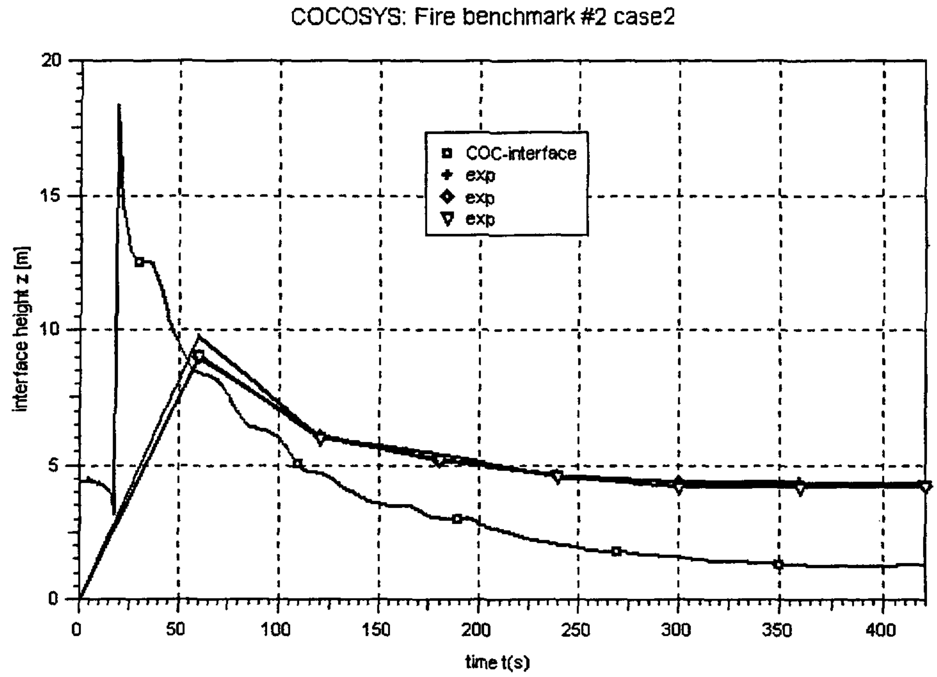

Fig. 3-22 Interface height in case 2

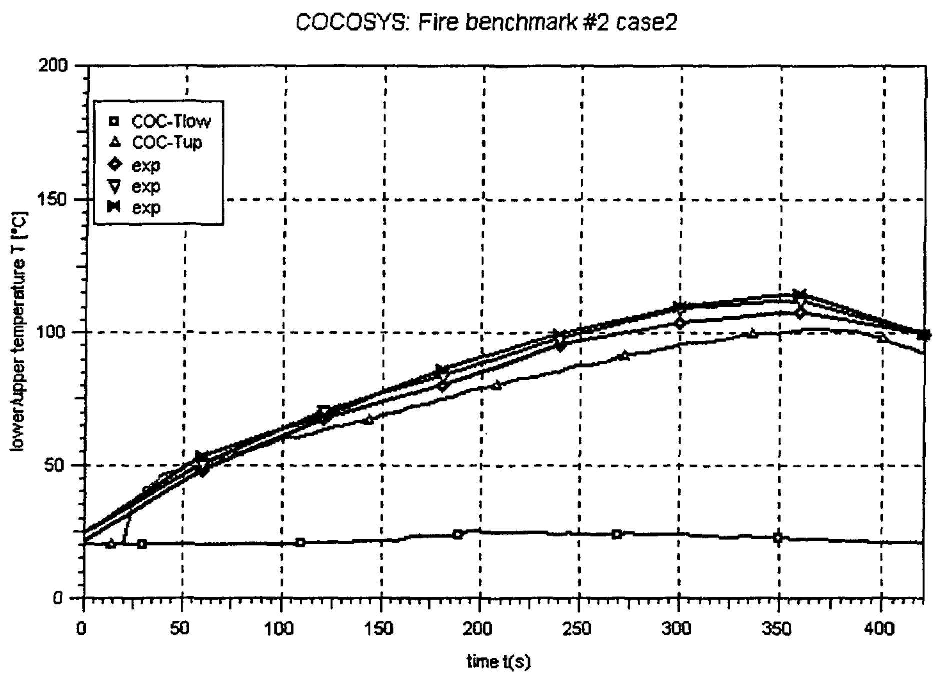

Fig. 3-23 Upper layer temperature in case 2

3.3 Case 3

Allthough the ventilation system has been used and the doors are open in case 3, the behavior is very similar to case 1 and 2. Fig. 3-24 to Fig. 3-30 show the results of the optimal COCOSYS calculation compared with the experimental measurements.

Fig. 3-31 presents the injected and burned mass of heptan. About 30% of the heptan mass remains unburned. This value is compared to the value specified in the benchmark description relatively high.

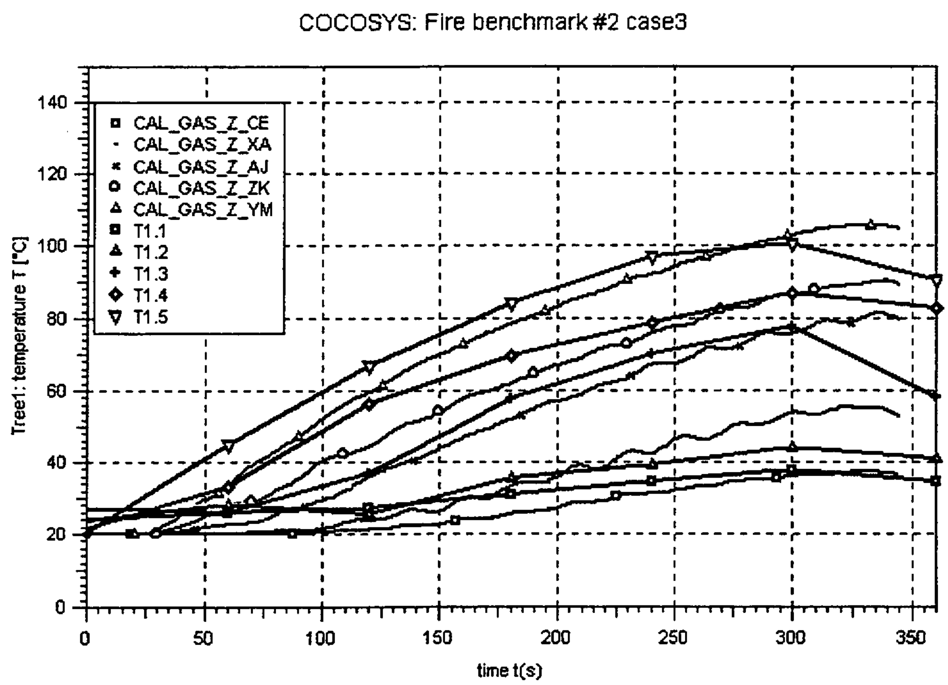

Fig. 3-24 Case3: Temperatures at lower part of tree 1

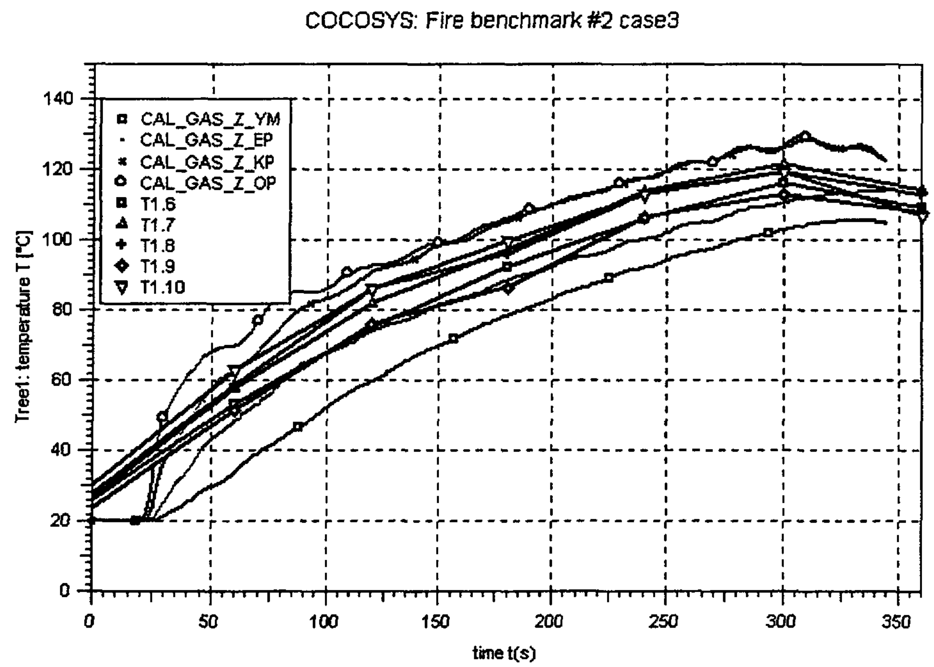

Fig. 3-25 Case 3: Temperature at upper part of tree 1

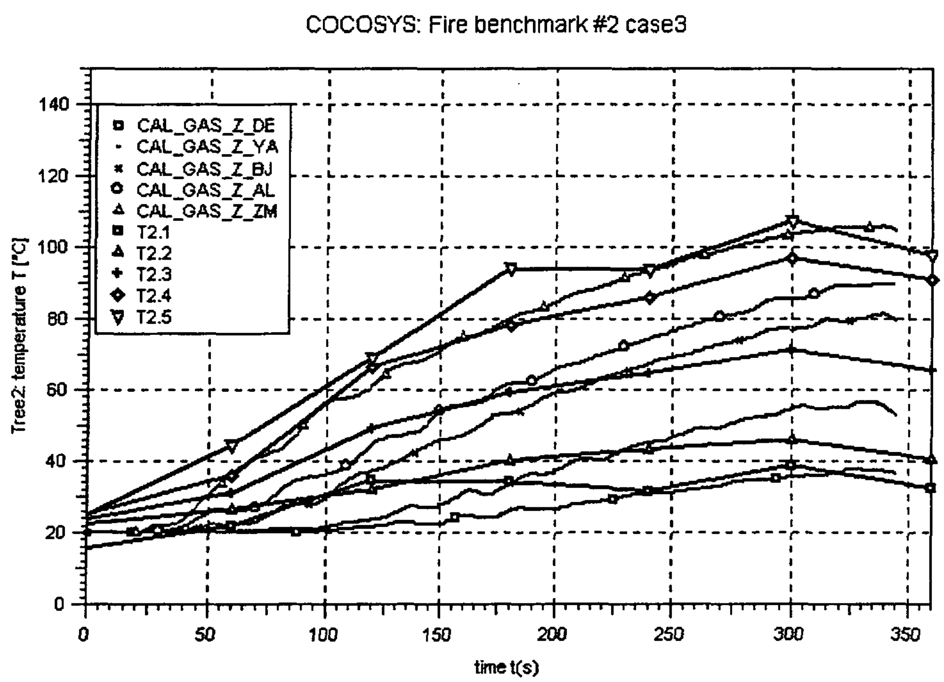

Fig. 3-26 Case 3: Temperature at lower part of tree 2

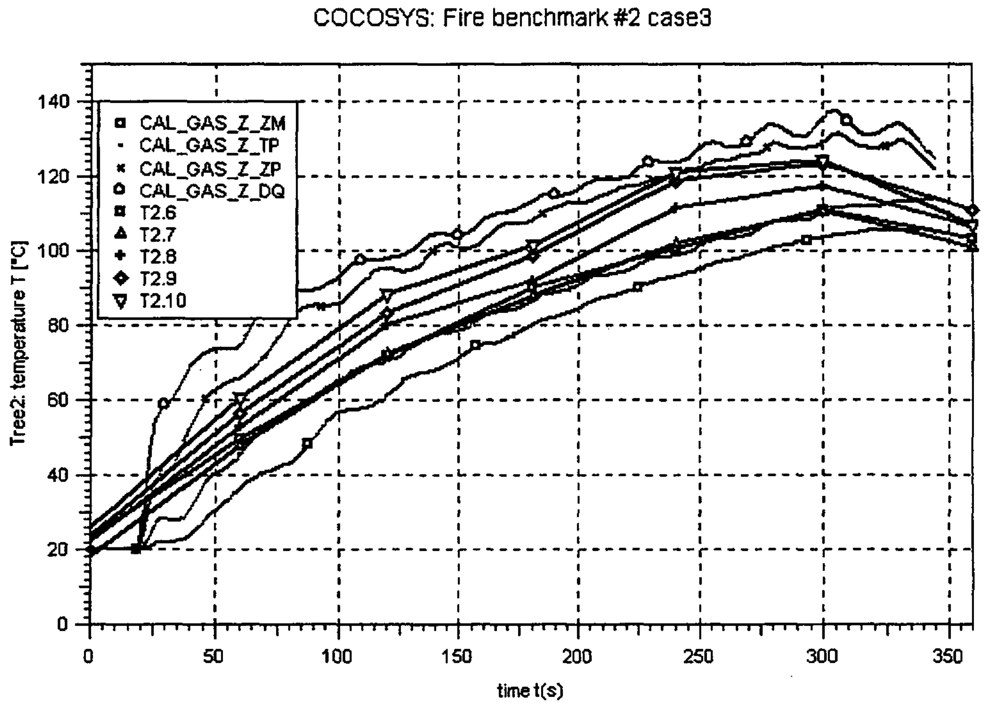

Fig. 3-27 Case 3: Temperature at upper part of tree 2

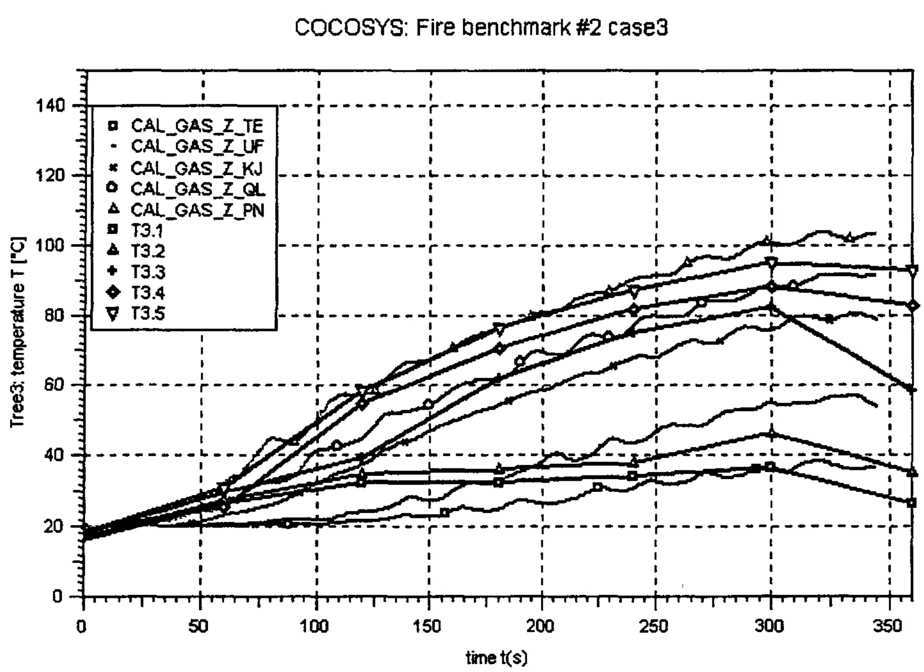

Fig. 3-28 Case 3: Temperature at lower part of tree 3

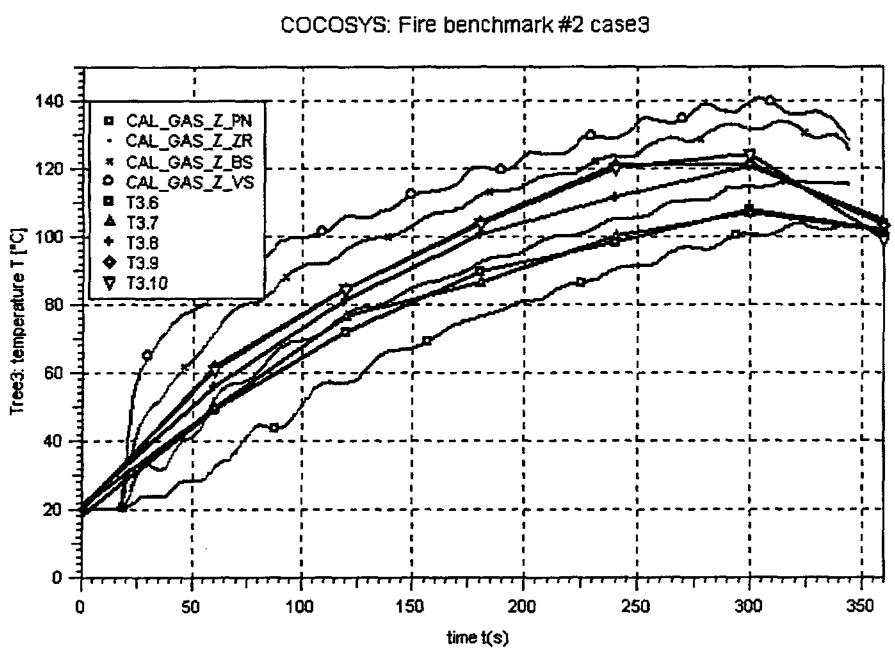

Fig. 3-29 Case 3: Temperature at upper part of tree 3

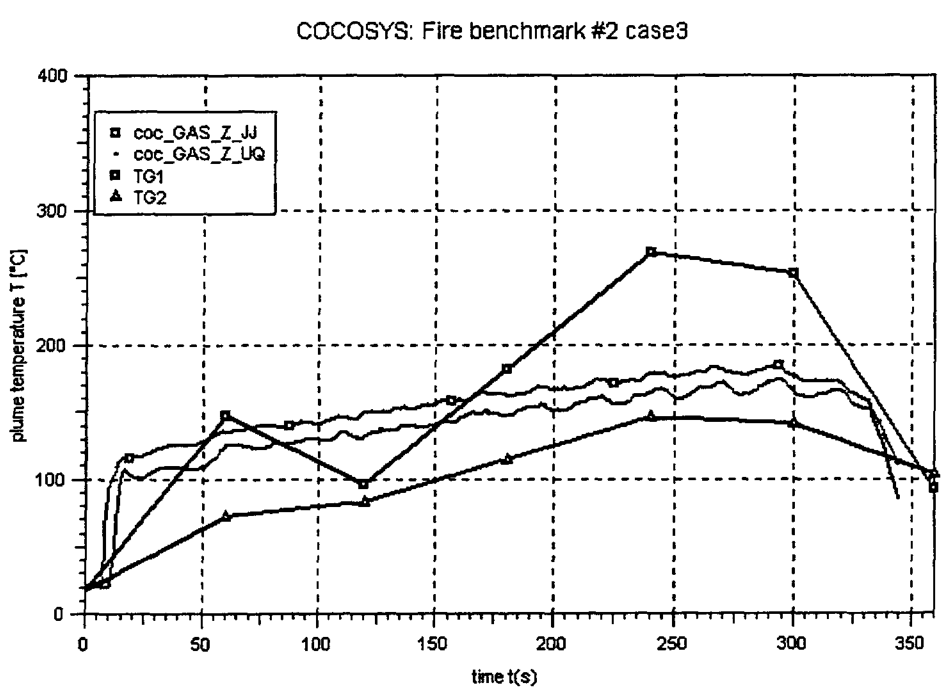

Fig. 3-30 Case 3: Plume temperatures

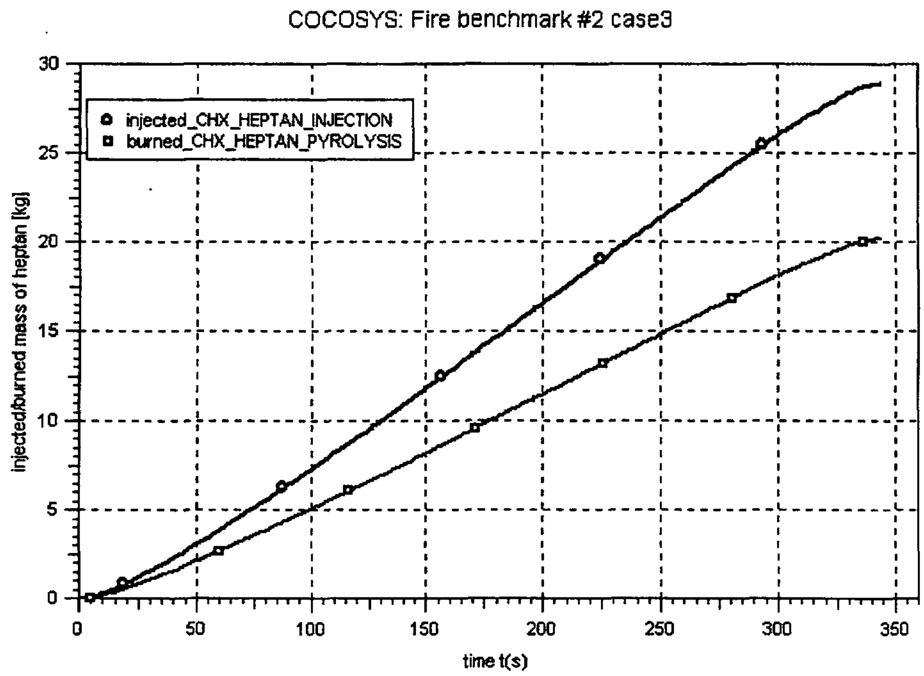

Fig. 3-31 Case 3: Injected and burned heptan mass

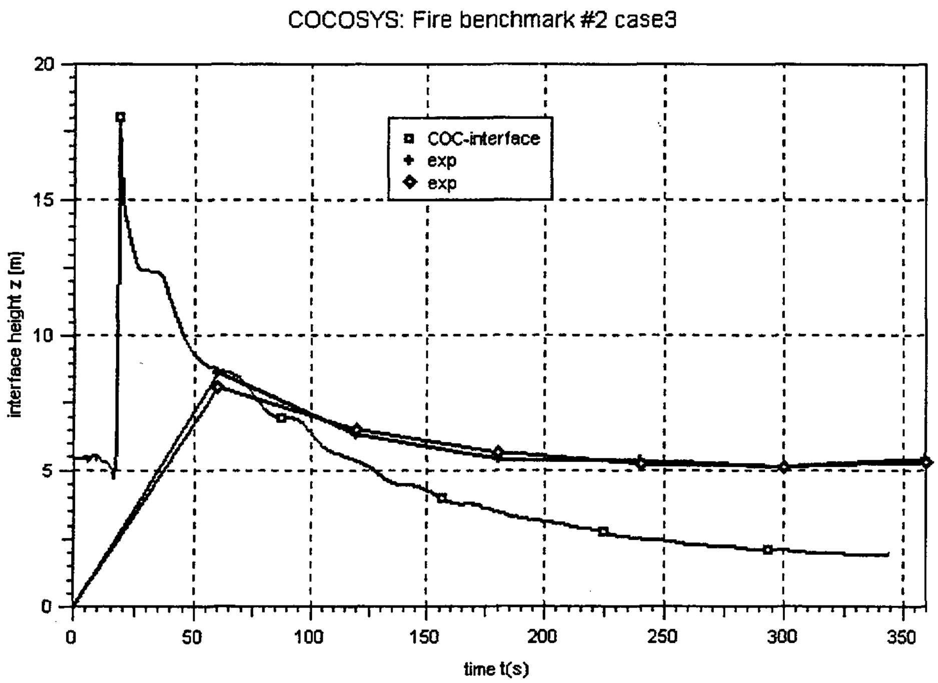

Fig. 3-32 Case 3: Interface height

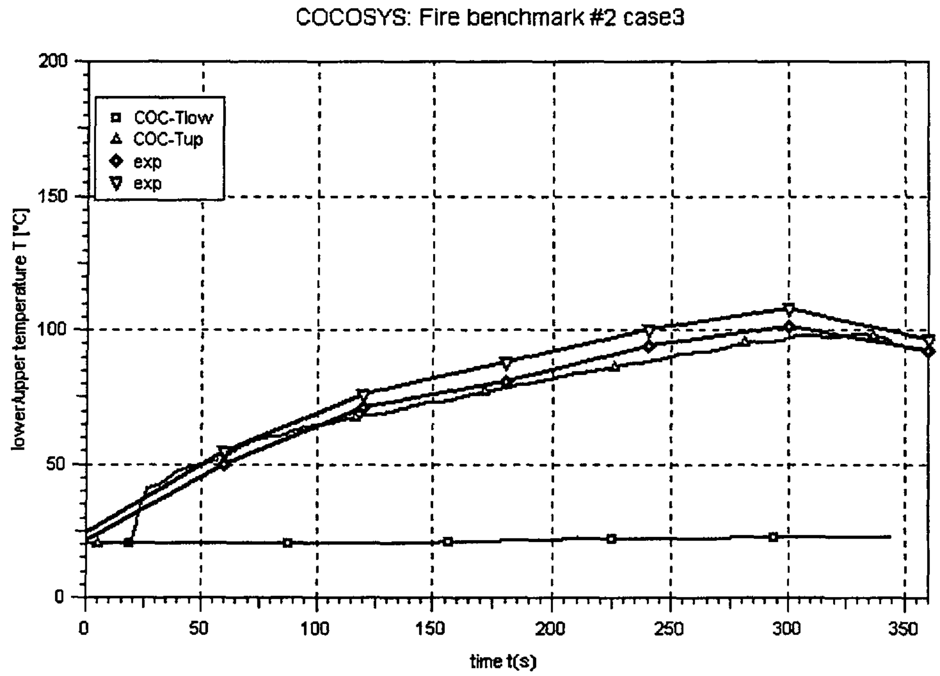

Fig. 3-33 Upper layer temperature

3.4 Comparison between the cases

Between the different experiments (case1 to case 3) the experimental boundary conditions have been somewhat changed. From case 1 to 2 the surface of the pool have been increased. And in case 3 the ventilation system has been used and the doors are open. The calculated heat release rates (Fig. 3-34) and temperatures at T1.10 (Fig. 3-35) show a consistent behavior according to the modifications. The increasing of the pool surface leads to an increased heat release rate and increased temperature. Starting the ventilation system (with open doors) lead to a further increase of heat release rate and a reduced burning time. The difference between case 2 and case 3 is relatively small (compared to that between case 1 and 2) because in each case there are oxygen rich conditions. An additional ventilation has only a minor effect in this case.

Although the temperatures are to high, the CFX code delivers consistent behavior too. Fig. 3-36 presents the results of CFX and COCOSYS (*COCfull* variation) in comparison with the experimental data.

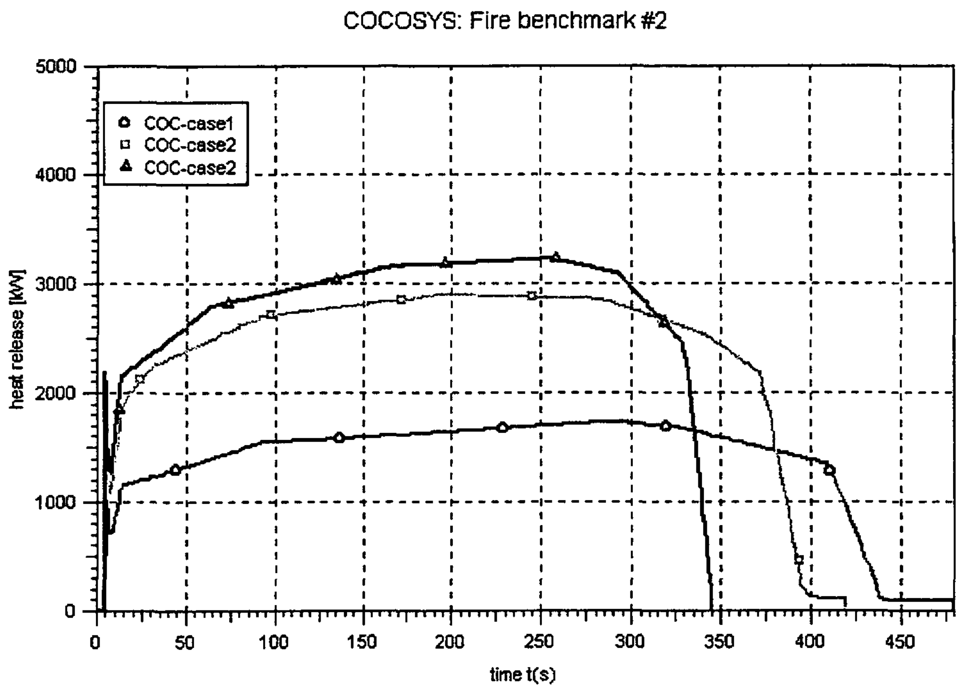

Fig. 3-34 Calculated heat release rates for the 3 cases

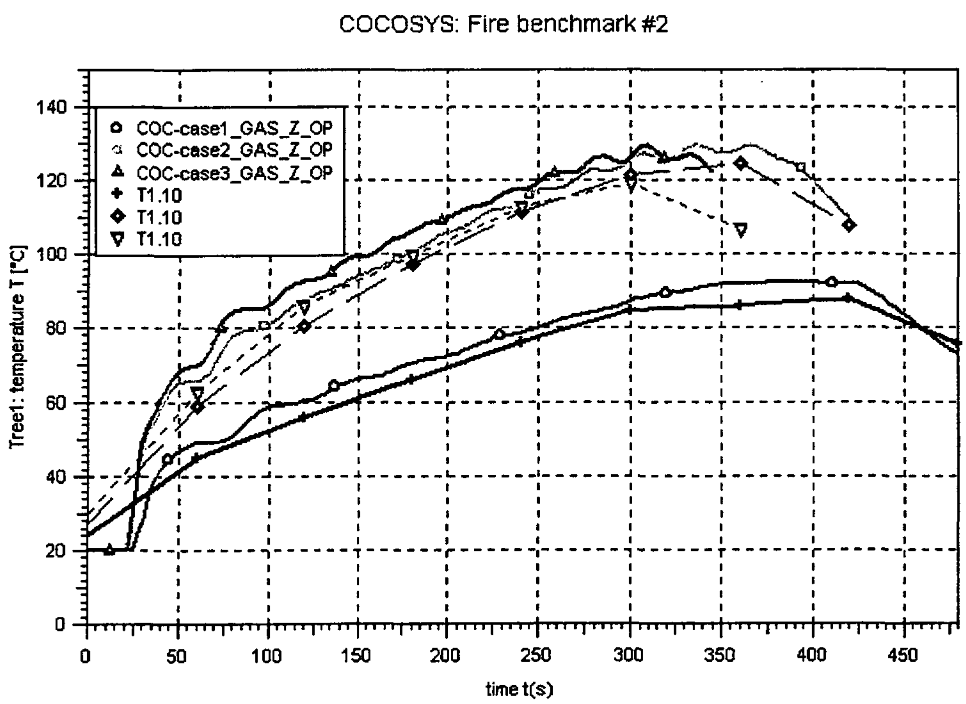

Fig. 3-35 Comparison of the measured and calculated temperatures at T1.10

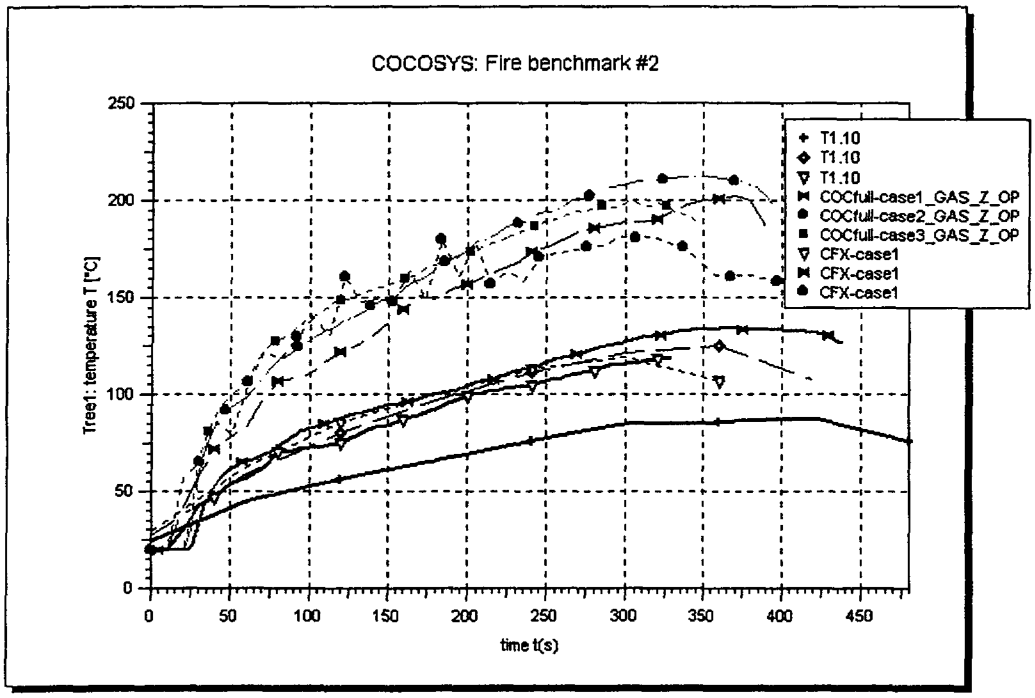

Fig. 3-36 Comparison of CFX and COCOSYS for all cases

4 Conclusions - Next steps

COCOSYS show for the temperature good results in comparison with the experimental data. The calculated temperature stratification in the hot gas layer is somewhat to high. The missing plume model leads to some restriction for the calculated plume temperatures. It has to be pointed out, that the reaction efficiency has been adjusted to the experimental data. The resulting value of about 70 % burned heptan mass seems to be somewhat low. Therefore it would be nice if some more experimental data would be available (concentrations, temperature decrease after burning, velocities). Up to now, COCOSYS has also no model to simulate the soot behavior.

The influence on temperature on different simulation of some boundary conditions (heat transfer to walls, infiltration) leads to a temperature decrease of about 20 K. In comparison to the effect of the efficiency factor this is rather low. One reason may be, that there are oxygen rich conditions, why the differences between case 2 and case 3 are also very small.

The CFX results are delivering too high temperature, corresponding to the initial COCOSYS calculations with complete burning of heptan. Concerning CFX the stability has to be improved (especially for case 3), the infiltration has to be checked. It has already be found, that an reduction of the so-called eddy-break-up-factor would improve the results.

For COCOSYS it is planned to use the detailed model, where the pyrolysis rate is calculated by the program. Therefore some additional initial data is necessary. The efficiency factor should be checked against other experiments.

Group Project 1

International Collaborative Project

to Evaluate

Fire Models

for Nuclear Power Plant

Applications

Nick Williams
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Scott Kelly

Performance Based Design FP 571
Professor J. Barnett
Spring 2002

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FP 571 PERFORMANCE BASED DESIGN
SPRING 2002
GROUP PROJECT 1

1. Introduction:

The purpose of this project is to evaluate the ability of computer fire models to predict fire growth in a large hall; such as the turbine hall in a nuclear power plant. Fire protection engineers (FPE) are frequently asked to conduct fire safety evaluations of buildings and structures. Following a performance based design approach, FPE's draw upon risk analysis in selecting the most probable fire scenarios that may take place in the structure. These fire scenarios are then scrutinized to predict heat transfer, room temperatures, and smoke movement. This information allows the FPE to evaluate the performance of the structure according to pre-established fire safety goals and objectives. Due the complexity of fire and fire growth in a structure, FPE's are forced to make broad assumptions in order to achieve useful results. Until recently, FPE's were limited to hand calculations using numerical analysis techniques. Similar to most scientific fields, computers have greatly enhanced the FPE's ability to take fire scenarios and predict building performance. This report is part of a class assignment undertaken by graduate FPE students at Worcester Polytechnic Institute. Our class results will be forwarded as part of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. Our group was tasked with using JASMINE, a computation fluid dynamics computer model described below, to model Part 1, Case 1 of Benchmark Exercise #2. This report is written with the general assumption that the reader is familiar with this international collaborative.

2. Initial Assignment:

Our initial class assignment is described below:

1. Identify key issues in Benchmark Exercise #2 as part of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications.
2. Describe model and associated challenges with using the model to complete Benchmark Exercise #2.
3. Complete item 2 using Jasmine, a CFD model. First complete Part 1 of the exercise and then attempt Part 2.

3.0 Purpose of Benchmark Exercise #2:

To challenge fire models in respect to issues associated with predicting the effects of fire in a large volume.

1. **Objectives of Benchmark Exercise #2:**

1. To examine scenario(s) that will provide a harder test for zone models, in particular with respect to fire spread in large volumes representative of, say, a turbine hall.
2. If possible, to make use of experimental data to fulfill the requirement of more thoroughly testing the predictive capability of both zone and CFD fire models. Again, as noted in the exercise description, the emphasis when selecting scenarios was on large smoke filling volumes.

1. **Description of Benchmark Exercise #2:**

1. Part 1 includes three cases based on full-scale experiments inside a test hall using two Heptane fires of different diameter. Thermocouples were used to record temperatures directly above the fire and at locations in the test hall. Bi-directional probes were used to measure gas velocity in the case with open doors. The geometry, material properties of walls and ceilings, ambient conditions and ventilation conditions are provided in the exercise. The following table is a summary of Part 1:

Case 1-Priority		**Case 2**		**Case 3**
doors closed no mech. Exhaust natural leakage pool diameter = 1.17m		doors closed no mech. Exhaust natural leakage pool diameter =1.6m		doors open (*0.8 m x 4m*) mech. Exhaust (*11 m^3 s^{-1}*) ignore natural leakage pool diameter = 1.6m

2. Part 2 is an optional exercise. This part includes three cases inside a rectangular building with dimensions similar to a real turbine hall. As part of our assignment, we will model a two level building more representative of a turbine hall. The geometry, material properties, and conditions are also provided. We are also asked to include an open gated hatch in the floor/ceiling between levels. For Part 2, we are asked to find the effect of the fire on cable targets inside the hall. Since we will have two levels, we will model one cable target just under the lower level ceiling, and model two cable targets near the roof as steel structural members. The difference between the three cases in Part 2 is in the ventilation for the hall.

2. Expected Model Output Part 1:

CFD
Temperatures at thermocouple trees (T1.1,...,T1.10,T2.1,...,T2.10,T3.1,...,T3.10)
Temperatures at plume thermocouples (TG1.1 & TG.2)
Infiltration flow rate (cases 1 & 2)
Mass flow rate in/out door 1 (case 3)
Mass flow rate in/out door 2 (case 3)
Velocities at the two doorways (case3) (V1.1,...,V1.3,V2.1,...,V2.3)
Total heat loss rate to solid boundaries
Heat loss through mech. Exhaust (case 3)
Interface height (using reduction of thermocouple tree data)
Upper layer temperature (using reduction of thermocouple tree data)
Total heat release rate (within whole hall)

7.0 Expected Model Output Part 2:

1. Similar to Part 1, but different locations for the thermocouple trees. The gas temperatures are to be provided at 1-meter intervals.
2. The gas temperature directly above the fire is requested at two locations (CFD models), but now at heights 9 m and 19 m.
3. Three doorway velocities should again be considered at 0.5 m, 1 m and 3.5 m height, on the vertical enter line of each opening.
4. The total heat loss through the doorway opening should be provided if possible.
5. Upper and lower layer oxygen concentration should be provided in the case of zone models. For CFD models the oxygen concentration at the thermocouple tree locations should be provided.
6. For each cable/steel structural member target, the following should be provided, where possible, at each reported time:
    1. maximum incident flux
    2. maximum surface temperature
    3. maximum enter-line temperature

1. Key Issues:

For the purpose of this assignment, we first defined key issues as one of the following:

1. Expected model outputs

2. Main modeling assumptions and inputs (to be developed as the report is completed.

3. Issues in need of clarification, or additional research.

4. Issues which will be difficult to model.

1. Using the model to produce the expected outputs of the exercise.
2. Assumptions for the heat release mechanism.
3. Assumptions for radiation treatment (if included, important issues may include the treatment radiation transfer to solid surfaces, the absorption/emission in the gas phase and radiation from soot plume.

4. The number of control volumes or elements.
5. Assumptions in turbulence model.
6. Modeling the two obstructions inside the hall (Part 1)
7. Modeling the air infiltration.
8. Accounting for the air movement with mechanical ventilation.
9. Effective selection of elements accounting for long computation times associated with CFD model.
10. Choosing a combustion mechanism (stoichiometric ratio, mass burn rate).
11. Utilize the data from Table 3 (Fuel mass release rates) to model the fire.
12. Selecting nodes to compare to experimental data.
13. Modeling the cable/structural steel targets.

14. Reconstructing the model for case 2 (new geometry, added physical features)

2. Part 1 Case 1:

Our second and final class assignment was to use the fire model provided to our group to model Part 1 Case 1.

10.0 Group Background:

Based on the fact that this project is being completed both as a class assignment and as a submittal as part of the aforementioned exercise, it is appropriate to describe the group members for any particular reader of this report. The group consists of three members who are all pursuing Master of Science (M.S.) degrees in Fire Protection Engineering (FPE). Two group members are senior Mechanical Engineering undergraduate majors who are pursuing the M.S. FPE degree under a 5 year B.S./M.S. program. One group member has a Bachelor of Science degree in Civil Engineering accomplished prior to the introduction of Windows based computer programs. This is the second semester in the FPE program for all group members. The first semester includes core courses in Fire Dynamics, Building Firesafety, and Suppression courses. Prior to this project, no group members had any Computational Fluid Dynamics (CFD) experience or fire modeling experience with any fire modeling program. One group member utilized extensive AUTOCAD experience to assist in using the fire model.

11.0 JASMINE:

According the software manufacturer BRE, "JASMINE (Analysis of Smoke Movement In Enclosures) uses the numerical technique of computational fluid dynamics (CFD) to describe the heat and mass transfer processes associated with the dispersion of combustion products from a fire. The processes of convection, diffusion and entrainment are simulated by the Navier-Strokes equations. JASMINE has been developed, validated and improved over a twenty year period and includes the key processes of buoyancy, convection, entrainment, turbulence, combustion, thermal radiation and boundary heat transfer relevant to the movement of smoke."

In summary, JASMINE is a complex CFD fire modelling program that can produce accurate results, when compared to other models, provided the program users have extensive fire dynamics knowledge and fully understand the program. JASMINE does come with several example sessions and a help manual. However, our group found the fire and geometry in the example sessions to be simplistic and did not assist in preparing the model to evaluate the fire and geometry presented in this exercise. The help manual is thorough but more of a dictionary listing of terms than something that can be used to troubleshoot some of the problems we encountered. Most noteworthy were problems encountered with creating a geometry which reflected the pitched roof and then creating a grid for analysis. More details regarding these issues and the assumptions taken to obtain results are included throughout this report.

12.1 Materials:

For the large hall structure considered in Benchmark #2, the walls and ceilings are constructed of a .001m layer of sheet metal on the outside with a .05m layer of mineral wool on the inside. The floor is constructed of concrete. The two objects inside the building were treated as adiabatic concrete. Our first attempt to model the walls and ceilings was to use a function provided by JASMINE that allows the user to insert objects. Using this function the walls were constructed of sheet metal and mineral wool was wrapped as individual objects inside the entire structure. This process was very time consuming and actually inhibited the program from producing results. JASMINE appears to place permanent grid lines on all geometry lines; therefore, this produced too many nodes within the wall materials for an analysis.

Our second attempt for selecting the materials was to create an equivalent material using thermal circuit principles from heat transfer theories. However, as our fire is the heat source, this is a transient heat transfer, and this does not allow the materials to be simplified into one material using this principle.

Our final approach was to consider the relative thickness of the inner mineral wool as compared to the thin sheet metal and to also consider the limited conductivity of the mineral wool. Therefore, in our effort to continue with our first attempt to achieve results for Case 1, Part 1, we decided to input only the mineral wool as the wall material and make this material "thermally thin" or isothermal in the model. This may not truly reflect the heat loss through the walls and ceiling, but as mentioned earlier, it may eliminate some of our problems with JASMINE placing too many grid nodes inside the walls.

12.2 The Fire:

The single fire source was constructed using equation 1 provided in Benchmark Exercise #2:

The combustion efficiency was .8, the heat of combustion used was 44,600 kJ/kg, and the fuel mass release rate was taken from the data for Case 1 in Table 3 of Benchmark Exercise #2. This data was placed into an Excel spreadsheet and graphed for each given time in a scatter plot and curve fit to represent the HRR curve that needed to be placed into JASMINE. The graph showing our results is included as Appendix 1 of this report.

JASMINE utilizes various windows for inputs and allows the user to select an option that will design the fire. The following is a copy of the JASMINE fire originally used in our analysis:

The fire in Part 1 Case 1 is a circular Heptane fire with a 1.17 m diameter. Since JASMINE, as shown above, only models the fire with X & Y dimensions, an equivalent area was calculated to allow for a square fire of equivalent area. Any data difference in the model values from the experiment due to this equivalent area should be nominal based on the size the test hall. JASMINE allowed us to select Heptane as the fuel. In order to match the HRR curve extracted from the exercise data, our JASMINE fire was modeled in three phases. The first phase or growth phase was modeled as an ultrafast t squared fire. The function was modified to provide a growth that is similar to the experimental fire. The second phase was modeled as steady state with a time period that closely matches the steady period shown in Appendix 1. The last phase was a decay phase using the JASMINE default value for the decaying phase of the fire. The time for the end of the fire also matches the data provided.

12.3 Geometry:

All group members spent extensive time trying to model the geometry of the large hall in JASMINE. The pitched roof provided a challenge since all angles for compartments modeled in JASMINE are right angles. The roof was created by placing block objects into a rectangle room with incremental steps to represent the pitched roof. Although this increases the surface area available for heat transfer, it allows for a more accurate prediction of smoke movement. Appendix 2 of this report shows the modeled test hall for Case 1 with the vents included to represent natural leakage. The duct for the mechanical exhaust system is not included in the space based on the assumption that this small amount of material in a large test hall would not greatly affect our model results.

Although this created a room which was similar to the test hall, we found this geometry to be too complex to achieve results. In order to create a slope similar to the diagonally pitched roof, many steps were placed into the space. This presented great problems when taking the next step to prepare the CFD grid. JASMINE creates permanent grid lines matching the geometry created by the user. Therefore, each individual step along the roof became a node for the model to evaluate. The spacing was less than 50 mm which seemed to prevent JASMINE from conducting any analysis.

In order to obtain results for Case 1 our group calculated an equivalent volume rectangular piped to prevent further problems with the grid. Using calculations for an equivalent volume, the height of the hall became 15.84 meters while the other dimensions remained the same. Our group recognized that this changes the predicted the smoke movement, and presents a different surface area for heat transfer. Our modeled upper layer will develop at a different rate due to this geometry change. Four vents were placed in the locations prescribed in the exercise to represent the natural leakage that would actually take place. A picture of this geometry is provided in Appendix 3.

12.4 Preparing a Grid:

This aspect of the modeling was the most demanding aspect of the exercise for our group. A large pare of our difficulty is most likely due to our overall lack of CFD experience. Our group was provided two versions of JASMINE, one limited to 5,000 elements, and one not limited. Since the CFD computation is time comprehensive, the number of elements needs to be smartly managed to obtain results in a reasonable time. Our intention was to limit the initial selection of control volumes by preparing a grid that only concentrated on placing elements near and above the fire and near the vents. This would provide a shorter initial analysis and allow our group to examine results and make adjustments. However, as noted in our 'geometry' section (12.3) above, significant problems were encountered when JASMIME placed grid lines coincident with all geometry lines. Since our step period was so small to duplicate the pitched roof, elements were spaced too close for analysis. The original grid was over 450,000 nodes.

Using our final geometry, the grid spacing was manipulated manually to place more control volumes in areas that required more accuracy. These areas including near and above the fire and near the vents in the walls. This grid placement focuses the computer model on these areas and smartly limits our nodes to reduce computation time. Our final grid was 117,000 nodes.

12.5 Radiation

JASMINE allows the user to select none, near node, six flux, and a DT method. Our group selected a six flux radiation model. Our fire is modeled using the total heat release rate (HRR). Selecting six flux for radiation allowed for JASMINE to account for the radiation emitted and absorbed from the 4 walls, the ceiling, and floor. The materials values were taken as .95 as prescribed in the exercise. The two objects were treated as adiabatic. Modeling radiation in this manner increases the computational time for the model, but should yield more accurate results.

12.6 Turbulence model

JASMINE has options available for the selection of turbulence. Our group selected the Eddy breakup combustion default selection recommended by the JASMINE users manual for most problems. In selecting Eddy breakup, turbulence model is automatically selected as K-Epsilon to appropriately model the gas flow supporting combustion. The heat transfer for function for the wall was the general default function in JASMINE.

12.7 Running the Simulation:

Our original intention was to run the model with the simplified geometry and the ones elected material and then attempt to run further simulations with the original stepped roof geometry with one selected material. If the simulation was successful, this would tell us that our original modeling of the sheet metal and mineral wool together as "thermally thick" or with transient conduction was the source of error. However, our first simulation took over 80 hours to complete only 400 seconds of the intended 800 second fire simulation. Therefore, our results are based on one simulation with geometry and material noted above. Due to computer speed and capacity, data was saved every 40 seconds. In obtaining 400 seconds of data, we were able to reach the decay or third phase of our modeled fire which began at approximately 360 seconds.

1. Results:

Each data set was saved over 40 second intervals to save computing time and space. Again, our group found retrieving specific results from JASMINE difficult at first and time-consuming. We were to find data for specific points on the thermocouple trees used in the experiment. However, our results in JASMINE are presented according to each node in the grid spacing. Therefore, we had to match the node spacing with the thermocouple spacing the retrieve the desired results. The results obtained are reasonable considered our inputs and assumptions. For graphed results, see here.

Thermocouple Temperatures

The following table shows thermocouple temperatures provided in the format requested in the exercise:

Time (s)	T1.1 (°C)	T1.2 (°C)	T1.3 (°C)	T1.4 (°C)	T1.5 (°C)	T1.6 (°C)	T1.7 (°C)	* *T1.8 (°C)*
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*20.0*
40.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*20.0*
80.0	20.8	20.4	20.4	20.9	22.9	24.8	26.8	*31.7*
120.0	21.6	21.6	21.6	23.4	36.1	40.1	42.6	*43.2*
160.0	22.6	24.0	35.8	41.3	44.5	46.2	47.4	*46.9*
200.0	26.6	29.8	40.6	46.4	51.3	54.7	57.4	*58.0*
240.0	30.0	34.6	43.0	51.4	58.4	62.9	66.1	*64.6*
280.0	34.2	38.6	45.5	57.4	65.1	69.6	72.8	*70.0*
320.0	37.2	41.6	52.2	62.6	70.1	74.6	77.7	*73.6*
360.0	40.3	45.6	57.2	66.5	74.0	78.4	81.3	*76.3*
400.0	42.7	50.7	60.6	69.4	76.6	80.8	83.7	*77.3*

Time (s)	T2.1 (°C)	T2.2 (°C)	T2.3 (°C)	T2.4 (°C)	T2.5 (°C)	T2.6 (°C)	T2.7 (°C)	* *T2.8 (°C)*
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*20.0*
40.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*20.0*
80.0	20.6	20.4	20.3	20.4	21.5	23.9	29.0	*37.3*
120.0	21.6	21.6	21.5	22.5	35.4	40.5	45.6	*47.7*
160.0	22.8	25.2	34.0	40.8	44.5	47.0	50.1	*53.7*
200.0	27.4	29.9	40.2	45.4	50.6	55.0	61.1	*67.3*
240.0	30.0	35.4	41.9	50.4	57.6	63.2	70.0	*74.2*
280.0	34.4	38.8	42.8	56.9	64.6	70.1	76.9	*80.0*
320.0	37.4	42.0	49.7	62.0	69.6	75.2	81.7	*84.0*
360.0	40.4	45.6	53.7	66.2	73.6	79.0	85.4	*87.0*
400.0	42.1	47.0	60.5	68.9	76.1	81.4	87.4	*85.9*

Time (s)	T3.1 (°C)	T3.2 (°C)	T3.3 (°C)	T3.4 (°C)	T3.5 (°C)	T3.6 (°C)	T3.7 (°C)	* *T3.8 (°C)*
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*20.0*
40.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*20.0*
80.0	21.0	20.6	20.4	20.4	20.9	24.4	32.6	*53.3*
120.0	22.3	22.3	22.4	23.8	34.0	40.3	46.9	*55.5*
160.0	23.4	24.9	31.9	39.8	44.5	47.5	53.4	*69.3*
200.0	27.5	31.4	39.1	43.9	49.1	54.4	63.6	*87.5*
240.0	30.6	37.0	40.2	48.9	56.4	62.8	72.9	*96.7*
280.0	34.8	40.0	42.3	55.7	63.4	69.8	79.5	*102.6*
320.0	38.1	43.3	47.3	61.8	68.7	74.7	84.5	*107.3*
360.0	39.7	46.7	53.6	65.7	72.5	78.5	88.0	*111.5*
400.0	41.2	49.4	59.5	68.3	74.9	80.9	89.1	*96.5*

The last thermocouple (#8) is at the roof height 15.84m.

Infiltration Flow Rate

The following table shows the infiltration flow rate through the vents:

	VELOCITY @ LOWER VENT EAST WALL			VELOCITY @LOWER WEST WALL		
Time (s)	Lower Vent Edge	Middle of Vent	Upper Vent Edge	Lower Vent Edge	Middle of Vent	Upper Vent Edge
0.0	0.00	0.00	0.00	0.00	0.00	0.00
40.0	0.00	-0.68	-0.83	8.33E-02	0.53	0.52
80.0	-0.19	-0.81	-0.40	5.53E-02	1.06	0.96
120.0	-0.21	-0.81	-0.42	4.25E-02	1.06	1.01
160.0	-0.11	-0.40	-0.21	-6.85E-03	0.54	0.51
200.0	1.87E-02	4.34E-02	-1.02E-03	-2.25E-02	-6.90E-02	-1.66E-02
240.0	0.13	0.43	0.20	-7.80E-02	-0.34	-0.12
280.0	9.06E-02	0.74	0.56	-0.12	0.50	0.20
320.0	5.07E-02	0.97	0.86	-0.16	-0.68	-0.29
360.0	7.50E-02	1.21	1.15	-0.20	-0.85	-0.37
400.0	0.15	2.29	2.25	-0.37	-1.58	-0.71

(The node alignment in our model only allowed data to be collected for the middle of the upper vents)

Velocity @ Middle of East and West Wall Upper Vents

	EAST WALL	WEST WALL
Time (s)	V (m/s)	V (m/s)
0.0	0.00	0.00
40.0	0.71	0.75
80.0	1.54	1.62
120.0	2.08	2.11
160.0	2.24	2.31
200.0	2.58	2.70
240.0	2.90	3.03
280.0	3.10	3.24
320.0	3.22	3.37
360.0	3.25	3.42
400.0	2.03	2.17

Variation in velocity reflects are movement affected by the two objects in the space.

Interface Height

In order to extract an interface height, we used two different methods.

The first method was to simply use the 3D contour visual aids provided by JASMINE (see pictures) to see the change in temperature in the test hall. We were then able to change temperature contours to represent a two layer 3D picture. Placing the grid spacing over this contour picture we were able to find the interface height. This became more difficult as the mixing of temperature layers increased as the time period increased. The following table shows the interface height (in terms of distance from the floor):

Time (s)	Layer Height (m) (Contour)	Layer height (m) (NIST)
0.0	15.84	15.84
40.0	15.84	15.84
80.0	13.84	12.06
120.0	10.8	8.6
160.0	7.98	4.89
200.0	6.84	4.81
240.0	5.4	3.36
280.0	4.38	2.76
320.0	3.4	1.53
360.0	2.0	1.09
400.0	1.0	.24

(Contour means first method, NIST means second method below)

The second method was drawn form the Journal of Research of the National Institute of Standards and Technology, "Data for Room Fire Model Comparisons," (Peacock, Davis, & Babrauskas, 96,4,1991). This paper describes a method to" take a limited number of point-wise measurements to determine a layer interface and temperature."

Here are the steps taken to obtain data using this method:

1. Temperature data for all three thermocouple trees was averaged at each thermocouple height (as suggested in the Benchmark Exercise)
2. As described by Peacock, Davis & Babrauskas, the equivalent two layer zone height is the height where the data temperature equals Tn, where . In this equation, Cn is a coefficient, normally .2, Tb is the temperature at the bottom of the room. Tmax is the maximum temperature.
3. Also described by Peacock, Davis, & Babrauskas, the interface height is calculated by iterating between data points to find the interface height at Tn.
4. The upper layer temperature is the average temperature from all three thermocouple trees above the interface height.

Thermocouples above fire
The temperature at two thermocouples above the fire:

Time (s)	TG.1 (^{0}C)	TG.2 (^{0}C)
0.0	20.0	20.0
40.0	122	21.0
80.0	573	136
120.0	218	85
160.0	385	123
200.0	496	174
240.0	681	188
280.0	641	192
320.0	656	197
360.0	670	208
400.0	173	118

The upper layer temperature:

Again, we used both JASMINE 3D contours and the NIST method described above.

Time (s)	Upper Layer Temperature (Contour)	Upper Layer Temperature (NIST)
0.0	--	--
40.0	--	--
80.0	29.4	31.5
120.0	40.5	39.2
160.0	42.5	43.1
200.0	47	50.9
240.0	56.6	53.8
280.0	57.1	58.8
320.0	63.2	63.1
360.0	66.9	66.6
400.0	68.8	68

The total heat release within the whole hall is **513.2 MJ.**

1. Conclusion:

As participants in this international exercise, we do not have access to the measured results from the experiment to compare our modeled results. Therefore, we cannot comment on how comparing our model results with the experimental data.

However, our results appear to be reasonable and comparable to other groups within our class. More importantly we have proven that computer fire model results cannot be taken at face value as hard and fact predictions for building evaluation or design. CFD models are powerful tools and a complex model such as JASMINE can be used to provide more accurate results then most computer simulations. However, a tool such as this can be dangerous. Basic knowledge of fire dynamics and fire protection engineering may allow a user to obtain results from these models that may not be accurate or worse, not conservative. In order to achieve results that can be used in building evaluation and design, the user needs extensive fire dynamics and fire protection engineering experience couple with total understanding of CFD and the computer model at hand. Our experience in this exercise highlights the need for great caution when making fire protection decisions based on fire model simulations.

Appendix 1 Part 1, Case 1 HRR vs Time curve

Appendix 2 JASMINE 3D representation of initial geometry

Appendix 3 JASMINE 3D representation of final geometry

FP 571: Performance Based Design
Benchmark Exercise #2: Fire in a Large Hall
February 25, 2002

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Garrett Kaye

Introduction:

As part of the curriculum for Professor Barnett's Performance Based Design course (FP571, Spring 2002), our class is participating in the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. Specifically, we are dealing with Benchmark Exercise #2, which is entitled "Fire in a Large Hall". Our class of nine students was divided into three separate groups, and each group was assigned a different computer model to evaluate the scenario described later in this paper. It is important to note that we were told to ignore the fact that the hall is actually a nuclear power plant facility, and simply model the space as a large hall. This is because as fire protection engineering students, our main concern is to determine how accurately fire models can represent fires in a large space, rather than dealing with any additional nuclear power related complexities.

Case1:

Large Hall
Dimensions: 27 m x 13.8 m x 19 m
Pitched roof
Two large obstructions on floor
Fire source located 16m from west wall and 7.4 m from south wall
Heptane pool fire with a diameter of 1.17 m

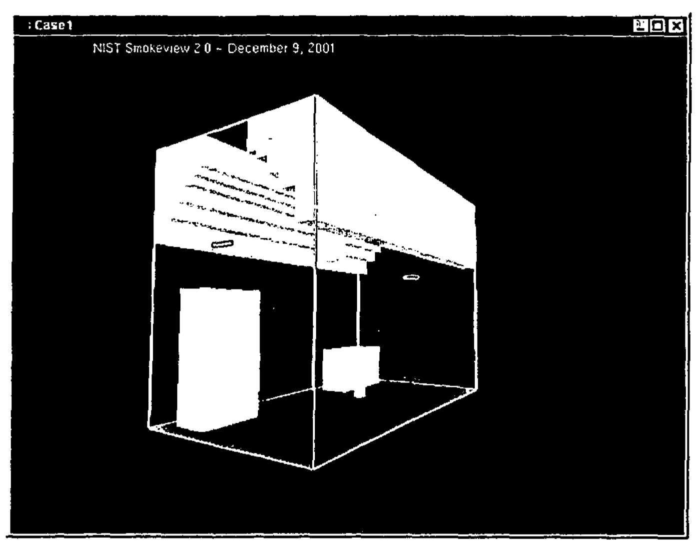


Figure1: Picture of modeled space

The Fire Model:

Our class looked at a total of three (3) computer fire models: two computational fluid dynamics (CFD) models, and one zone model. The CFD models we looked at are called Fire Dynamics Simulator (FDS) and Jasmine, respectively, while the zone model is called CFast. Our group was assigned the FDS model.

FDS is a CFD model of fire-driven fluid flow, developed by the National Institute of Standards and Technology (NIST). FDS software numerically solves a form of the Navier-Stokes equations, and is appropriate for low-speed, thermally driven flow with an emphasis on the smoke and heat transport from fires. The first version of FDS was released in February 2000, while the second version was released recently in December 2001. Both versions of FDS are written in Fortran.

The Combustion Model:

Our group chose to use the second version of FDS for Benchmark Exercise #2 because of the improvements that were made since the first version was released. The first version of FDS contains a relatively simple combustion model that utilizes "thermal elements". Thermal elements are "massless" particles convected with a flow and heat release at a specified rate. According to the user manual[1], this model is easy to implement and relatively cheap computationally; however, it lacks the necessary physics to accommodate under ventilated fires.

The second version of FDS is more comprehensive, and handles oxygen consumption more naturally by solving an equation for a conserved scalar quantity, known as the "mixture fraction". The mixture fraction is defined as the fraction of gas at a given point in the flow field that originated as fuel. The model assumes that combustion is mixing-controlled, and that the reaction of fuel and oxygen happens infinitely fast (i.e. instantaneously). The mass fractions of all the major reactants and products can be derived from the mixture fraction by means of "state relations", which are empirical expressions solved by a combination of simplified analysis and measurement.[1]

FDS is based on a set of complex equations that describe the transport of mass, momentum, and energy resulting from fire-induced flows. However, the actual forms of the equations that FDS uses have been simplified to reduce the calculation time required. The technical user manual[2] says that this simplification of equations is justified because the general equations of fluid dynamics describe a rich variety of physical processes, many of which have nothing to do with fires. As a result of this simplification, FDS models scenarios as quasi-steady, where the characteristics of each cell (such as gas temperature and velocity) are uniform throughout the cell at any given time. The accuracy with which the actual fire dynamics can be simulated therefore depends on the number of cells that can be incorporated into the simulation, which is ultimately limited by the performance of the computer used to run the simulation. Given the processing speed and memory of today's computers, simulations are typically limited to less than one million cells. In real life, combustion processes take place at scales of 1 mm or less, while the scales associated with building fires are on the order of meters to 10's of meters. Therefore, in order to simulate all relevant fire processes, the range of scales for length that need to be accounted for is roughly 10^4 to 10^5. The lesson to be learned from all of this is that FDS cell size and distribution could have a significant impact on the accuracy of results.

FDS Input:

The FDS input file is a text file with the file extension '*.data'. In the input file, the name of the output files need to be specified. If this detail is forgotten, earlier output files with the same case name will be overwritten and the data will be lost. The input file determines the characteristics of the fire scenario through written Fortran code. Listed are some of the inputs for this exercise, however this is not a complete list of all the variables that can be specified:

- Time limit for the run
- Global parameters
- Describing the fire,
- Physical dimensions (x, y and z),
- Cell distributions (x, y and z),
- Obstructions
- Boundary conditions
- Vents
- Detectors and thermocouples
- Output files

In addition to the input file there is a database file that gives the user the ability to specify thermal properties for different materials. There are several default properties given by NIST that the user can utilize.

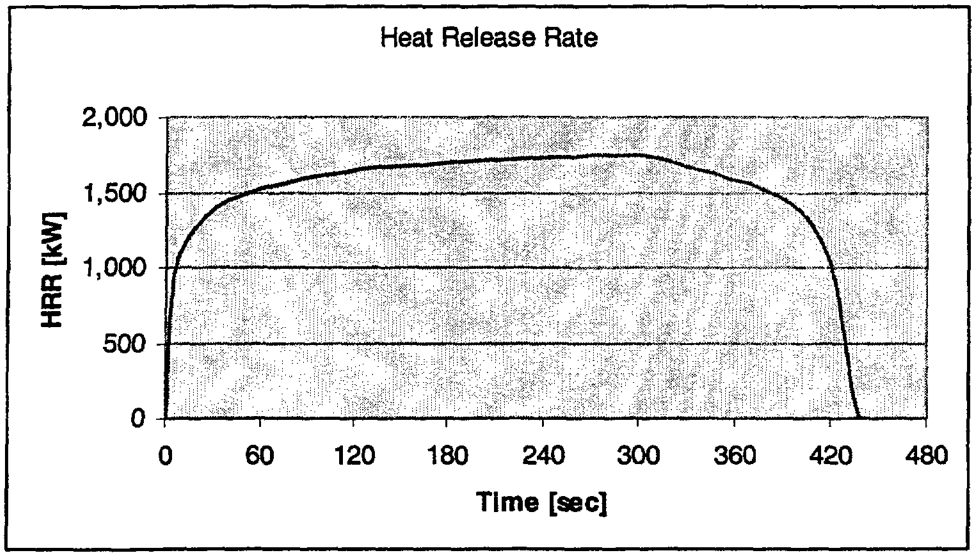
The input file is written by the user and is the only way for the user to affect how FDS will do calculations. Since the user must write the input in code, this gives an unnecessary dependence between the results and the user's knowledge of FDS and Fortran code.

Benchmark Exercise No. 2, Case 1:

As mentioned previously, case 1 is a small fire with only natural ventilation.

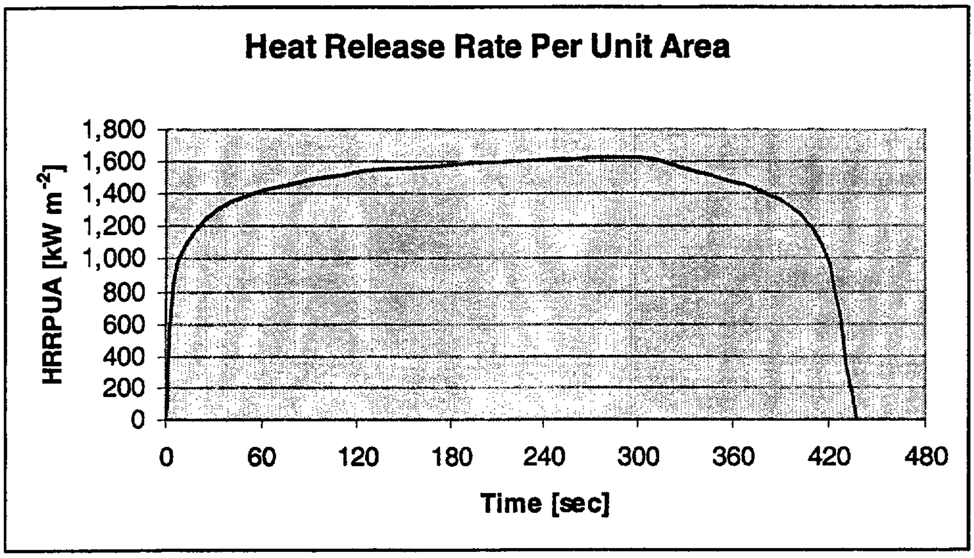
The Fire:

In the handout, the fire is described using mass loss rates at given times during the fire. Using this data with the heat of combustion (ΔH_c) for heptane, a heat release rate for the fire is easily created. Furthermore this gives us the possibility to specify a heat release rate per unit area. Since this is a pool fire, it is reasonable to assume the fire to grow instantaneous after ignition and no growth time normally associated with t^2 fires.



The decay period of the fire can be specified using FDS by inputting when a decline occurs in the hear release rate at a certain time in the simulation. This requires more understanding on Fortran code which is beyond the knowledge of our group, so we only ran the simulation for 300 seconds.

With a fire area of 1.09m^2, the heat release rate per unit area can easily calculated which gives the following graphical presentation.



Physical Dimensions and Cell Grid:

FDS allows the user to specify the physical dimensions and number of cells associated with each direction. Unless otherwise instructed, FDS will distribute the cells normally over each dimension. A Poisson solver based on Fast Fourier Transforms in the calculations also limits the number of cells in each direction. The dimensions of the grid should be of the form $2^m3^n5^l$, where m, n and l are integers. A good example of how this works is the number 72, which can be written as: 2^33^3; however numbers like 51, 73, and 109 cannot be specified.

Since all surfaces must line up with the grid, no objects or other physical shapes can be circular or diagonal. In this exercise the roof is diagonal, and the fire and mechanical vent is circular. For those shapes, an equivalent area must be found that will simulate the same shapes.

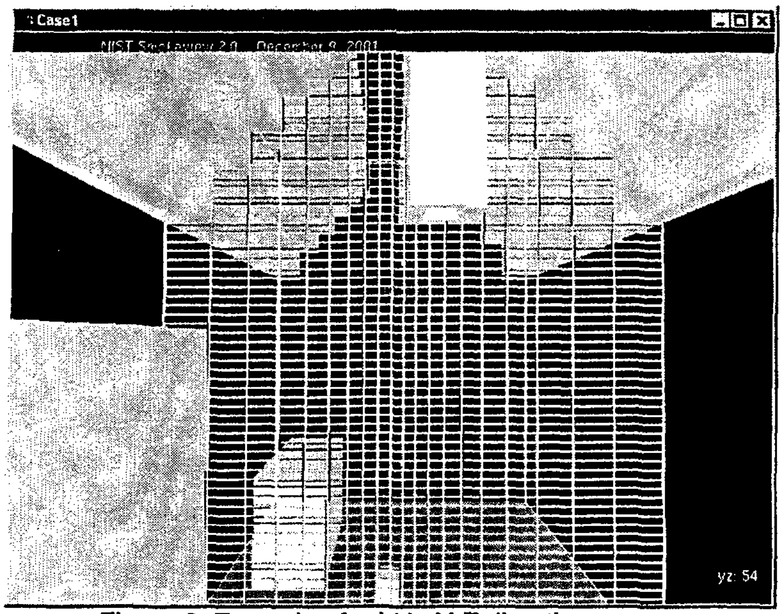


Figure 2: Example of grid in Y-Z direction

FDS gives the user the option to concentrate cells around areas of interest which helps minimize the number of cells used. This in turn reduces the computational time of the scenario. This option is described later in the sensitivity study.

Fire, Objects and Vents

The fire is located 1m above the floor near the center of the room and there are two large rectangular objects on the floor in the hall. The surfaces of these two obstructions were modeled as concrete, with properties specified in the handout. This is fairly easy incorporated in the input file. All objects in the hall must be given specific x, y and z values describing where they are located (x1,x2, y1,y2, z1,z2). If the dimensions do not line up with the grid, FDS will move them to the closest grid. This is because all calculations are done from cell to cell and there can not be anything dividing a cell.

When modeling the roof geometry, there is a trade off between surface area and volume since there cannot be any diagonal lines. Instead we had to make the roof with only vertical and horizontal lines thus making it look like steps. This will impact the flow near the roof, but FDS2 does have a solution to this problem. To lessen the impact from these steps, a parameter must be written into each surface line in the input file. According to the user manual[1], this is not a perfect solution to the problem, but it does lessen the impact from velocities around sharp corners.

Surfaces

As mentioned earlier, the obstructions inside the hall are simulated as concrete blocks. The floor is also concrete, while the walls and the roof is a combination of sheet metal and mineral wool. According to the user manual[1], FDS has the capability to simulate sheet metal over an insulated surface. However, while trying this option, the program would not start and gave an error for the surface. Even with the default sheet metal in the database file given by NIST, the same error occurred. Describing a surface as only mineral wool was possible, but to see if there were any significant differences in the results, several runs with different surfaces were done. Details regarding this are discussed later in the report.

A solid surfaces affected by convective or radiative heat transfer from the surrounding gasses can be specified as either thermally-thin or thermally-thick.

Specifying the thermal properties of the surface in the database file does this. For thermally-thin surfaces, a product of the specific heat, density and the thickness of the layer are specified. A thermally-thin layer can further be specified as insulated so no heat is lost to the backing material. Thermally-thick surfaces are specified through the thermal diffusivity, the thermal conductivity and the thickness of the material. Setting these parameters will direct the code to perform a one-dimensional heat transfer calculation across the thickness of the material. In neither case does the heat get transferred through the entire wall into the next room, but for this case it doesn't matter since we are only modeling one room.

Runs

As a part of the sensitivity study, several runs were completed. The differences in these runs were:

- Number of cells
- Cell distribution
- Surfaces
- Heat release rate

	Case1a	Case1b	Case1c	Case1d	Case1e*
HRRPUA	1700 kW m^{-2}	1700 kW m^{-2}	1700 kW m^{-2}	1500 kW m^{-2}	1700 kW m^{-2}
Surfaces	Concrete and mineral wool	**All concrete**	Concrete and mineral wool	Concrete and mineral wool	Concrete and **insulated sheet metal**
Pdim./ cells	x- 27m/108 y- 13.8m/30 z- 19m/75	x- 27m/108 y- 13.8m/30 z- 19m/75	x- 27m/108 y- 13.8/56 z-19m/75	x- 27m/108 y- 13.8m/30 z- 19m/75	x- 27m/108 y- 13.8m/30 z- 19m/75
Cell distribution	Transformed in the y-dir.	Transformed in the y- dir.	**Normal**	Transformed in the y-dir.	Transformed in the y dir.

* Case1e did not work

We used Case1a as the base run, while the other runs where done to see if the changes had any significant impact on the results. Case1e was supposed to be the base run, but since this case did not give any results we had to choose another one.

Sensitivity Study:

Surface, for the different surfaces the difference in 'All concrete' and the 'Concrete and mineral wool' runs showed some difference in the heat of the smoke layer. The difference was not significant, but in the order of about 10% lower for the temperature rating of the thermo-couples. The change in the thermal values for the surfaces are of the wall might give different values for the hole run, so to be conservative the higher temperature will give more severe results.

The grid size and grid spacing is of more interest. The runs with denser cells around the fire had fewer cells than the runs with a normal distribution of cells. There could not be found any change, less than 5% in the temperature ratings, but the number of tracer-particles fell drastically with normal distribution. This is expected from the fact that the fire will happen in an area of fewer cells and this will have an effect in how the fire will 'burn' in the model. The details regarding this is outside the knowledge of the members of the group, but as long the runs with fewer, but denser cells around the fire, give somewhat same results we can assume that this error is within the expected range.

Changing the fire size give lower themperature reading of the thermo-couples, as expected. The model is reacting to the change in the heat release input, so the model is not doing anything unexpected here.

Results

Finding the smoke layer is not easily determined with a CFD model. The visual output in 'Smokeview' show the tracer particles as the model runs. From these visual readings, it is shown that the smoke layer is not descending below 4 meters, which is the height of the smaller object in the space.

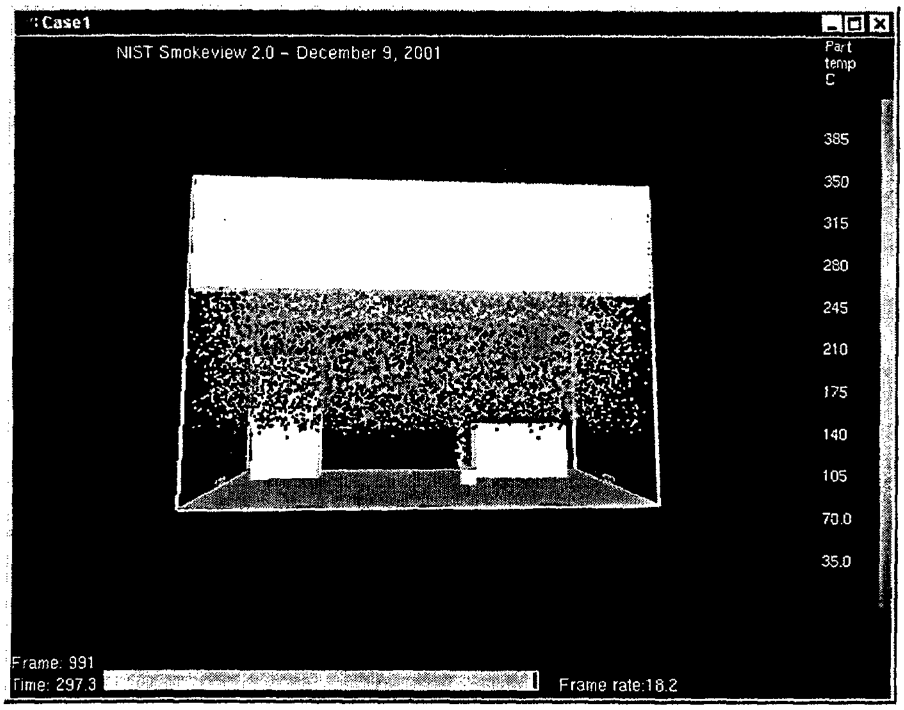


Figure 3: Smoke layer interface at 300s

In the handout, a method is described using the temperatures given by the thermocouples. This method uses a one-dimensional analysis utilizing upper and lower temperatures and conservation of mass.

$$(H - z_{int})T_{up} + z_{int}T_{low} = \int_0^H T(z)dz = I_1$$

$$(H - z_{int})T_{up} + z_{int}\frac{1}{T_{low}} = \int_0^H \frac{1}{T(z)}dz = I_2$$

which can be rewritten as

$$z_{int} = \frac{T_{low}\left(I_1 I_2 - H^2\right)}{I_1 + I_2 T_{low}^2 - 2T_{low}H}$$

Where T_{low} is the temperature at the lowest discrete measurement location (TN.1) and I_1 and I_2 are calculated from the discrete data set using a quadrature rule, e.g. Simpson's Rule. T_{up} is then calculated by applying the mean value theorem over the integral $z=z_{int}$ to $z=H$

$$T_{up} = \frac{1}{H - z_{int}} \int_{z_{int}}^{H} T(z)dz$$

Mass Flow Rates

For Case1 there was only natural leakage. In order to simulate this, four openings to the exterior were placed on the east and west walls. The location and size of the vents were specified in the handout.

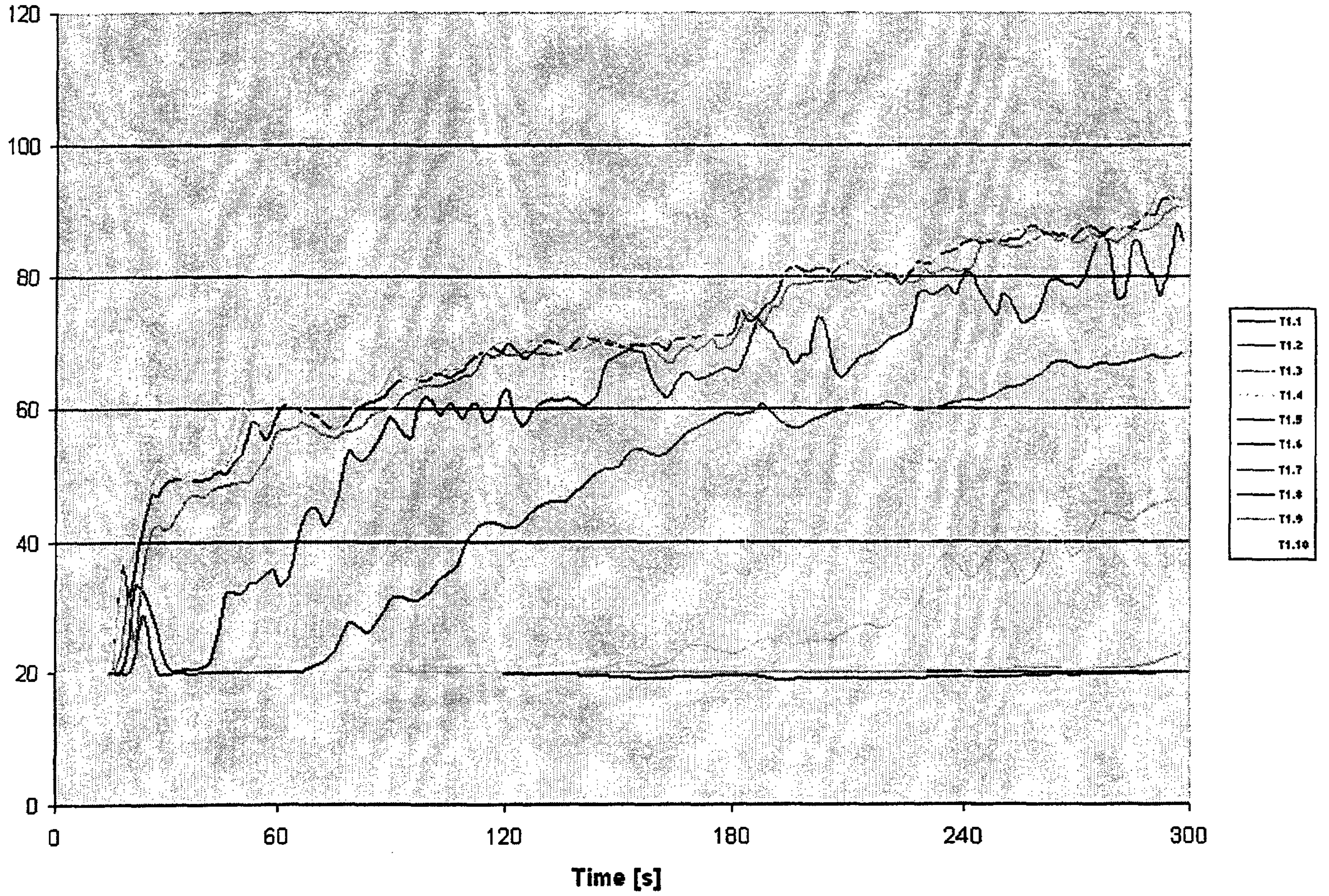
FDS2 uses thermocouples to measure different quantities. So a thermocouple can measure temperature and velocities as well as other characteristics. Locating thermocouples near the vent openings and measuring the velocities at those openings found the mass flow rates. The mass flow rate can then be found by assuming a uniform velocity throughout the opening. Where positive direction is into the enclosure.

Location	Velocity [m/sec]	Density [m^3/kg]	Area [m^2]	Mass flow rate [kg/sec]
West, bottom	1.7	1.20	0.5	1.0
West, top	-2.6	1.07	0.5	-1.4
East, bottom	1.7	1.20	0.5	1.0
East, top	-2.6	1.07	0.5	-1.4

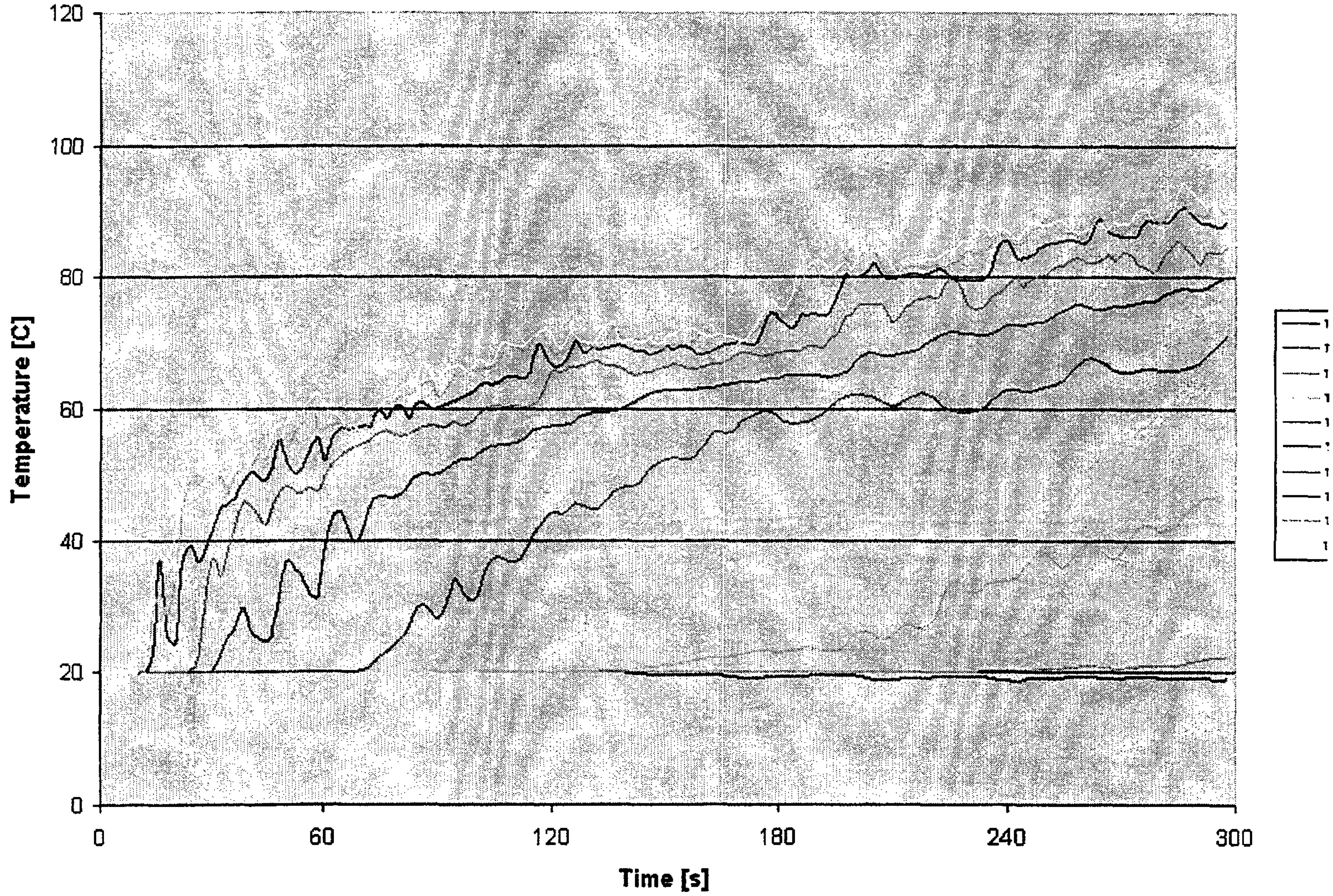
Total heat loss can be measured, but only as a visual presentation through Smokeview. The technical way of showing this is found in the Smokeview user manual, but it must be specified in the input data file. The heat loss is shown as a change in the color on the surfaces. This feature takes a lot of computational time and was only done in the base run. The smoke view file and the associated files take a lot of computer storage space and will be made available on a CD. Another way of measuring heat loss to the walls is to place thermocouples along that are, but the uncertainty in the location and number of thermocouples needed were outside the limits of this group.

The upper layer temperature was found with the thermocouples in the building. A total of three (3) thermocouple trees were located in the space. The temperature measuring of these trees are presented below in charts.

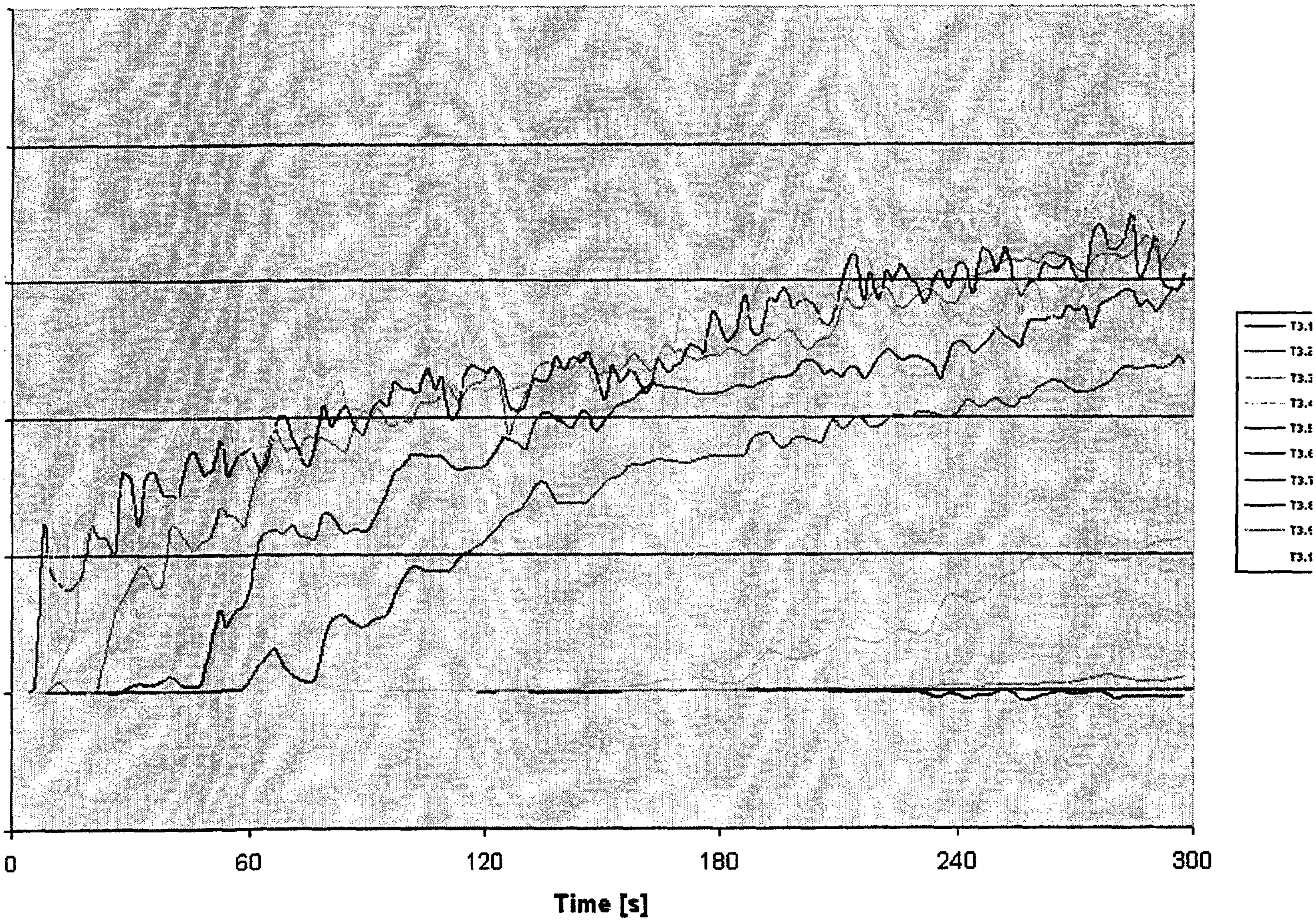
Thermocouple Tree 1



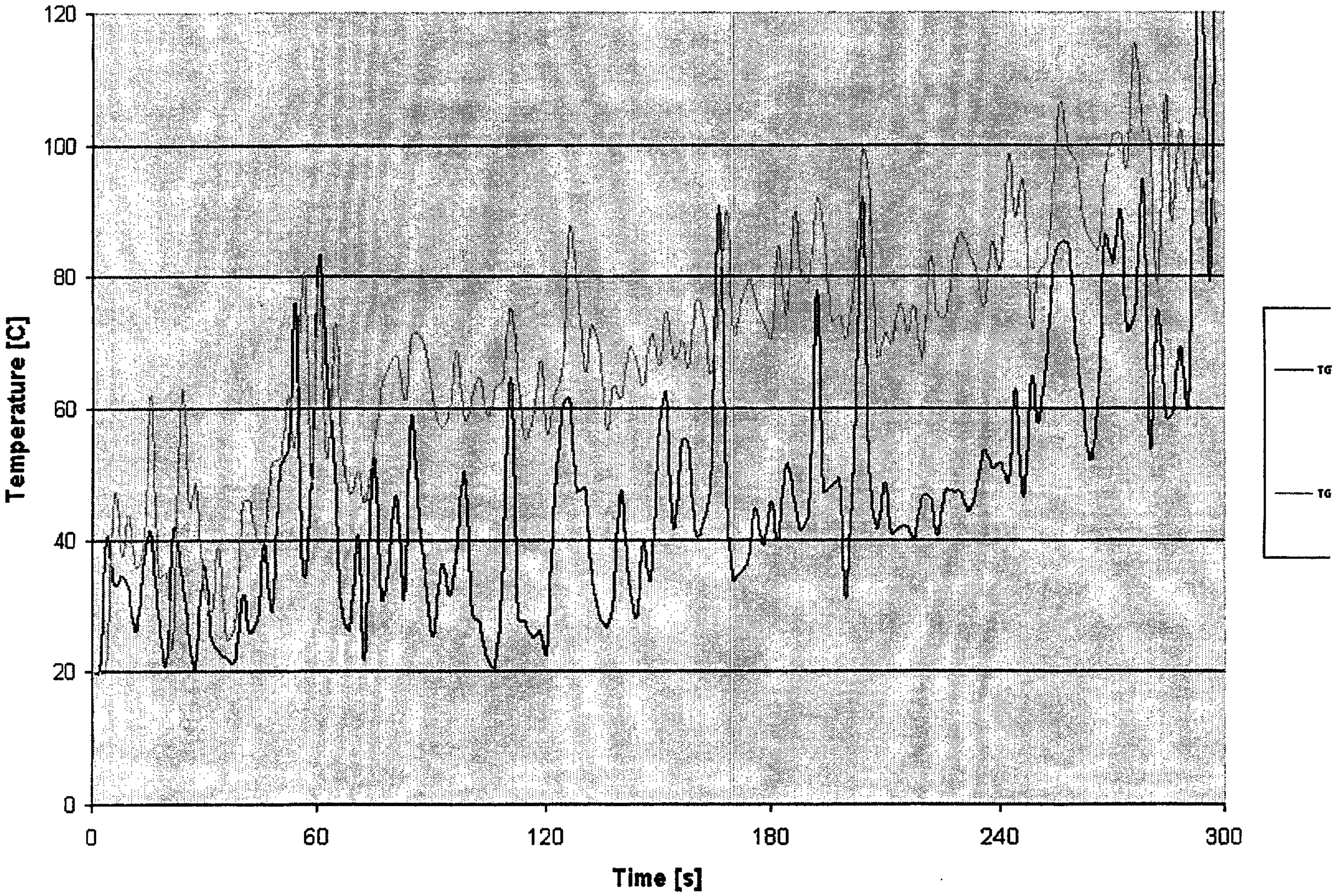
Thermocouple Tree 2



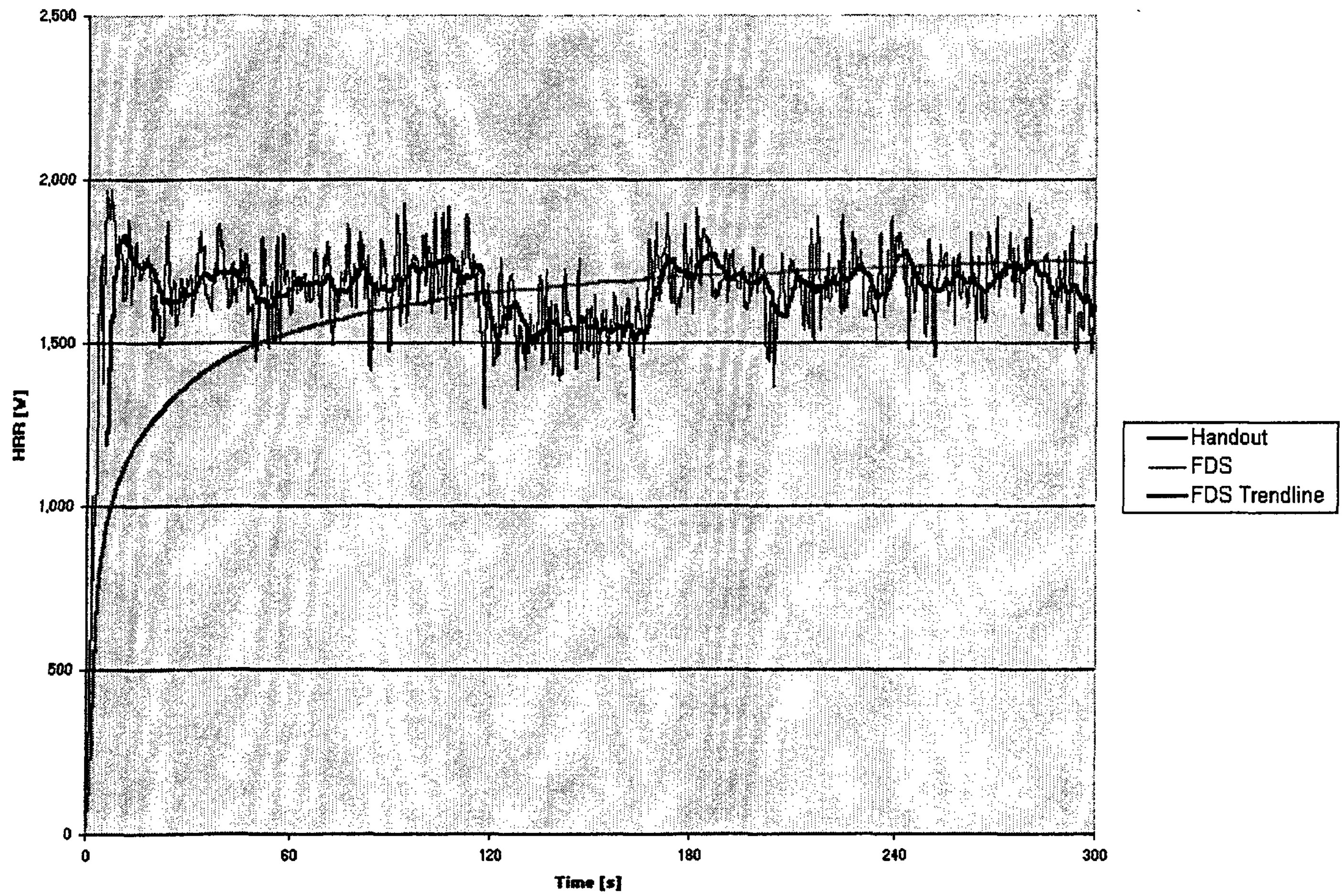
Thermocouple Tree 3



Plume Thermocouples



Heat Release Rate



Reference:

1. Fire Dynemics Simulator (Version 2) – User's Guide, Kevin B. McGrattan et al, NIST, November, 2001
2. Fire Dynamics Simulator (Version 2) – Technical Reference Guide, Kevin B. McGrattan et al, NIST, November, 2001
3. Handout regarding Benchmark 2 exercise

Analysis of Benchmark Exercise Two: An Examination of Large Turbine Hall Fires with the CFAST Fire Modeling Code

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The Savannah River Site (SRS) has an obligation to fulfill Department of Energy (DOE) expectations[1, 2]. The DOE expectation is that software quality assurance (SQA) is in place that will ensure that computer software will perform its intended functions in a consistent manner and that software modifications will not result in unanticipated problems. SRS is in the process of improving the site SQA program.

The SQA program is currently being applied to CFAST, Version 3.1.6. In the process, code capabilities and limitations are being evaluated. A typical problem requiring analysis at SRS is evaluating heat transfer to a liquid filled process tank and estimating evaporation from the tank. An understanding of how to accomplish this using the output available from CFAST is required. In addition, several sample problems must be established that provide input and output so that, when the code is initially installed, it can be demonstrated that the installation was successful.

As part of the SQA effort, Benchmark Exercise 1 (Part 1) was developed into a sample problem format and work is in progress on Benchmark Exercise 2 (Part 1) for use as an additional sample problem. Under this present effort, preliminary evaluation of Benchmark Exercise 2 (Part 1) has been completed for cases 1, 2 and 3. Since CFAST is limited to a rectangular geometry, the ceiling height was adjusted to 15.84 m to maintain the turbine hall volume. A lower oxygen limit of 12%, as used in Benchmark Exercise 1, a radiative fraction of 20% and a relative humidity of 50% were used. For the wall layers, the specification stated sheet metal on top of mineral wool. A three layer material with mineral wool (5 cm thick) between two layers of sheet metal (each layer 1 mm thick) was created. Pyrolysis rates and ventilation conditions are as identified in the specification for part one of Benchmark Exercise 2.

In conclusion, SRS is charged with verifying and validating the CFAST software. Demonstration of code capabilities and limitations as well as establishment of sample problems has been accomplished by exercising benchmark problems 1 and 2. In addition, a non-fire mechanical ventilation flow case has been established.

[1] Implementation Guide for use with DOE Orders 420.1 and 440.1 Fire Safety Program. G-420.1/B-0 G-440.1/E-0. September 30, 1995.

[2] Quality Assurance for Safety-Related Software at Department of Energy Defense Nuclear Facilities. DNFSB/TECH-25. January 2000.

Large Eddy Simulations of Fire Tests in a Large Hall

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In cooperation with the fire protection engineering community, a numerical fire model, Fire Dynamics Simulator (FDS), is being developed at NIST to study fire behavior and to evaluate the performance of fire protection systems in buildings. Version 2 of FDS was publicly released in December 2001 [1, 2]. The model is based on the low Mach number form of the Navier-Stokes equations and uses a large eddy simulation (LES) technique to represent unresolved, sub-grid scale motion. The fire is modeled by solving a transport equation for the conserved scalar quantity known as the mixture fraction, a linear combination of the fuel and oxygen that indicates the mass fraction of the gas originating as fuel. The advantage of the mixture fraction approach is that all of the species transport equations are combined into one, reducing the computational cost. Thermal radiation is modeled by solving the radiative transport equation for a non-scattering gray gas using what is known as the Finite Volume Method [3]. Using approximately 100 angles, the finite volume solver requires about 15% of the total CPU time of a calculation, a modest cost given the complexity of radiation heat transfer.

FDS has recently been applied to a series of benchmark fire tests performed as part of the "International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications." The tests analyzed here make up Benchmark Exercise #2. Three fire tests were performed in a large fire test hall. In each, a pool of heptane was burned for about 5 minutes, during which time gas temperatures were measured in three vertical arrays and at two points within the fire plume. The fire size and ventilation configurations were changed from test to test. Details of the tests can be found in these same proceedings.

The heat release rate of the fires in each case was calculated from the measured mass loss rate of fuel, thus the model is not making a prediction of the total energy output. While it is possible to predict the fraction of the total energy output that is emitted from the fire as thermal radiation, we chose to apply an empirical fraction of 35 % based on numerous experiments. The purpose of the numerical model in this exercise is to predict how the energy from the fire is transported throughout the test hall as a function of time. The key to handling this problem properly is to simulate well the mixing of hot combustion products and fresh air within the fire plume. The technique adopted by FDS for this purpose, Large Eddy Simulation (LES), is not widely used in the fire community because of the extensive development of various Reynolds-Averaged Navier-Stokes (RANS) models, some of which are demonstrated within these proceedings. The benefit of LES over RANS is that it renders a more faithful representation of the fire and plume dynamics because it captures fluid motion at length and time scales consistent with the underlying numerical grid. For example, animations of the fire and smoke plume show the pulsating and oscillating behavior observed in actual experiments. With the RANS approach, this motion is filtered out and the fire and plume are rendered as time-averages of the actual flow fields. While both approaches have been demonstrated to work in a variety of fire applications, we believe that that LES approach will eventually be adopted more widely because of its more faithful rendering of fire behavior.

Of course, the outcome of an LES calculation is only as good as the underlying numerical grid. If the governing equations of motion are approximated on a numerical grid whose cells are too large relative to the characteristic length scales of the fire or fire plume, not only will the realistic fluid dynamics be lost, but the mixing will be under-estimated, and in the case here, the upper layer temperatures predicted by the model will be hotter than those measured. For this reason, up to now the LES technique has not been considered of practical use to the fire protection engineer. What has made the technique useful is faster, cheaper computers and better numerical methods. A recent advancement for FDS has been the implementation of multiblock gridding, that is, the use of more than one structured numerical grid in a single simulation. Until recently, FDS used a single uniformly-spaced rectangular mesh to divide up a largely rectangular space into hundreds of thousands or millions of cells. The benefit is ease-of-use, the downside is that it is difficult to adequately resolve the numerical grid in regions of interest, like the fire plume, when a large space is to be modeled. Preliminary calculations of the benchmark fire tests required on the order of 80 CPU hours on a 1.7 Ghz Pentium IV processor. By using more than one numerical grid, the CPU time was reduced to 20 hours, and the resolution in the region of the fire and plume was improved.

The figures in the accompanying presentation show the geometry of the test hall and the layout of the various numerical grids used in the simulation. The finest grid surrounding the fire is 4 m by 4 m by 10 m high, with grid cells 13 cm on a side. Five other separate grids are used to cover the rest of the space at a resolution of 40 cm. Within each grid, the cells are uniform in size. In all, 216,000 grid cells are used in the calculation. Ten minutes of real time are simulated. Some simplifications to the geometry include making the burner and the exhaust duct square rather than round, and approximating the sloped ceiling as a series of stair steps. Otherwise, everything else is as specified in the problem description. Heptane (C_7H_{16}) is used as a fuel. Temperature and velocity predictions are recorded at all of the specified locations.

The results of the three calculations agree well with the measurements. For Test 1, the predicted temperatures at the 5 upper thermocouple locations in each array are within 10 °C of the measured temperatures, usually on the high side. The lower 5 temperature locations show good agreement as well, with the greatest difference being for the lowest two thermocouples, which under-predict the measured temperatures by roughly 10 °C. Given slightly higher temperatures in the upper layer, it is not surprising to see slightly lower temperatures somewhere else since the model is energy conserving. The model assumes that there is no air movement in the hall except for that induced by the fire or the ventilation system, thus one would expect for the level of mixing to be slightly under-predicted. The prediction of the temperature at the lower thermocouple location in the fire plume is about 100 °C higher than the measurement. The prediction at the higher location is about 10 °C higher.

For Test 2, the agreement between model and experiment is better than in Test 1. The reason for this is that the predicted and measured temperatures within the plume are within 10 °C of one another. The simulations of Tests 1 and 2 were conducted with the exact same gridding and assumptions. The reason for the better agreement in Test 2 stems from the better agreement in the plume itself. In general, for a given level of grid refinement, a larger fire is easier to model than a smaller one, as in this instance. Another explanation of disagreement in plume temperatures is that often in large scale fire tests air movements within the test space throw the fire plume slightly off of its natural centerline, in which case numerical predictions are often high. In any case, in all three tests, the agreement between model and experiment at the upper plume thermocouple location is within 10 °C meaning that the gases filling the hot upper layer are within a very close range to the actual gas temperatures.

When these calculations were first attempted with a single numerical grid spanning the entire hall with cells between 20 and 30 cm in size, the temperatures in the upper layer were over-predicted. The difference in predicted and measured temperatures was reduced as the grid cells in the region of the fire were reduced in size. This effect is made obvious by looking at animations of temperature contour plots through a vertical centerline plane. When the grid cells are too large to resolve the eddies that entrain fresh air into the plume, the hot gases are not diluted as much in the simulation as in reality, and upper layer temperatures tend to be over-predicted. As in many studies we have performed in the past on fire plumes, we find that very good agreement with experiment is achieved when the fire is spanned by roughly 6 to 8 grid cells. Of course more is better, but this level of resolution has been found to produce very good results at a modest computational cost. Research continues to reduce computational effort by means of the multiple grids employed here, plus parallel processing of the different grids.

[1] K.B. McGrattan, H.R. Baum, R.G. Rehm, G.P. Forney, J.E. Floyd, and S. Hostikka. Fire Dynamics Simulator (Version 2), Technical Reference Guide. Technical Report NISTIR 6783, National Institute of Standards and Technology, Gaithersburg, Maryland, November 2001.

[2] K.B. McGrattan, G.P. Forney, J.E. Floyd, and S. Hostikka. Fire Dynamics Simulator (Version 2), User's Guide. Technical Report NISTIR 6784, National Institute of Standards and Technology, Gaithersburg, Maryland, November 2001.

[3] S. Hostikka, H.R. Baum, and K.B. McGrattan. Large Eddy Simulations of the Cone Calorimeter. In *Proceedings of US Section Meeting of the Combustion Institute, Oakland, California*, March 2001.

5th meeting of the International Collaborative Fire Model Project

Preliminary Results for Benchmark Exercise # 2 using CFAST and JASMINE

Stewart Miles, Fire and Risk Engineering Centre, BRE, UK

Part I of Benchmark Exercise # 2 is based on a series of fire experiments, performed in the VTT test hall in Finland between 1998 and 1999 as part of the ECSC Steel Research Programme. Each test involved a heptane pool fire one meter above the floor, lasting approximately six minutes. The instrumentation included thermocouple readings at three vertical columns, extending from the floor to the ceiling, and at various locations within the fire plume. These readings provide the main measurements against which numerical predictions are being compared for the current benchmark exercise. The measured temperatures have been processed to give estimates of upper layer temperature and layer height, where it is here assumed that a two-layer representation holds, and these are being used in the comparison against zone model predictions.

The benchmark specification document [1] contains full details of the test hall and the three cases being modelled. This was released in conjunction with a summary of the measurement data against which to compare predictions.

For case 1 and 2 there was no mechanical exhaust and the doorway openings to the hall were closed. However, the building is not airtight, and so the effect of air infiltration must be modelled somehow. The suggested approach [1] is to include four small openings, each of area 0.5 m^2, two at ground level and two at a height of 12 m. For case 3 there was mechanical extraction at 11 $m^3 s^{-1}$ through a duct 12 m above the floor, and for this case the two doors were each opened to an area of 3.2 m^2. An additional complication is provided by the sloping cross-sectional shape of the ceiling, providing a further challenge to zone models in particular.

This extended summary describes briefly some simulations undertaken by the author and the findings drawn from them, and accompanies the presentation slides. Simulations of all three cases have been performed with a zone model (CFAST/FAST version 3.1.6) and a CFD model (JASMINE version 3.1.2). A sensitivity analysis has been undertaken for a number of parameters, including the thermal properties of the walls and ceiling, the size and location of the restricted ventilation openings (cases 1 & 2) and the 'equivalent ceiling height' in the CFAST simulations. A CFD mesh sensitivity analysis has been conducted also.

All CFAST simulations have been performed with a single compartment with one or two horizontal flow vents to the outside, and for case 3 an additional vertical HVAC vent to the outside. The ceiling has been approximated as being flat, and for the majority of simulations was located at a height of 15.84 m, which gives the same enclosure volume as inside the actual test hall. The sensitivity to the choice of ceiling height has been investigated by performing simulations with the ceiling at 13 m and 18 m. The fire source for each case has been defined in terms of the specified time-dependent pyrolysis rate and a heat of combustion of 44.6×10^6 J kg^{-1}. Furthermore, the radiative fraction was set to 0.2. For the 'baseline' simulations the walls and ceiling were defined as conducting boundaries consisting of sheet steel on top of mineral wool, with thermal properties and thicknesses as specified in the problem definition. The sensitivity to the choice of thermal boundary condition at the walls and ceiling has been investigated by using sheet metal only, mineral wool only and non-conducting (adiabatic) boundaries.

A further parameter that has been investigated in the CFAST simulations for cases 1 and 2 is the size and location of the restricted ventilation wall openings for the 'infiltration' process. Here the four original 0.5 m^2 openings have been replaced by four 0.01 m^2 openings in one simulation and by two large openings of 16 m^2 (at floor level only) in another. The effect of increasing and decreasing the height above ground of the upper openings in the original specification has been investigated also. Note that in the CFAST simulations, where there are two vents at the same distance from the floor they are combined into a single opening (with an area equal to the sum of that for the individual openings).

JASMINE simulations of all three cases have been performed. The geometry of the test hall was modelled as accurately as possible with a Cartesian mesh, with the result that the sloping sections of the ceiling were approximated by a staggered (staircase) boundary. This gives the correct volume within the ceiling space, but will have some influence on the heat and momentum transfer at these sections of the ceiling. JASMINE models the Reynolds Averaged Navier Stokes (RANS) equations of fluid motion, and employs a κ-ε turbulence model to represent the effect of the turbulent motions on the flow field. Time-dependent simulations were performed using a one-second time-step and the fuel pyrolysis rate given in benchmark specification. An eddy break-up combustion model was employed, using a single step reaction mechanism for heptane and an effective heat of combustion of $0.8 \times 44.6 \times 10^{6}$ J kg^{-1}. Radiation transfer was calculated using a six-flux model, combined with an emissive power model to calculate the radiation exchange from CO_2 and H_2O combustion products.

Convection and radiation heat transfer to the solid boundaries was included. Conduction into the boundaries was calculated approximately using the concept of a time-dependent conduction depth into a semi-infinite material. Furthermore, the steel sheet was ignored in these calculations, so that the conduction losses will in general have been under-estimated. However, the conductivity of the solid was increased for some simulations to investigate the effect of increased conduction losses on the gas temperatures and smoke layer height.

The ventilation openings have been modelled exactly as specified. However, additional simulations have been performed for case 1 with narrow slot openings instead of the square ones (but with the area of each maintained at 0.5 m^2), and with partially porous east and west walls, where the porosity was set to give an equivalent flow area as the vents.

A numerical mesh containing approximately 130,000 elements was used in most of the simulations. A mesh refinement study was performed for two simulations, where the first 60 seconds was repeated using a mesh containing eight times as many elements, i.e. the resolution was increased by a factor of two in each direction.

The preliminary results from the CFAST and JASMINE simulations are reasonably encouraging and informative. Comparison plots of predicted and measured temperatures and layer depths are shown in the presentation slides. The effect of varying conduction losses, ventilation opening sizes etc are illustrated too.

Probably the most important finding, demonstrated by both the zone and CFD models, is the sensitivity of the gas temperatures to the conduction losses to the walls and ceiling. In the CFAST simulations the closest agreement with measurement was obtained by using either a sheet metal and mineral wool two-layer material or by using the sheet metal alone. In the JASMINE simulations the effect of ignoring the steel was apparent, with closer agreement with measurement obtained when the conduction losses were then increased. The results so far seem to indicate that the conduction into the steel is important. The smoke layer height, however, seems to be less sensitive to the boundary conduction loss calculation.

An important issue in the use of the zone model is the choice of 'equivalent ceiling height'. The sensitivity analysis performed so far indicates that while the upper layer temperature is sensitive to the choice of ceiling height, the layer height is sensitive only during the initial stage of the fire.

Both the zone model and CFD simulations indicate that the exact choice of openings in cases 1 & 2, to represent the infiltration process, is not critical. The only exception to this finding was in the CFD simulation with porous walls, which indicated a break down of stratification after about three minutes. However, the physical significance of implementing slightly porous walls in a CFD simulation is somewhat uncertain and this result should be treated with caution at this stage. The CFAST simulation with the very small openings produced high pressures inside the enclosure, at a level that would have been greater than anything achieved in the experiments. This supports the assumption that the building is not particularly airtight.

Reasonable agreement has been shown between measured plume temperatures and those predicted in the JASMINE simulations. The mesh refinement study has indicated some sensitivity to this parameter, with the finer mesh producing results closer to those measured. Further JASMINE simulations are currently being performed to investigate the mesh resolution and boundary conduction issues in more depth.

CFAST and JASMINE simulations will be performed for Part II of Benchmark Exercise # 2. This is a 'hypothetical' example for which there are no experimental measurements. However, the dimensions of the building are greater than in Part I, and have been selected to more closely represent a turbine hall. Full details of the geometry and cases to be modelled are provided in the specification document [1]. The fire source is representative of a large hydrocarbon pool fire. 'Target' cables and beams are included, for which the likelihood of thermal damage is to be estimated. Although the building geometry is rectangular, in some of scenario cases there is the added complexity of an internal ceiling, effectively dividing the space into two connected compartments.

1. Specification for Benchmark Exercise # 2 - Fire in a Large Hall, February 2002.

DETECTOR RESPONSE MODELING

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NFPA International

1.0 INTRODUCTION

The purpose of this paper is to present information regarding current fire detector response modeling. Fire detector response modeling in this paper refers to heat detectors, including sprinkler links. While smoke detectors can be modeled using current heat detection models, this is not highly recommended due to the magnitude of the uncertainties associated with the predictions.

It is hoped that this brief paper will provide sufficient information regarding heat detector modeling such that decisions can made regarding their applicability in nuclear power plants (NPP). If it is decided that the current model is insufficient for such applications, then this paper should provide enough information upon which to base a decision regarding future work.

2.0 DISCUSSION

2.1 Detector Modeling

The overall [smoke] detection process has been organized into five categories; property generation, bulk property transport, local property transport, sensor modulation, and alarm condition. [6] The first three categories are required by all detection models: the fire generates the hazard to be detected; the plume transports the hazard conditions to the ceiling; the ceiling jet transports the hazard condition to the point in space of interest. The final two categories are detector specific: "sensor modulation" can be thought of as modeling how the sensor "knows" what conditions are present; "alarm condition" is essentially the set point of the detector. In the case of a sprinkler or heat detector, sensor modulation models the heat transfer to the sensing device and the alarm condition is either a temperature (range) or a rate of temperature rise.

2.2 DETACT-QS

Currently, DETACT-QS is the only heat detector model that is publicly available. Other fire models may also be used to predict detector activation; however, this is not necessarily their only purpose.

2.2.1 Intent

DETACT was developed to calculate the response time of ceiling mounted heat detectors/sprinklers and smoke detectors, installed under large unobstructed ceilings, for fires with user defined, time dependent heat release rate curves [1]. DETACT is based on quasi-steady ceiling jet assumptions [2,3]. The thermally activated device must be located under the ceiling and within the ceiling jet.

2.2.2 Assumptions and Limitations

1) The detector is ceiling mounted and located at the points of maximum temperature and velocity within the ceiling jet below a ceiling [2]. The detector must be within 6% of the ceiling height from the ceiling [4].

2) The ceiling is unconfined, unobstructed, smooth, flat, and horizontal. The model does not account for hot gas layer effects due to walls or obstructions. The minimum wall to wall distance is 2 to 4 ceiling heights. Vertical obstructions are required to be less than 1% of the ceiling height for the ceiling to be considered smooth [2].

3) Only convective heat transfer is considered between the ceiling jet and the thermal detector; no conductive or radiative heat transfer is considered. The detector is treated as a lumped mass model [5]. The lumped mass model assumes that the thermal gradients are neglected within the thermal element.

4) Smoke detector activation is assumed at a ceiling temperature increase of 13°C [1]. (Although this is a gross over-simplification of the phenomenon, it is an all too commonly used assumption.)

5) Within the plume impingement area, temperature ($r/H \leq 0.18$: r = radial distance between plume centerline and detector; H = height of ceiling above the fuel) and velocities ($r/H \leq 0.15$) are uniform an assumed to be the maximum values in the plume [2].

6) The fuel package and the plume are assumed to be in an unobstructed vertical axis. No ventilation or stratification effects are considered. The heat release rate or the fire needs to be sufficiently large so that the plume can be assumed to be vertical and axisymmetric [2].

7) No transport time (or lag time) is considered for the hot gases to travel from the fuel to the detector [2]. Therefore, increases in heat release rate will effect the temperature and velocity of the ceiling jet immediately.

8) For each heat release rate input interval, the heat release rate is averaged over the interval and assumed constant. Fire heat release rate should not double in less than one minute [2].

9) Detector must be spot type [4].

2.3 SFPE Computer Model Evaluation Task Group Report

2.3.1 Intent

The draft report of the SFPE task group [4] states as its purpose: "This evaluation report provides information on the technical features, theoretical basis, assumptions, limitations, sensitivities and guidance on the use of DETACT. This evaluation is based on comparing predictions from DETACT with results from full-scale fire experiments conducted in compartments with ceiling heights ranging from 2.44 m to 12.2 m and peak fire heat release rates ranging from 150 kW to 10MW."

The type of evaluation that DETACT was subjected to is classified in ASTM E-1355 [7] as a "specified calculation." In the specified calculation, the model user is provided with a complete detailed description of model inputs, including geometry, test conditions, and the heat release rate history of the fire [7].

2.3.2 Conclusions

Actuation temperature is the most sensitive input parameter; i.e., for a given percentage change in the value of actuation temperature used by DETACT, it predicted a larger percentage change in the output parameter(s) of interest.

When slow t-squared fires are used, the predicted actuation time will greatly increase due to the relatively slow development of the fire. Very small source fires, especially smoldering, fall outside the bounds of the analysis and are unlikely to be accurately predicted, either for ceiling jet temperatures or detector actuation, by DETACT [4].

"Based on the comparison to predictions with measured values:

- As the ceiling height increased from 3.0 m to 12.2 m, the agreement between the predictions and the data improved. The lower ceiling heights are more sensitive to uncertainties in the experiment.
- There was better agreement between devices with higher RTIs (response time index) than with devices with lower RTIs.
- The compartment evaluation scenarios demonstrate that DETACT should not be used in situations where the limitations/assumptions of the model cannot be met, since the model cannot be used with any reasonable expectation of reliability. For example, the use of DETACT would not be appropriate in small areas where a gas layer would develop prior to activation." [4]

2.4 Proposed Tasks

2.4.1 Scenarios to be Modeled

The first task is to define those scenarios requiring the prediction of fire detector activation. The scenario definition should include a geometrical description of the room of fire origin (turbine hall, control room, etc.) and specify the fire that may be experienced in that space. Presumably, the type of heat detector and its description is a "given" for each NPP.

2.4.2 Scenario Differences

The scenarios described in 2.4.1 are next compared to the limitations presented in 2.2.2. Any inconsistencies are to be noted for the following step.

2.4.3 Questions

The series of questions below (in no particular order) is intended to facilitate the discussion:

1) Do the limitations shown in 2.2.2 preclude using DETACT in NPP?

2) Are the identified NPP scenarios sufficiently similar to those used in the development of DETACT (see 2.2.2) to justify further work?

3) If they are not sufficiently similar is it still worthwhile to investigate using DETACT in NPP scenarios? For example, since there is no other detector model available, are we "forced" to use it?

4) Is there a "best" way to use DETACT in NPP? Some of the choices for "best" include:
   - as is (i.e., no changes)
   - modify program based on available data
   - develop post-processor adjustment factors (may require using CFD models to generate ceiling jet temperature and velocity profiles and develop correlations based on the results)
   - develop a new DETACT for NPP (i.e., extract property generation, bulk property transport, and lumped mass models from DETACT and couple those to NPP-specific ceiling jet temperature and velocity correlations)

5) Is ceiling jet temperature and velocity experimental data available for the scenarios of interest?

2.4.4 Benchmark Exercise

If there is sufficient interest in pursuing detection modeling in NPP the questions posed in 2.4.3 must be addressed first. Assuming that the decision is to proceed, some sort of benchmark exercise will be needed. In order to undertake such an exercise experimental data sets depicting the scenarios of interest must be readily available. The number of data sets needed will depend on the nature of the exercise.

The nature of the exercise will depend on the answer to Question 4 of 2.4.3. If the decision is made to compare DETACT prediction to experimental data and develop post-processor adjustment factors, then a relatively small number of data sets is required (probably three to four). If the decision is made to use the DETACT lumped mass model as the "sensor modulation" and "alarm condition", and the "property generation" and "bulk property transport" portions of DETACT along with a NPP specific ceiling jet correlation, then more data sets will be required: at least six. The idea here is that three data sets could be used to develop the NPP specific ceiling jet correlations, and the other three could be used to benchmark the resulting model.

It may be advantageous to use ASTM 1355 [7] as guidelines for this benchmarking exercise. Several types of model evaluations are presented: blind calculation (basic description of scenario provided); specified calculation (detailed description of model inputs provided); and open calculation (most complete information provided, including experimental or other benchmarking data). Using ASTM 1355 would provide some structure and formality to the exercise.

3.0 SUMMARY

The limitations imposed on the use of DETACT will most likely preclude its widespread use in NPP. However, assuming that there is a need for detector modeling in NPP, the question then becomes one of deciding what is the best (most expedient, most defensible...) course to meet this need.

Presumably, four of the five components necessary for NPP detector modeling are present in the current version of DETACT-QS. The DETACT component which needs either replacement or augmenting is that describing "local property transport." In order to address NPP specific local property transport, post-processing adjustment factors or a new component must be developed for DETACT.

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A NEW MODEL FOR TIME LAG OF SMOKE DETECTORS

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ABSTRACT

For smoldering fires existing time lag theories and observations of smoke detectors are reviewed shortly and shown to be unsatisfactory. The author showed earlier by that fluid dynamic phenomena cannot explain in an acceptable manner the observed controversy. Using general theory of filtering a model is proposed for time lag, where small smoke particles partially separate from the carrier fluid while penetrating into the smoke detector. At small flow velocities the separation seems so effective that detection time is delayed much or smoke may remain undetected totally. Since only scattered direct experiments are available for comparison, and no resources for own measurements were avialable at this phase, the model is presented for fire science community to be tested and evaluated.

INTRODUCTION

Earliest possible detection of fires has been the goal of active fire prevention through ages by any possible means. Since the introduction of numerical room fire simulation codes there has been detailed tools to predict conditions and times for fire detector response. Majority of these tools treat phenomena outside the detector. The long chain from the incipient fire to detector has been modelled at different degrees of sophistication starting from experimental plume models combined with zone type room fire models and ending with various kinds field model simulations. At the moment large eddy simulation (LES) techniques (McGrattan et al. 1998) to determine smoke properties at detector location presents possibly the heaviest end of the calculation tools available for the problem (Cleary at al. 1999, Farouk et al. 2001).

Despite that there are links not yet modelled to the same degree of accuracy as LES simulation treats smoke transport and coagulation; one of these is smoke penetration into the detector. A smoke detector has partially permeable walls separating the gas volume in the detector from the volume around it. Walls of commercial detectors consist mostly of mesh, or perforated plates. In each form they delay fire detection as compared to a fully open detector. Heskestad (1977) modelled coupling of conditions inside the detactor to outside conditions based on scaling principles. Since then practically all modelling of smoke penetration into detectors has based on his work.

TIME LAG THEORIES AND DATA

Heskestad (1977) drafted a theory using dimensional analysis arguments for the time lag Δt of a products-of-combustion fire detector

$$\Delta t = \gamma \, l / \bar{v} \tag{1}$$

where $\bar{v}$ is the mean convective flow velocity around the point detector, l the characteristic length scale, and γ a non-dimensional coefficient characteristic for the geometry. According to Heskestad Equation (1) is valid presuming 'viscosity effects are not considered important'.

Bukowski (1975) as well as Johnson and Brown (1986) observed large delays of fire detection for artificial cold smoke or smoldering smoke in a real size room although the behaviour was neither quantified nor fully systematic. Brozovsky's (1991) measurements showed, that the simple relationship predicted by Equation (1) did not hold for low ceiling jet velocities. In Figure 1 his observations (dots) are plotted as a function of velocity $\bar{v}$. Thin solid lines represent exponential fits by Brozovsky (1991) on his limited set of data; his exponential fit at low values ($\bar{v} < 0.13$ m/s) is a plausible approximation. Unfortunatelly, he did not extend measurements to speeds exceeding 0.2 m/s. Therefore, it is very uncertain, what the behaviour would be at higher velocities. Thus the curve crossing the point (0.4 m/s; 1 s) is only an extrapolation without experimental confirmation beyond 0.2 m/s. No single set of data was available covering the whole interesting region of velocities. More recently Qualey at al. (2001a,b) observed long detection times for low velocity ceiling jets as a result of smoldering fires. Unfortunatelly they did not measure ceiling jet velocities at detector location or other relevant data to allow quantitative comparison.

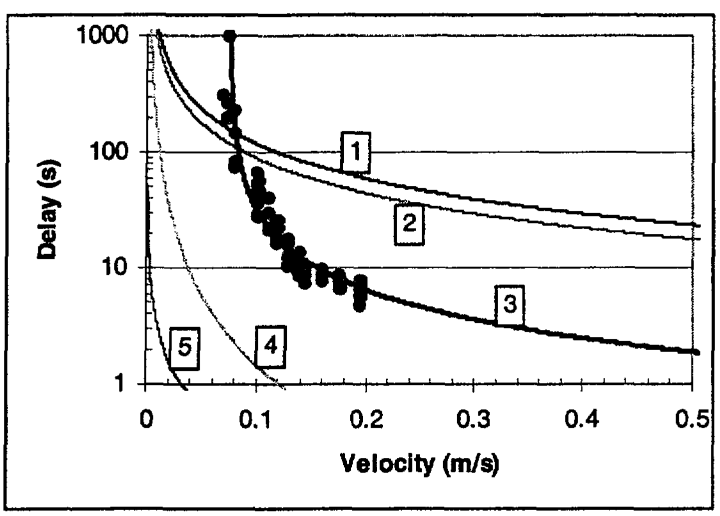

Figure 1. Entry lag time dependence on flow velocity past a detector. Dots (experimental data, Brozovsky 1991). (1) and (2): The delay time according to Equation (1) as explained in text. (3): Fit according to Equation (2), critical velocity $\bar{v}_0$ = 0.075 m/s). (4) and (5): Calculated models (Keski-Rahkonen 2001) explained in text.

EXPERIMENTAL DATA REDUCTION FOR FIRE MODEL VALIDATION

Due to power law dependence on velocity an *ad hoc* modification of Equation (1) was attempted (Keski-Rahkonen 2001)

$$\Delta t = \gamma l / (\bar{v} - \bar{v}_0) \qquad (2)$$

This fit seemed plausible as shown in by line 3 in Figure 1. Since Brozovsky's data cover only a rather limited range, Equation (2) is only one of the many possible fits on the data set. Fits of Equation (2) on another data set (Cleary et al. 2000) is shown in Figure 2. Again, plausible fits were obtained for the delay times. P1 was an optical detector ($\bar{v}_0$ = 0.01 m/s) and I1 ionizing detector ($\bar{v}_0$ = 0.02 m/s). Unfortunatelly, experimental errors seem still to be rather high.

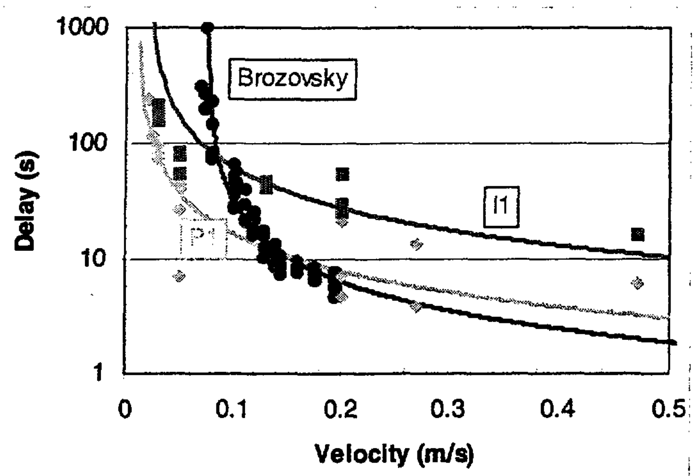

Figure 2. Detector time lag as a function of ceiling jet velocity according to experimental observations (dots: Brozovsky 1991, squares: I1 by Cleary et al., 2000 diamonds: P1 by Cleary et al. 2000). Full lines arbitrary fits on data using Equation (2).

These examples show, critical flow velocity exists, but is hard to explain. The behaviour described by Equation (2) seems to indicate, if the the fluid is taken as a continuum, the flow has non-newtonian character plugging at velocities lower than $\bar{v}_0$. Qualitativelly, such a flow occurs, if the fluid, which here is actually an aerosol, behaves collectivelly like a non-newtonian continuum fluid of Bingham plastic (Irvine and Capobianchi, 1998). The analytical theories of such fluids would in principle allow calculation of the flow in and out of the detector (Kawase and Moo-Young 1992, Patel and Ingham 1994). However, there seemed not to be available experimental data of rheological properties of smoke, which could settle this question. The tacit assumption has always been smoke, like air, behaves as an almost perfect newtonian fluid. Looking smoke as an aerosol and rejecting one phase approximation seemed to shed new light on the problem, and to make non-newtonian flow both unlikely and unnecessary as is shown below. The method is fully described by Keski-Rahkonen (2002), and is shortly depicted here.

THEORY ON FILTRATION MECHANISMS

In a filter, like in a dense mesh, particles deviate from streamlines due to several mechanisms. That property has been used for particle size separation for long (Fuchs et al. 1962, Sinclair et al. 1979), but it is still a subject of intense studies (Lee et al. 1990, Sasse et al. 1994). Particles may collide with the wires on the mesh and stick on them. The main mechanisms of deposition are diffusion, inertial impaction, interception and gravitational settling. In the first approximation efficiences due these factors add linearly when estimating total efficiency of filtration. Approximating the filtering element by a cylindrical body, simple partial differential equations can be derived for the aerosol concentration in laminar flow region (Cheng 1993). For derivation of the equation it is assumed: (1) The concentration is in a steady-state condition; (2) the flow field in the device is a fully developed laminar flow; (3) the effect of diffusion in the direction of flow is neclected; (4) no production or reaction of aerosol occures in the device; and (5) the sticking coefficient of the particle is 100% on the collection surface.

Penetration P of aerosol through these devices can be expressed in a power series of exponential functions in the form

$$P = \sum_{n=1}^{\infty} a_n \exp(-\beta_n m) \tag{3}$$

where a_n is a numerical expansion coefficient, β_n an eigenvalue of the differential equation describing particle diffusion, and m nondimensional argument of the driving mechanism. Since the eigenvalues β_n grow fast with n, for real devices a few lower terms in the expansion of Equation (3) yields sufficent accuracy.

For diffusion batteries, used here as a model for a wire screen, Cheng and Yeh (1980), and Yeh at al. (1982) derived an equation

$$m = A_0 \, Pe^{-2/3} + A_1 R^2 + A_2 \, Pe^{-1/2} \, R^{2/3} \tag{4}$$

The pressure drop Δp through the screen is (Yamada et al. 1988)

$$\Delta p = \frac{16 \eta \alpha h u}{\kappa d_f^2} \approx \frac{32 \eta \alpha}{\kappa} \frac{u}{d_f} \tag{5}$$

FLOW THROUGH THE SCREEN

To estimate the flow of smoke through the detector the problem is divided into two formally different modes: flow of air, and flow of smoke particles. The detector is idealized to a hemisphere surrounded by an insect screen. From air flow in the outer field modelled using potential flow the continuity equation in steady state form yields the pressure inside the detector p_i. Once it is known, filtration theory can be applied in the sense of perturbation theory to calculate penetration of smoke particles through the screen to estimate the detection time. Spherical coordinates are selected such a way, that flow enters into the detector for azimuthal angle $0 \le \varphi \le \varphi_0$.

The pressure difference Δp through the screen is given by (Truckenbrodt 1980)

$$\Delta p = \begin{cases} p - p_i & = q(1 - a - c\sin^2\varphi) \quad 0 \le \varphi \le \varphi_s \\ p_s - p_i & = (b - a)q \qquad \varphi \ge \varphi_s \end{cases} \tag{6}$$

where a is a constant to be determined. Applying Equation (6) into Equation (5) a similar set is obtained for the flow velocity

$$u = \frac{\kappa d_f q}{32\alpha\eta} \begin{cases} 1 - a - c\sin^2\varphi & 0 \le \varphi \le \varphi_s \\ b - a & \varphi \ge \varphi_s \end{cases} \tag{7}$$

By a straightforward calculation one can derive an approximate equation for the air inflow $\dot{V}_i$ into the detector

$$\dot{V}_i \approx 0.460\, \pi r^2 q \frac{\kappa d_f}{32\eta} \tag{8}$$

The used symbols are deltailed in the full paper (Keski-Rahkonen 2002)

SOOT FLOW THROUGH THE SCREEN

(To be completed)

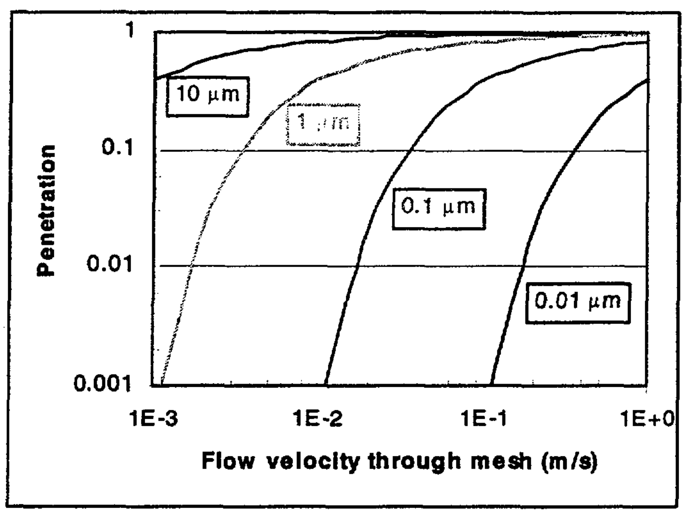

Figure 3. Penetration through a mesh as a function of flow velocity for different diameters of particles.

CONCLUSIONS

Long reaction times of smoke detectors for cold smoke has been known for long. Reviewing a series of measurements it was shown, there is a finite value of ceiling jet velocity, below which the time lag becomes large. It was shown by the author, that neither any presented model nor also in principle any newtonian single fluid model is able to explain this threshold. A two phase model is proposed here, where ideal fluid (air) carries solid smoke particles. At small ceiling jet velocities these particles are selectivelly filtered out of the flow, as smoke penetrates in the detector through the insect screen. The presented model was carried over from, and verified in aerosol reaearch. Still, detailed experiments should be carried out for smoke detectors for direct comparison with the predictions of the proposed theory.

ACKNOWLEDGEMENTS

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Appendix D: View Graphs Used for Presentations

Contents

U.S. NRC Goals and Plans for Research to Support Risk-Informed Regulation

Mark Cunningham, Chief
Probabilistic Risk Analysis Branch
U.S. Nuclear Regulatory Commission

Goals for Risk-Informed Regulation

- **Commission established new policies for risk-informed regulation in 1996**
  - **Focus on licensee activities commensurate with their significance to public risk**
  - **Utilize probabilistic risk assessment (PRA) methods, to the extent feasible, in a risk-informed regulatory framework**

Research to Support Risk-Informed Regulation

- **Availability of analytical tools is key to success of risk-informed regulation**
- **Office of Research, U.S. NRC is actively conducting research to improve PRA methods**

Key Areas of Research

- **Human reliability analysis**
  - **Atheana method developed**
- **Fire risk analysis**
  - **Fire modeling**
  - **Circuit failure analysis methods**
  - **Significance determination process**
  - **Fire risk requantification**

Fire Modeling Research

- Evaluate capabilities and limitations of fire models for applications in nuclear facilities
- Benchmarking and validation of fire models
- Develop best-estimate methods and determine uncertainties in predictions

International Collaborative Project for Fire Modeling

- Project established in 1999
- Report on 1^{st} benchmark exercise on cable tray fires completed
- Contributions from all participants of significant value to the NRC
- NRC intends to continue its full support of the project

Memorandum of Understanding between NRC and NIST

- **MOU established in February 2000**
- **Evaluate NIST fire codes, CFAST and FDS, for adoption in NRC's regulatory framework**
- **NRC staff detailed to NIST**
- **Mutual interest and benefits to both government agencies**

NRC Proposal for International Validation Exercises

- **NRC will sponsor full-scale tests at NIST for international benchmark exercises**
- **Test program planned for 3 years from 2002 to 2004**
- **NRC invites project participants to exercise respective fire models**
- **NRC solicits input for program**

NRC Goals for Validation Program

- **Benchmark range of fire models**
  - **Empirical models used in NRC inspection process**
  - **FIVE (Revision 1) methods to be used in NRC/EPRI requantification program**
  - **CFAST and other zone models**
  - **FDS and other CFD models**
  - **Lumped-parameter models**

NRC Goals for Validation Program – Cont'd

- **Determine suitable models for best-estimate predictions for range of scenarios**
- **Determine margins in predictions for different types of models**
- **Determine uncertainty in predictions**

FIRE SAFETY RESEARCH AT NIST

Fire Research Division
Building and Fire Research Laboratory (BFRL)
National Institute of Standards and Technology (NIST)
http://www.bfrl.nist.gov/

Anthony Hamins
May 2, 2002

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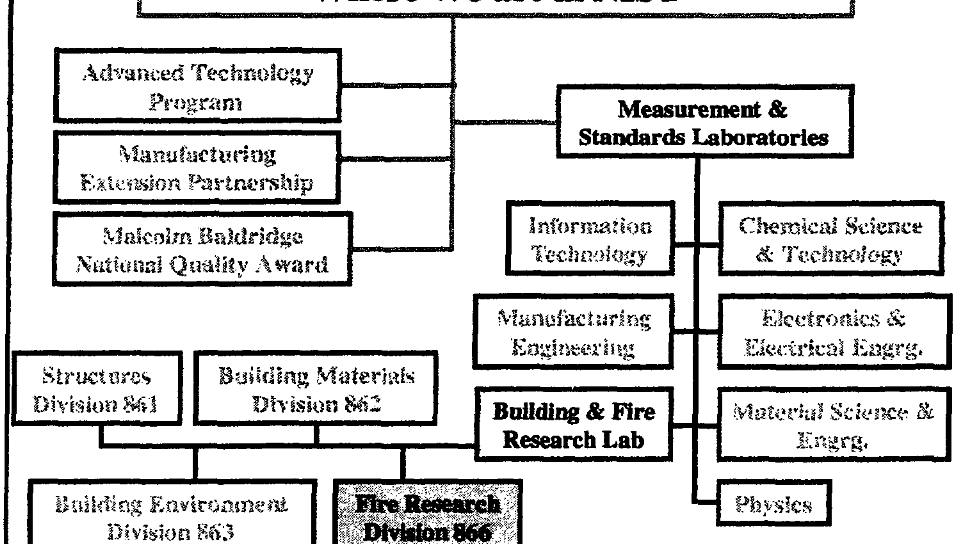
Where We are in NIST



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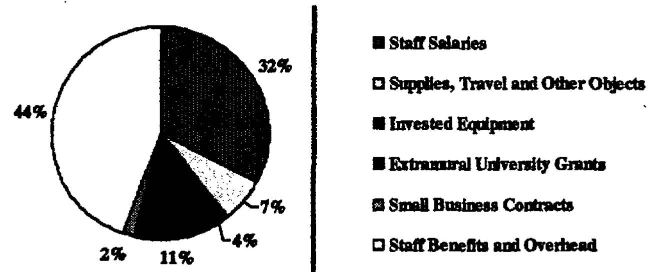
Fire Research Division



BFRL Fire Research Budget (FY02): STRS ($6 M); OA ($6 M)

Staff: 58 FTE (24 PhDs), 25 Guest Scientists (ATF, NRC, Univ.) & 3 post-docs

Background: engineers, mathematicians, chemists, physicists

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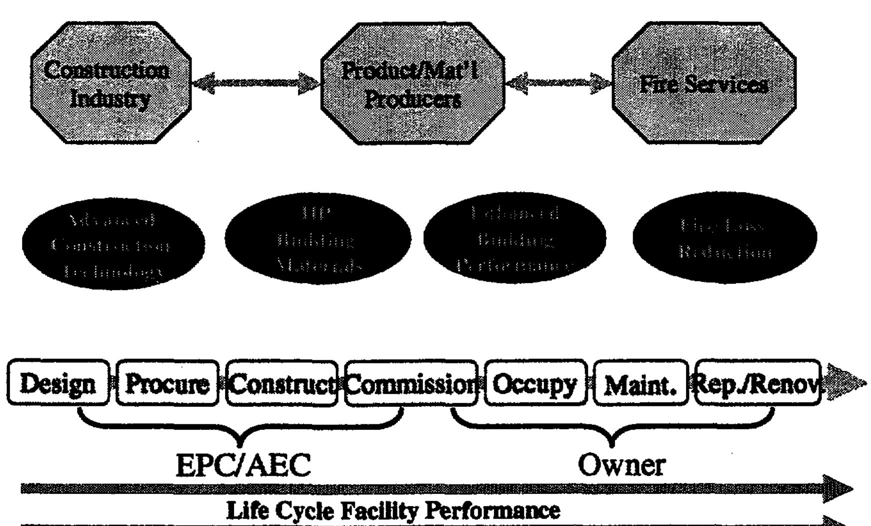
BFRL Focus: Four Technical Goals



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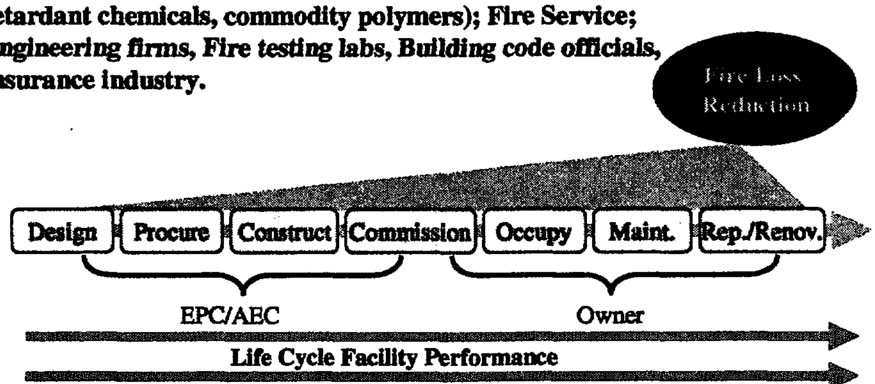
Fire Loss Reduction Goal

Goal: Enable engineered fire safety for people, products, facilities; and enhanced fire fighter effectiveness

Customers: Manufacturers (fire protection equipment, fire retardant chemicals, commodity polymers); Fire Service; Engineering firms, Fire testing labs, Building code officials, Insurance industry.



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Strategy to Reduce Fire Losses (1/2)

Reduce *residential fire deaths, injuries and property losses* by

- adapting measurement and predictive methods to better understand conditions leading to *flashover*,
- enabling early and certain fire and environment sensing,
- advancing cost-effective fire suppression technologies; and
- enabling new/improved materials whose fire resistance does not negatively impact performance, cost, or the environment.

Reduce *fire fighter line-of-service deaths and burn injuries* by

- providing new *technology*, measurement standards, and training tools; and
- enabling shift to an information rich environment.

Enable cost-effective *engineered fire safety* for people, products, facilities, and first responders by

- advancing *fire measurement and prediction methods*
- accumulating and archiving data, and
- accelerating their transfer to practice.

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Strategy to Reduce Fire Losses (2/2)

Reduce fire fighter and occupant vulnerability in extreme fire events which threaten *homeland security* by

- **applying measurement and predictive methods to *identify role of fire in World Trade Center collapse*, and**
- **improving methods of *structural fire protection* and *protection of emergency responders*.**

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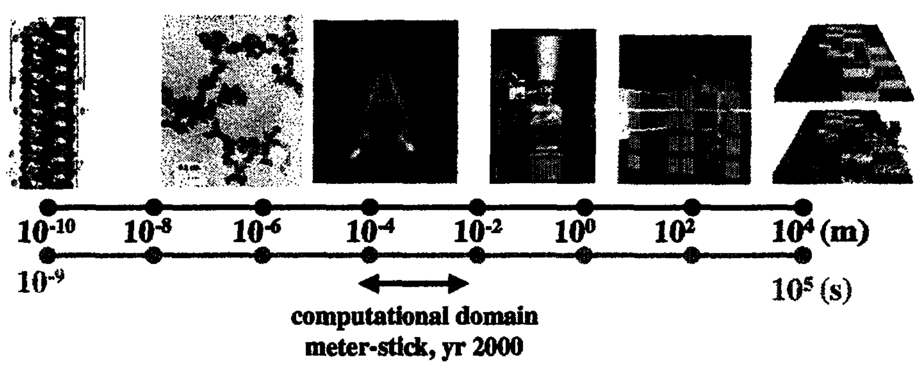
Technical Challenges to Fire Research



Challenge: Understand/predict fire behavior over 14 orders of magnitude in length (and time) scale

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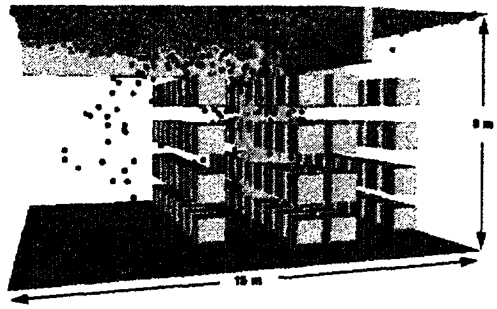
Fire Dynamic Simulator (McGrattan)



- fire protection applications
- performance based design
- fire investigations
- education/training

- runs on fast PC
- large eddy simulation (LES) of gas phase flow
- mixture fraction
- Finite volume method for radiation transport equation based on 100+ discrete angles

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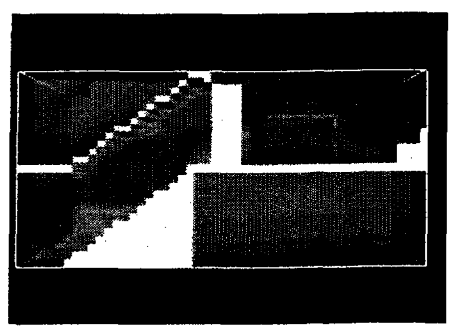
Fire Reconstruction Modeling Project (Madrzykowski)

- **NYC – 3 fire fighters die inside apt. bldg. following flashover & wind driven fire**
- **DC – 2 fire fighters fatally burned in townhouse fire**
- **Keokuk, IA – 3 fire fighters die inside house following flashover**



- **New tool used to gain insight into fire events resulting in some fire fighter fatalities**
- **Continuing to improve model capabilities in response to needs and feedback from investigations**

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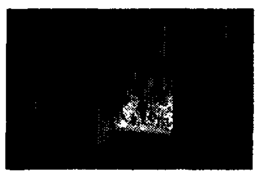
COMMUNITY-SCALE FIRE SPREAD (R. Rehm)

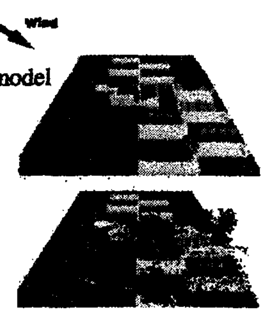
1993 Laguna Fire (Newsweek)

Site Specific Fire Model
- Fire spread between buildings and the natural environment
- Fire protection strategies
- Quantitative planning & training tool



- Full-scale performance data of building materials and assemblies.

- physics-based fire spread calculation using NIST FDS model



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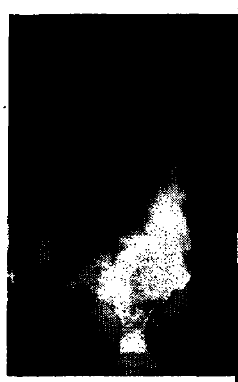
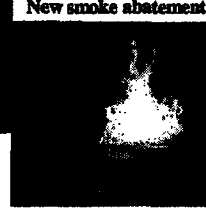
Large Fire Laboratory Operations (Mulholland)

- **renovated facility on-line ($ 7 M)**
- **implement advanced measurement capabilities ($1.5 M)**



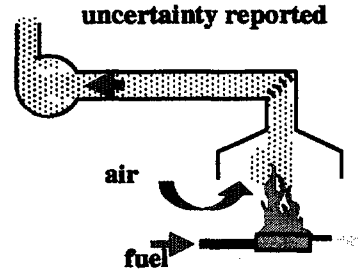
~10 MW heat release rate

New smoke abatement system



New calibration burner

- **Best-practices to ensure minimal, quantified uncertainty reported**



- **O_2-depletion calorimetry**
- **mass flow measurement in duct using He doping**

"

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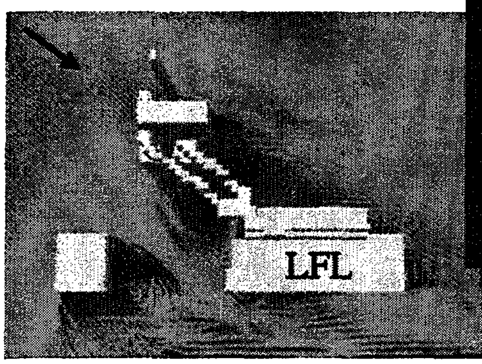
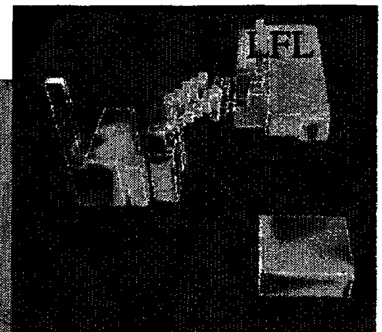
Wind Effects (Rehm)

- effects of topography & obstacles on wind fields
- effects of external winds on flows <u>inside</u> of the LFL



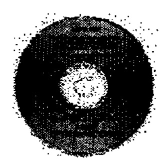
Simulated flow vectors 4 m above the ground near the LFL



Simulated surface pressure on the LFL

Information and Data (Reneke)

Fire Research Information System (FRIS)
- unique fire library (60,000 holdings)
- Planning underway for transition to e-FRIS



Fire Data Management System
- create a centralized database of fire data and exchange format for use by researchers & testing laboratories

Codes And Standards (Bukowski)

- NFPA Standards Council (+15 other NFPA Technical Committees)
- CIB W14 (Fire, TG37 - Performance-based Bldg. Regulations)
- ISO (TAG8, TC92)
- ASTM (E5, Fire Standards,...)
- Korean test method used for measuring fire resistance of wood construction
- Cigarette ignitability test methods
- ICC Performance Code Development Com.

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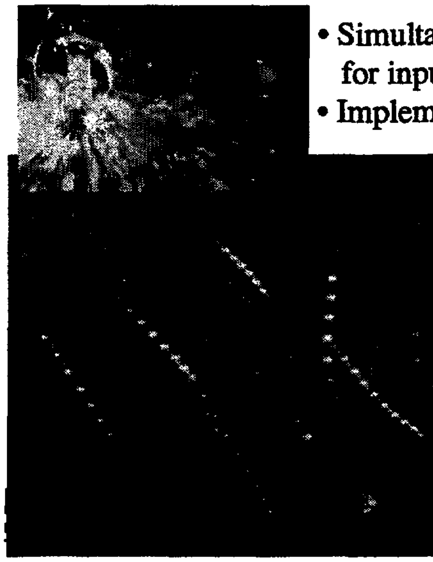
Planar laser measurements of Sprinkler Flows (Putorti)

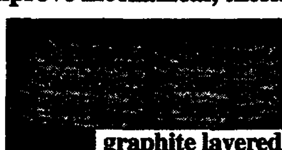


- Simultaneous sprinkler droplet size & velocity for input and validation of CFD fire models
- Implement in LFL

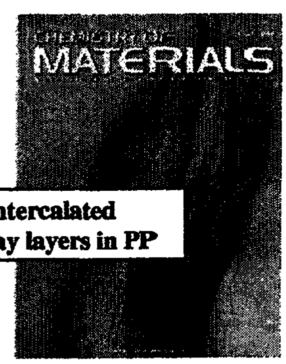
- Fluorescing droplets for sizing
- Particle tracking for velocity
- Non-intrusive, instantaneous
- Large area (1m by 1m)
- Laser sheet. 2D measurements.
- 2 lasers, 2 wavelengths, 2 pulses.
- High resolution film camera

Less Fire-prone Materials Project (Gilman)

Commodity polymers with nm-sized inorganic layers interspersed can improve mechanical, thermal & flame resistant properties.



graphite layered PP nanocomposite simulation



TEM of intercalated silicate clay layers in PP

viability of high-throughput approaches to formulate/screen new flame retardants/fire resistant materials explored.

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Prediction of Fire Growth and Spread (W. Pitts)

Predict detailed fire behavior:
- effects of geometry (realistic items)
- materials (dripping, bubbling, chemical effects)
- charring

Challenge: develop a physics-based pyrolysis model relating fuel flux to heat feedback

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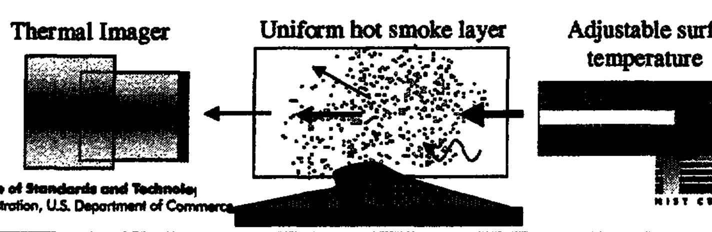
Characterization of Thermal Imagers (Widmann)

Develop an evaluation facility to test the capabilities and limitations of commercially available thermal imagers.

Infrared viewers see through smoke for fire fighting applications.



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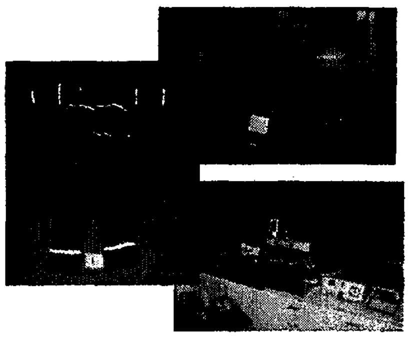
Protective Clothing Project (R. Lawson)

- Develop instruments & methods for measuring thermal environments for fire fighters' protective clothing and equipment - NIST, USFA, NIOSH & FDNY



Decision Aids Project (W. Jones)

- Develop a prototype advanced (smart) fire alarm panel that will
  - identify the location of a fire in a building
  - determine fire characteristics
  - operate as part of the cybernetic building systems
- Develop prototype fire service devices
  - standardized graphic/icons for information
  - scalable, prioritized communication
  - wireless transmission

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NIST Response to 9/11 Events

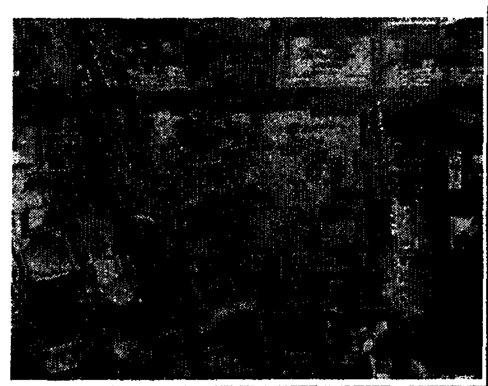
I. National Building and Fire Safety Investigation of the World Trade Center Disaster

II. Structural Fire Protection

III. Human Behavior, Emergency Response & Mobility

IV. Building Vulnerability Reduction

V. National Construction and Infrastructure Forum



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IRSN

Future Fire Research at IRSN

- IRSN strategy in Fire Research
- Experimental programs in progress
- Fire scenarios selected
- Fire research needs

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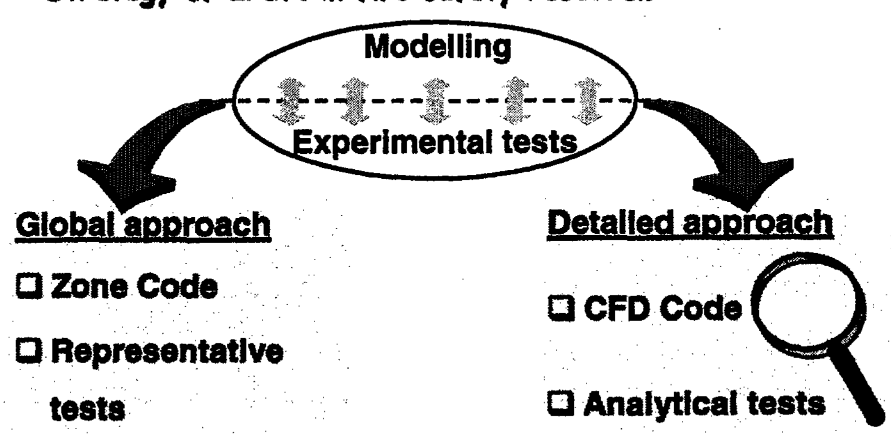
IRSN

IRSN Strategy in Fire Research

- Strategy of IPSN in fire safety research



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IRSN — IRSN Strategy in Fire Research

- **Fire Modelling**
  - ✕ Approach of Modelling

Global Approach
FLAMME_S
Fast and global evaluation studies

Detailed Approach
ISIS
More precise evaluations in specific complex configurations

Two Zone & CFD Approaches
SYLVIA
To provide different modelling levels for various users

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IRSN — Experimental program in progress

- ✕ **Representative tests**
  - ♦ FLIP: Fire scenario in a confined and forced ventilated enclosure
  - ♦ DIVA: Fire propagation through several rooms
- ✕ **Analytical tests**
  - ♦ CARMELA: Electrical cabinets

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IRSN

Fire scenarios selected (1/2)

- **Fire scenarios ranking Approach**

  - Lists of fire scenarios of each IRSN team :
    - Emergency plans
    - Deterministic fire risk assessment
    - NPP fire PSA
  - First ranking by each team (ignition source frequency, dominant scenarios of fire PSA or importancy of releases)
  - Last ranking of all fire scenarios

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Fire scenarios selected (1/2)

Glove box fire	1st rank	Nuclear facility
TBP/TPH fire	2nd rank	Nuclear facility
Fire of solid waste drums	2nd rank	Nuclear facility
Electrical cable fire	4th rank	NPP
Relay room fire	5th rank	NPP
Pyrophoric metal fire	6th rank	Nuclear facility
Electrical cabinet fire	6th rank	NPP
Fire propagation to a compartment located above	6th rank	NPP
Fire in the Containment	9th rank	NPP
Fire in a benchboard of the control room	10th rank	NPP

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Fire Research Needs

- **Topics selected**
  - × Combustion parameters
  - × Soot production
  - × Improvement of the plume model in a confined and *ventilated configuration*
  - × Explosion hazards due to the non-burnt residues
  - × Fire propagation towards other fire sources
  - × Damage criteria for equipment and electrical cables

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IRSN

Fire research needs
Combustion parameters

- **Objectives**
  - Caracterisation of the fire source (establishement models to estimate the combustion mass rate, the combustion efficacity, flamme spread velocity)
- **State of the Art**
  - Combustion parameters :
    HRR = m . S . ΔH
    m : combustion mass rate
    S : combustion area
    ΔH : combustion heat
    Vf : vitesse de flamme

    ΔH = χ . ΔHt
    χ : combustion efficiency
    ΔHt : complete combustion heat

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IRSN

Fire research needs
Combustion parameters

- **State of the art (cont')**
  - Parameters taken into account
    - *➔m, ΔHt et Vf are combustible caracteristics*
    - *➔m et Vf depends on size and geometry of the combustible, of its position vertical or horizontal and of its temperature*
    - *➔m, χ et Vf change during the fire scenario*
  - Tests
    - *➔m can be measured in a cone calorimeter*
    - *➔During full scale fire test the mass loss rate can be measured continuously but it is not easy to measure the HRR, moreover during flame propagation or fire extinguishing the combustion surface changes strongly*
  - Usually existing data are for unconfined fire (fire over oxygened)

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Fire research needs
Combustion parameters

Objectives and approach

- ✗ Models for computer zone codes
  - to estimate m according to the fire (combustible, geometry, position ...)
  - Taking into account S evolution notably during the fire growth and extinguishing
  - Impact of ambient confined (O_2 concentration, CO, CO_2, soots, Tgaz...) on m, Vf and χ
- ✗ Approach
  - State of art report (in progress)
  - In the first stage, study of fluid and solid combustible without radionuclid
  - 3 steps
    - *➔Scale effect on m and χ*
    - *➔effect of ambient conditions on m and χ*
    - *➔Effect of scale and ambient conditions on Vf*
  - Development and qualification of a model for a first combustible
  - Adaptation of the model to the combustibles of selected fire scenarios

May 2-3, 2002 ICFMP 5th meeting 10

FIRST APPLICATIONS OF A QUANTITATIVE FIRE HAZARD ANALYSIS TOOL FOR INSPECTION IN THE U.S. COMMERCIAL NUCLEAR POWER PLANTS

Naeem Iqbal and Mark Henry Salley

Division of Systems Safety and Analysis

Plant Systems Branch

Fire Protection Engineering and Special Projects Section

Presentation at 5th Meeting of the International Collaborative
Project to Evaluate Fire Models for Nuclear Power Plants Applications
May 2-3, 2002
National Institute of Standards and Technology, Gaithersburg, Maryland, USA

UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
WASHINGTON, DC 20555-0001

PURPOSE

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

- Support the NRC **Goal** of using **Risk Insights** with the Regulation in the new Reactor Oversight Process (ROP).
  (In the new ROP the NRC is moving towards a more risk-informed, objective, predictable, understandable, and focused regulatory process. Key features of the new program are a risk-informed regulatory framework, risk-informed inspections, a significance determination process to evaluate inspection findings, performance indicators, a streamlined assessment process, and more clearly defined actions the NRC will take for plants based on their performance).

- Advance the Fire Hazard Analysis (FHA) process from a primarily **Qualitative Approach** to more of a **Quantitative Approach.**

- Apply fundamental **Fire Protection Principles** using a simplified **Quantitative** FHA tool developed by the NRR staff.

- **Quantitatively** assess **fire hazards** at NRC-licensed nuclear power plants (NPPs).

PURPOSE (Cont'd)

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

- Evaluate potential for credible fire scenarios that could cause damage to essential fire safe-shutdown (FSSD) systems, components or equipment as a part of the ROP .

- NRR developed a Quarterly **Regional Inspector Fire Protection Training/Workshop Program as a part of ROP.**

- Sample Problem and Worksheets include in this presentation:
  - Radiative heat flux calculations
  - Centerline plume temperature
  - Sprinkler actuation time
  - Heat release rate necessary to cause compartment flashover

CURRENT LIST OF WORKING WORKSHEETS

U.S. Nuclear Regulatory Commission
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- Compartment hot gas layer temperature and smoke layer height with natural ventilation.
- Compartment hot gas layer temperature and smoke layer height with mechanical ventilation.
- Burning Characteristics of Fire, Heat release rate, Flame height, and Burning duration.
- Full-scale heat release rate of cable tray fire.
- Burning duration of solid combustibles.
- Flame heat flux from a fire to a target at ground level under wind free condition using point source radiation model.
- Flame heat flux from a fire to a target at ground and above ground level under wind free condition using solid flame radiation model.
- Centerline temperature of a buoyant fire plume.
- Sprinkler response time.
- Smoke detector response time.
- Heat detector response time.
- Ignition time of target fuel exposed to a constant radiative heat flux.
- Wall fire flame height.
- Line fire flame height.
- Corner fire flame height.
- Compartment flashover calculation.
- Pressure rise in a closed compartment due to fire.
- Explosion calculation.
- Fire resistance of structural members.

GOALS

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- Support the **Qualitative** assessment **Quantitative** values in FHA.
- Provide a tool which can be quickly used to assess potential for a credible fire scenario during NPP fire protection inspections on site.
- Integrate FHA tools and risk analysis.
- Over 3 year period, continue to develop more worksheets and improve upon the current worksheets in use.
- NRR is currently at the ½ way point.

NRC REACTOR OVERSIGHT PROCESS

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

- The primary objectives of the **Fire Protection Program** (FPP) at the U.S. commercial NPPs are to minimize both the probability of occurrence and consequences of fire.

- To meet these objectives the FPPs for NPPs are designed to provide reasonable assurance, through **Defense-in-Depth** (DID) that a fire will not prevent the performance of necessary safe shutdown functions and that radioactive releases to the environment in event of a fire will be minimized.

- NRC new ROP uses a risk-informed approach to evaluate the safety significance of inspection findings.

NRC REACTOR OVERSIGHT PROCESS (Cont'd)

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

- As part of ROP inspectors use a **Significance Determination Process** (SDP) to evaluate the significance of potential fire risks.
- Establishing **Creditable** fire scenario is an important step to SDP.
- **Qualitative** methods primarily used until now to evaluate fire scenarios.
- The worksheets add **Quantitative** values to inspection findings.

METHODS TO ESTABLISH THE FIRE SCENARIO

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- Fire load (BTU/ft^2) does not consider these other factors which greatly affect the compartment fire intensity:

  - the form of the combustible material (material/thermal properties)
  - ventilation openings
  - compartment dimensions
  - insulating capacity of walls

- NFPA 805, **Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants**, Appendix C, provide guidelines for detail fire modeling.

QUANTITATIVE FIRE HAZARD ANALYSIS METHODS

U.S. Nuclear Regulatory Commission
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- Worksheets are modeled after the U.S. Bureau of Alcohol, Tobacco, and Firearms (ATF) Fire Investigation Program.
- ATF Fire Investigators use similar approach.
- Selected a series of state-of-the-art **Fire Dynamics Correlation** from SFPE Handbook of Fire Protection Engineering, NFPA Fire Protection Handbook, Fire Dynamics by Drysdale, Principles of Fire Behavior by Quintiere, and Enclosure Fire Dynamics by Karlsson and Quintiere.

QUANTITATIVE FIRE HAZARD ANALYSIS WORKSHEETS

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- User-friendly, developed using Microsoft Excel® based on fire dynamics equations/correlations pre-programmed.

  - quickly apply fire dynamic principles found in the handbooks.
  - worksheet are protected to prevent tampering.
  - automatic unit conversion.
  - related material fire property data listed within each worksheet.
  - to reduce input errors from in accurate manual entries pull-down menus allows user to select the single input from the material fire property data table.

VALIDATION

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- Majority of handbook correlations in worksheets were developed from experimental data.

- Correlations used in the worksheets were validated in SFPE Handbook of Fire Protection Engineering, NFPA Fire Protection Handbook and new SFPE Engineering Guides.

REGIONAL INSPECTOR TRAINING

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

- Cover basic principles of fire dynamics, limitations, and bounding analysis.
- Quarterly training led by NRR **Fire Protection Engineers**.
- Inspectors independently developed fire scenarios and solve realistic problems.
- New worksheets presented at each quarterly training session.
- Provided with a detailed manual which contains fire dynamics theory and basis of worksheets.

CONCLUSION

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- By taking a commonly available computer spreadsheet software (like Microsoft Excel®), and creating a series of computational worksheets, different concepts like fire dynamics can be taught to, and put into reliable field application by inspectors.

- The use of the worksheet further reduces mathematical complexities and errors, and promotes greater application of fire science and engineering in field use.

- The NRR fire protection staff is in the process of developing additional worksheets for regional inspector application in the area of fire risk evaluation. The worksheets discussed in this paper are the second set completed and put into use. A complete suite of worksheets is expected to be completed in 2003.

SAMPLE WORKSHEET PROBLEM

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This is an example of how to do an engineering FHA using the NRC/NRR fire dynamics Microsoft Excel® spreadsheets.

PROBLEM STATEMENT

During a routine fire protection inspection, a NRC inspector discovers a significant oil leak in a station air compressor. It is important to determine whether a fire involving 20 gallon spill of lubricating oil from a compressor could damage the safety-related cable tray and electrical cabinet in an access corridor in the fuel building. The compressor is on a pedestal approximately 1.0 foot above floor level and has a 12 ft^2 (1.12 m^2) oil retention dike. The safety-related cable trays are located 8 ft (2.45 m) above the corridor floor with a horizontal distance of 4 ft (1.2 m) from edge of the compressor's dike. The horizontal distance between the compressor dike and the electrical cabinet is 5 ft (1.52 m).

The access corridor has a floor area of 20 x 15 ft (6 x 4.6 m), a ceiling height of 10 ft (3 m), and has a single unprotected vent opening (door) of 4 x 6 ft (1.22 x 1.4 m). The compartment has no forced ventilation. The compartment construction is 1 ft thick concrete. The corridor has a detection system and a wet pipe sprinkler system. The nearest sprinkler is rated at 165 °F (74 °C) with a RTI of 235 $(m\text{-}sec)^{1/2}$) and located 9.8 ft (2.98 m) from the center of the dike. Determine if there is a credible fire hazard to the safety-related cable trays and electrical cabinet.

Use the following worksheets to evaluate fire scenario.

1. Heat flux to the target (electrical cabinet) using point source model, $\dot{q}''_{cabinet}$
2. Heat flux to the target (cable trays) using the solid-flame radiation model, $\dot{q}''_{cable}$
3. Centerline plume temperature, $T_{P(centerline)}$

4. Sprinkler activation time, $t_{activation}$
5. HRR necessary to cause flashover, $\dot{Q}_{FO}$

ANALYSIS

Accidental spills of flammable and combustible liquid fuels and resulting fires depend on the composition of the fuel, the size and shape of the fire, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of the object exposed to the fire. Liquids with relatively high flash points (like lube oil or diesel fuel) require localized heating to ignite. However, once started, a pool fire spreads rapidly over the surface of the liquid spill. To perform a conservative FHA, it will be assumed that the 20 gallons of lubricating oil will be spilled into the diked area and the over heated compressor ignites the oil.

The summary results of the calculations are given in table. See Microsoft Excel® worksheets for details of the calculations.

Heat flux to target (electrical cabinet) $\dot{q}''_{cabinet}$ (kW/m²)	Heat flux to target (cable trays) $\dot{q}''_{cable}$ (kW/m²)	Centerline plume temperature $T_{P(centerline)}$ [°C (°F)]	Sprinkler activation time $t_{activation}$ (min)	HRR necessary to cause flashover $\dot{Q}_{FO}$ (kW)
12.50	17	689 (1272)	2	2100

SAMPLE WORKSHEET PROBLEM (cont'd)

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It should be noted that exposure to high plume temperatures could potentially cause the unprotected safety-related cable trays to fail. The flame heat fluxes to the electrical cabinet and the cable trays are high enough to damage them.

The results of the calculation demonstrate that a pool fire with a 12 ft^2 dike area in an access corridor could damage unprotected safety-related cable trays and electrical cabinets. The analysis also suggests that for the postulated oil fire, the sprinkler system, if operable, should activate and should provide some protection to the safety-related cables and equipment.

International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Application

5th Meeting May 2002

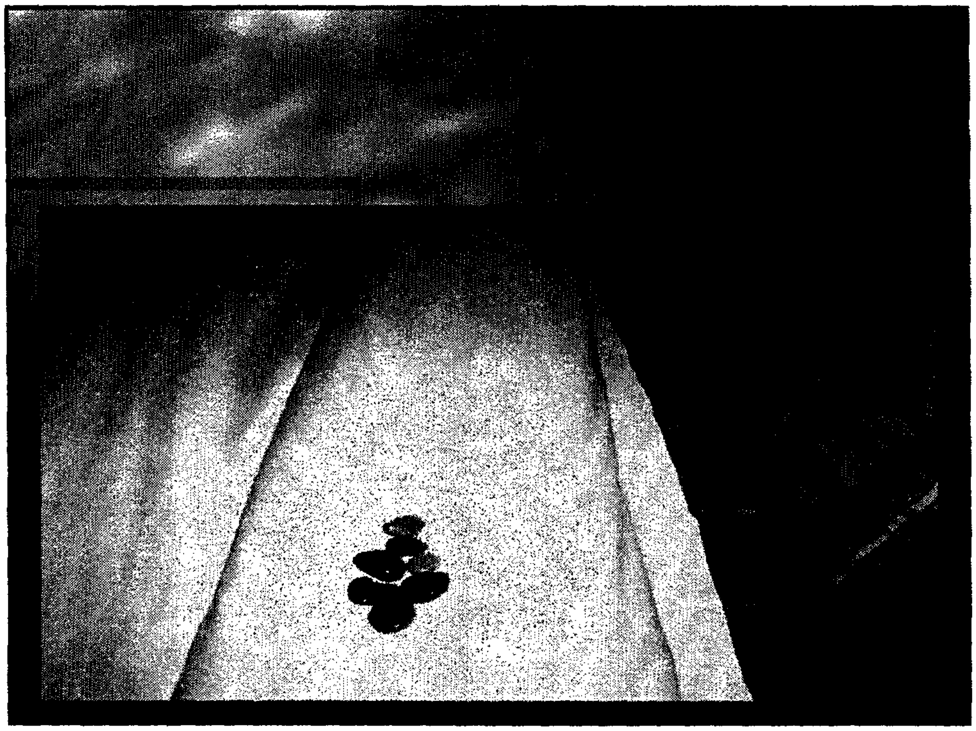
"Use of Fire Models in Risk Analysis for Nuclear Power Plants"

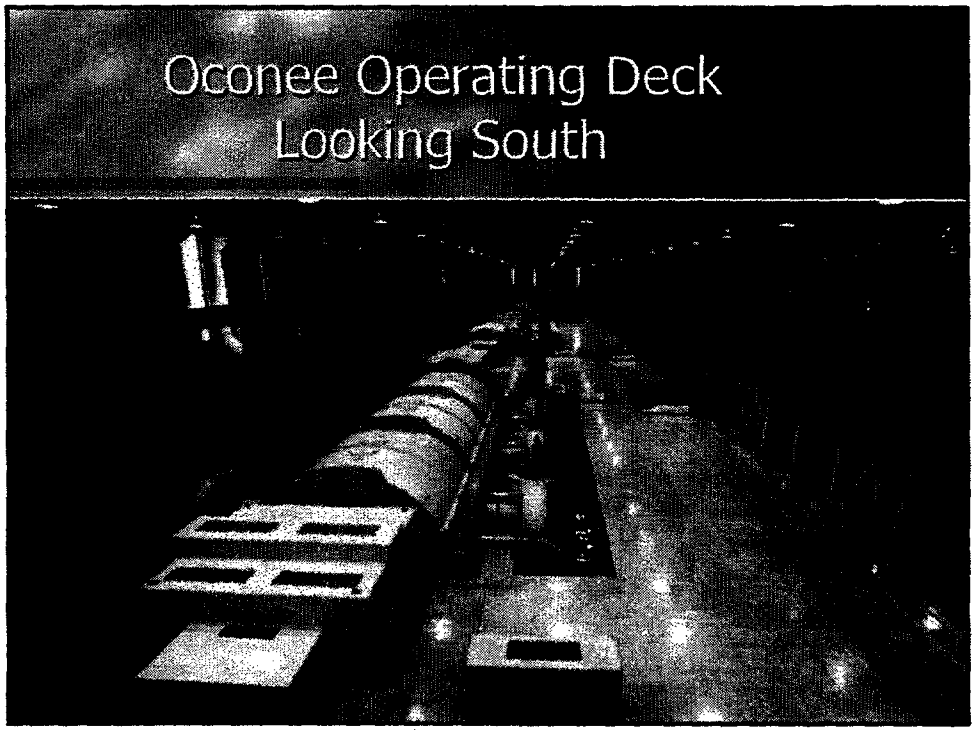
By Doug Brandes
Duke Energy
Charlotte, NC USA

Risk-Informed Applications of Fire Models

Example

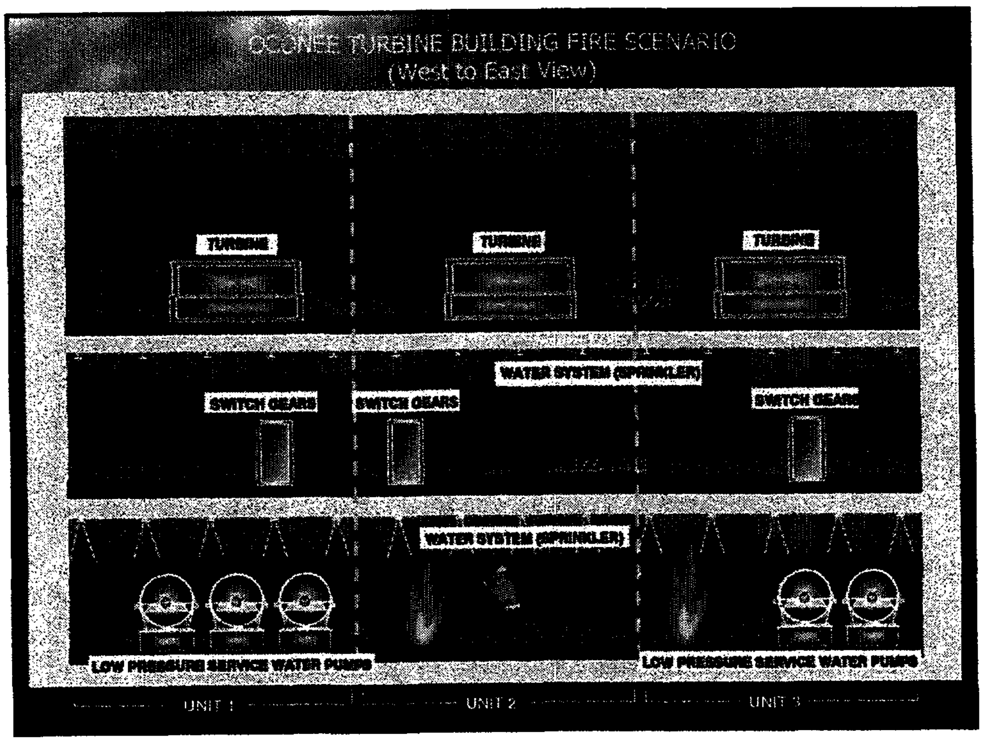
Oconee Nuclear Station Turbine Building Fire Scenario

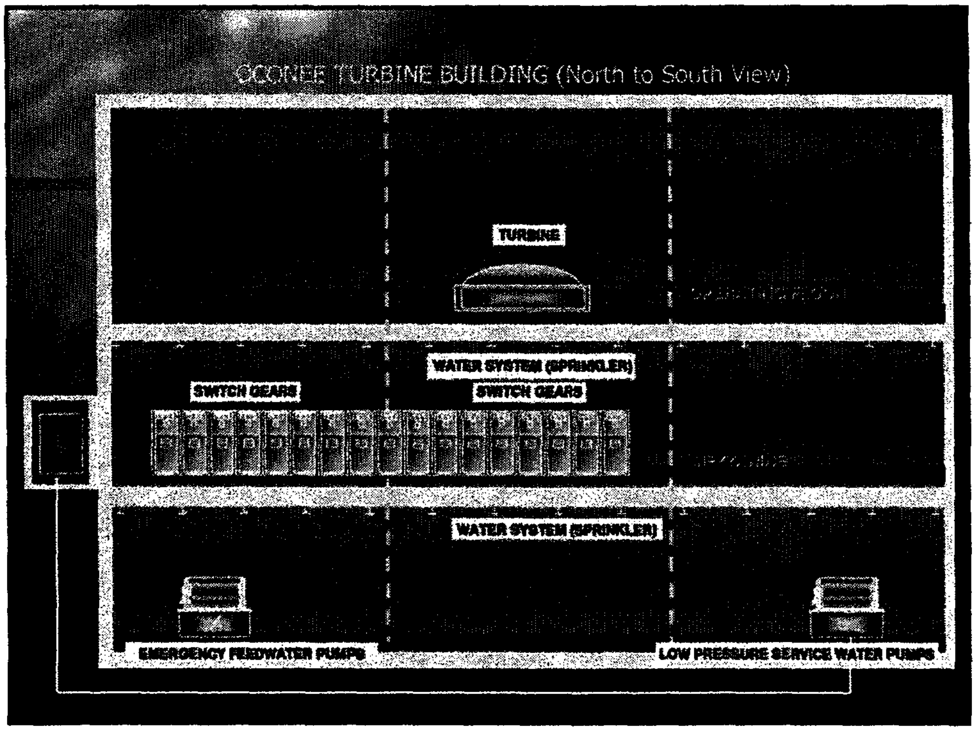



Oconee Operating Deck
Looking South

Current State

Postulate that Fire Propagates throughout





Future State

Fire Scenario Develops

Realistic Fire Propagation Scenarios

With Suppression

Without Suppression

What Can You Do For Me

- Conduct Research
- Develop Computer Models
- Translate Research and Scientific Code Language to "Low end' Engineering Language
- Validation Guidance

What Can I Do For You

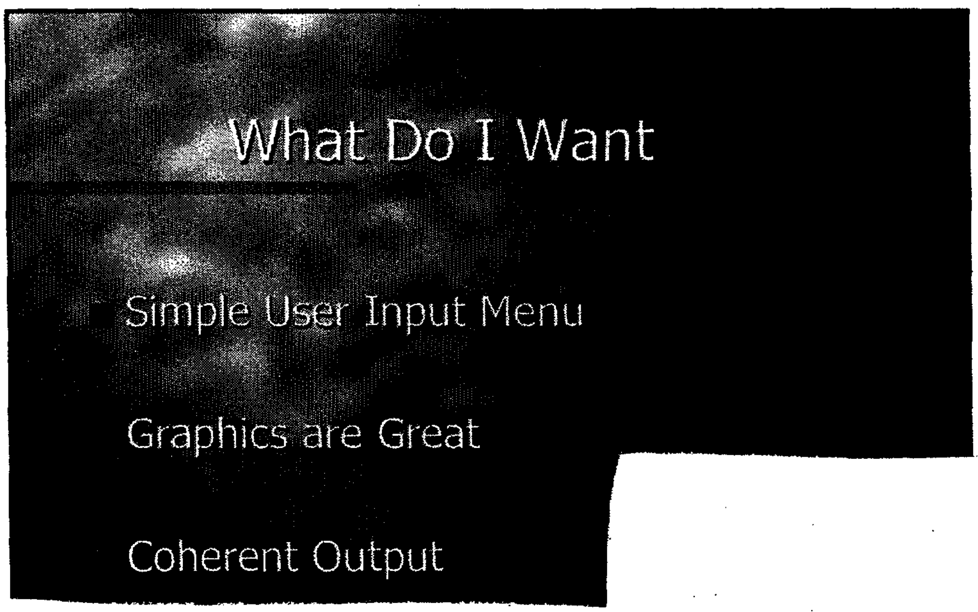
Provide Understanding of End Users Needs / Expectations

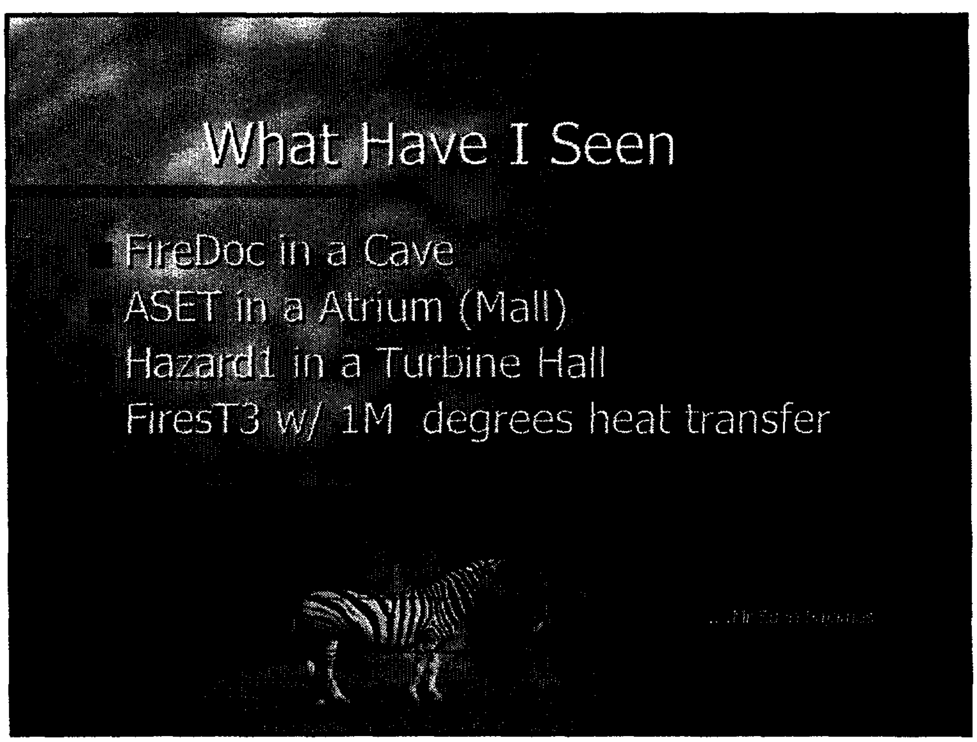
What Do I Need

- Simple input menu
- Understanding of input sensitivities
- Comprehensible users manual
- Understanding of validation
- Understanding of "degree of precision"
- Understanding of results

Additional Needs

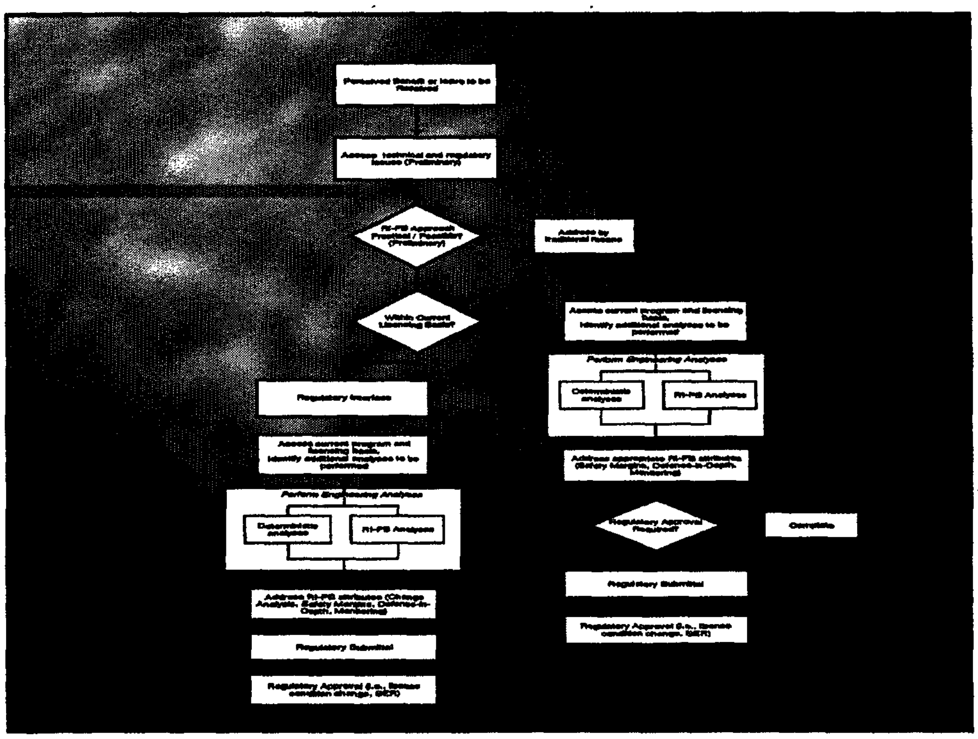
- Regulatory Acceptance
- Benchmarking between models
- Simplification for use in SDP

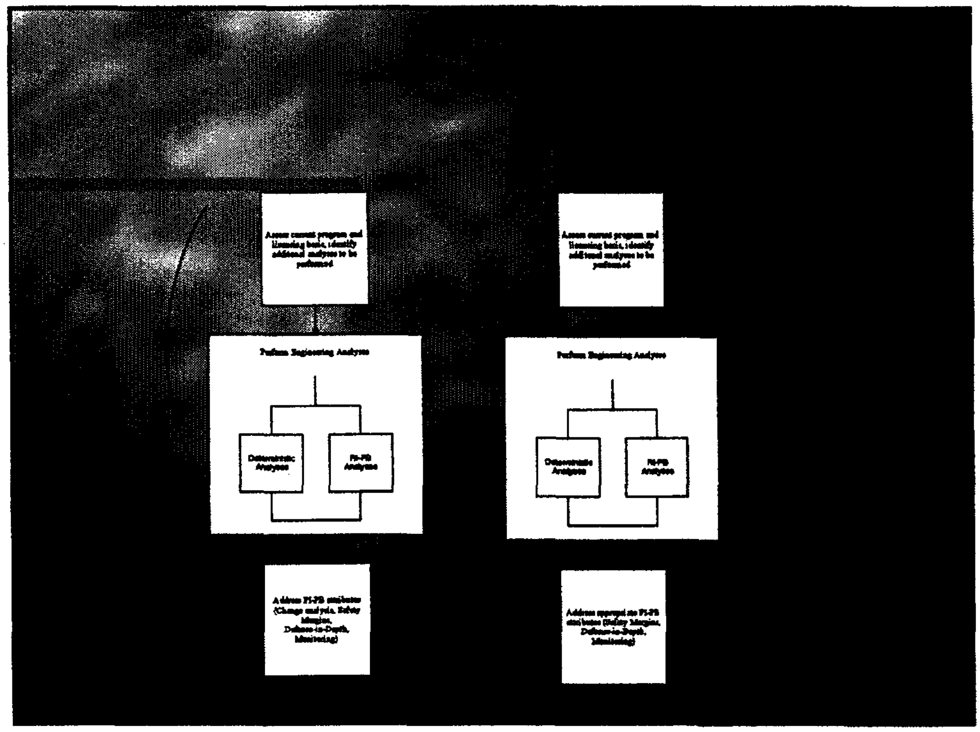

What Do I Want
Simple User Input Menu
Graphics are Great
Coherent Output

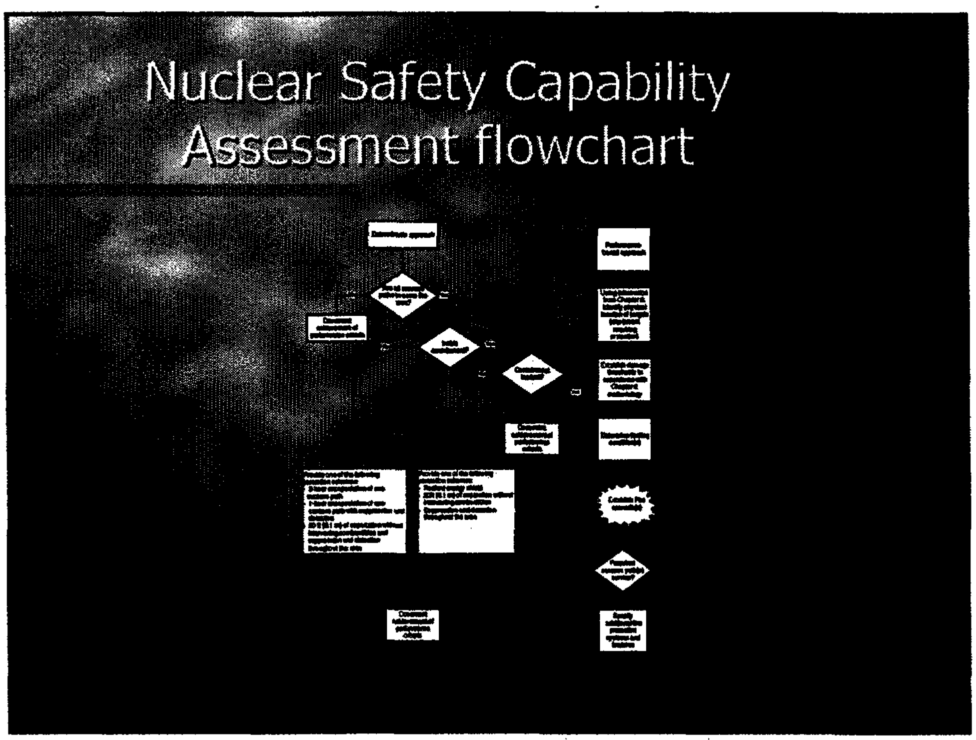

What Have I Seen
FireDoc in a Cave
ASET in a Atrium (Mall)
Hazard1 in a Turbine Hall
FiresT3 w/ 1M degrees heat transfer

Potential Benefits

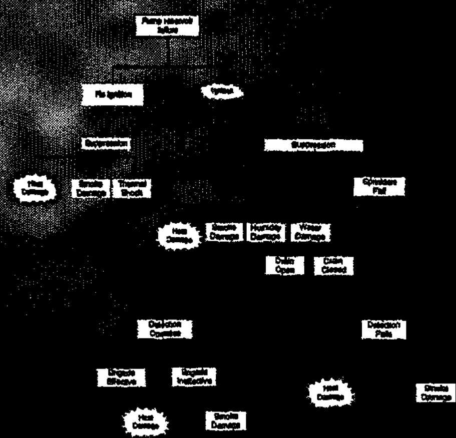
- Increase employment for Fire Protection Engineers
- Save $$$$$$$
- Increase confidence in decisions
- Increase focus on safety





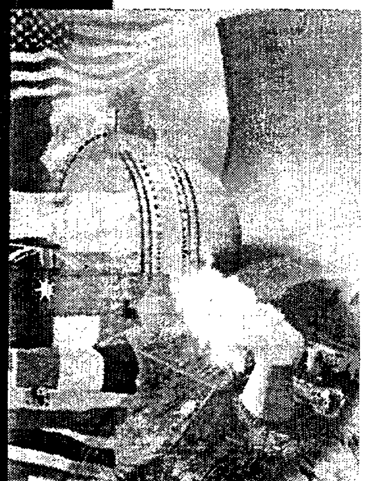

Nuclear Safety Capability
Assessment flowchart

Fire Event Tree



Conclusion

- This research initiative has potential to increase our understanding of the fire hazards in operating Nuclear Power Plants



The EPRI Guide to Fire Modeling: An Overview

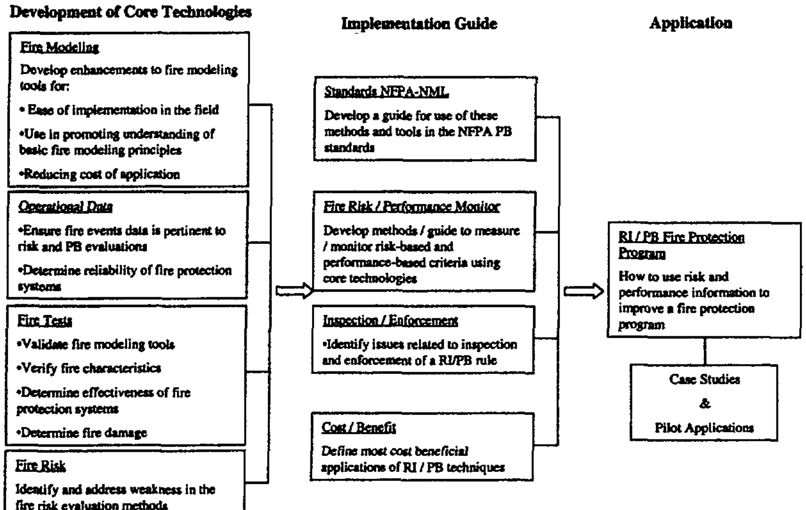
B. Najafi, F. Joglar,
Science Applications International Corp.

R. Kassawara
EPRI Project Manager

SAIC

EPRI

EPRI Perspective



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Outline

- Introduction
  - About fire modeling
  - Objectives
  - Fire Modeling Guidelines
    - Scope and development
- Steps to perform fire modeling
  - 5 steps to perform fire modeling
  - Supplemental guide
- Conclusions

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About Fire Modeling

- Fire modeling:
  - an approach for predicting various aspects of fire generated conditions inside a compartment
  - requires an idealization and/or simplification of the physical processes involved in fire events
- Any departure of the fire system from this idealization can seriously affect the accuracy and validity of the approach

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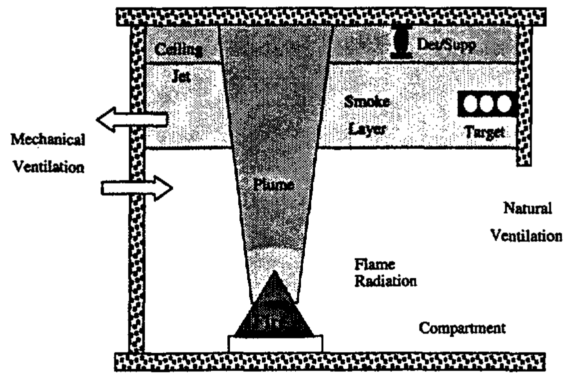
Modeled Fire Phenomena

- Exposure
  - Fire Plumes
  - Ceiling jets
  - Upper layer
  - Flame radiation
- Effects
  - Heat detection
  - Target response
- Fire
  - Predefined intensity



Fire Modeling in Nuclear Power Plants

- NPP's present a number of fire modeling challenges
  - The ability to address all this challenges is usually restricted by model capabilities
  - A procedural approach can help practicing engineers through the process of fire modeling
- In response to the need for this procedural approach, EPRI developed the Fire Modeling Guidelines

Objective of the Guide

Develop a process through which fire protection engineers in commercial nuclear facilities may use fire modeling to support day-to-day operation of their facilities.

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Scope of the Guide

- The guide is a complement and not a substitute to:
  - fire dynamics text books
  - code validation studies
  - user's guide(s) for a particular code(s)
- The guide does not address the issue of selection of fire scenarios.
- Users with the following characteristics will benefit the most:
  - Understanding of algebraic equations
  - General knowledge on compartment fire behavior
  - General knowledge on basic engineering principles, specifically heat transfer and fluid mechanics

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Development of the Guide

- Library of fire scenarios
- Modeling of fire scenarios
  - Scenario description
  - Prediction of fire conditions
- Lessons learned
  - The evaluation of the scenarios generated the knowledge base to develop the actual guidelines
- Methodology to perform fire modeling

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Selection of Typical NPP Fire Scenarios

- US NPP design and operation
  - Typical geometries and equipment layouts
- Risk significance
  - Fire IPEEE
- Industry experience
  - Utility and NRC surveys: How and where fire modeling has been used in the past.

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Typical NPP Fire Scenarios

- Switchgear room
- Cable spreading room
- Main control room
- Pump room
- Turbine building
- Multi-compartment corridor
- Multi-level compartments
- Containment

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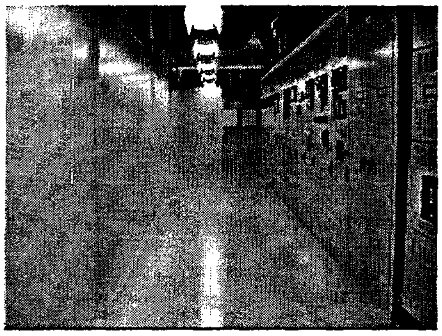
Switchgear Room

- Issues and challenges
  - High energy events
  - Fire barriers



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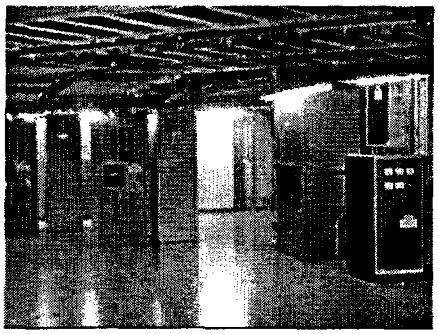
Cable Spreading Room

- Issues and challenges
  - Fire spread in cable trays; horizontal, vertical, or sloped
  - Fire propagation between cable trays; stack, parallel, or crossing
  - Congested ceiling (with cable trays) and *impact on ceiling jet*
  - Obstructed detection and suppression



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Main Control Room

- Issues and challenges
  - Fire propagation inside Main Control Board
  - Panel-to-panel fire propagation and timing
  - Habitability

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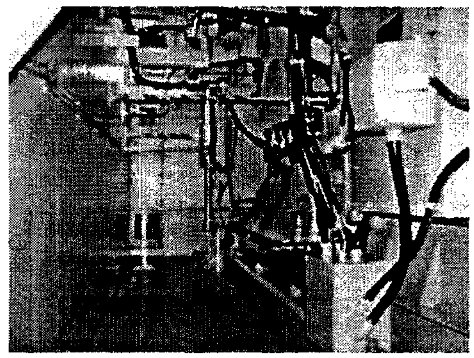
Pump Room

- Issues and challenges
  - Large fires in small compartments
  - Flashover
  - Integrity of boundaries



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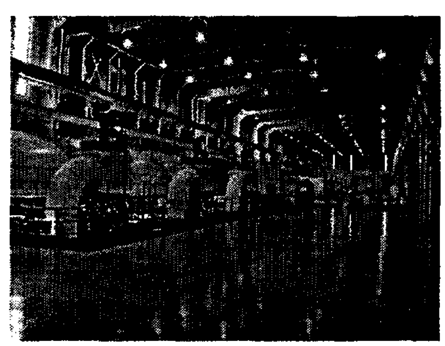
Turbine Building

- Issues and challenges
  - Large fires in large enclosures
  - Non-concrete, open boundary
  - Hydrogen fires



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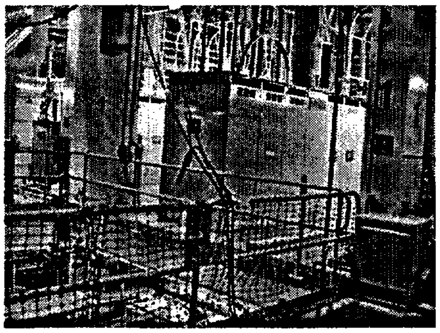
Multiple-elevations

- Issues and challenges
  - Smoke/hot gas spread upward
  - Fire propagation to floors below
  - Size and location of opening and use of single- or multi-compartment model



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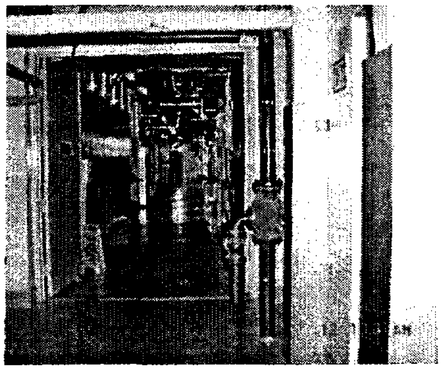
Corridor

- Issues and challenges
  - Different ceiling heights
  - Soffits and their impact on propagation of hot gases



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Containment

- The guide does not include a modeling example for the containment building
- Modeling issues in the containment building are addressed in other scenarios:
  - Large enclosure
  - Cylindrical boundaries
  - Domed ceiling

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Modeling Tools

Hand Calcs	Zone Models	Field Models
• FIVE-Rev1 – Excel tool – Most of hand calcs in FIVE – DETACT – MQH room temperature model • Negligible calculation time	• CFAST (NIST) • MAGIC (EDF) • COMPBRN-IIIe • Calculation times in the order of minutes	• Not included in the guide • Calculation times in the order of hours to days

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FIVE-Rev1

- Microsoft Excel tool with hand calculations included as Excel built-in functions.
- The library of functions include most of the hand calculations in FIVE plus the DETACT and the MQH models for detection and room temperature respectively
- The built in functions combined with Excel capabilities allow to perform sensitivity and uncertainty analysis.
- Available from EPRI

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CFAST

- Developed in the 90's for a broad range of applications including buildings, power plants etc.
- DOS based software with a GUI interface
- Multi-fire, multi-room, multi target fire simulation
- Available from NIST

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MAGIC

- Developed in the 90's by EDF for a broad range of applications including buildings, power plants etc.
- Windows based, user friendly graphical interface
- Multi-fire, multi-room, multi-target fire simulation
- Available from EPRI

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COMPBRN-IIIe

- Developed in the early 80's mainly for nuclear applications
- Still a DOS computer application
  - Difficult to input modeling parameters (vs. Windows applications)
  - Difficult to evaluate modeling results (vs. Windows applications)
- Single compartment model with one opening
- Uncertainty Analysis
- Available from EPRI

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Guide: 5 Steps to Perform Fire Modeling

- Step 1: Define modeling objectives
- Step 2: Describe the fire scenario
- Step 3: Select appropriate model(s)
- Step 4: Estimate fire generated conditions
- Step 5: Verify and interpret results

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Fire Modeling Guide: Step 1

- Define modeling objectives
  - Need to be expressed in terms of output parameters from fire models
- Example
  - "Evaluate the temperature at the surface of the target"

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Fire Modeling Guide: Step 2

- Describe the fire scenario
  - Compartment: geometry, ventilation, fire protection
  - Targets: location, flammability parameters, intervening combustibles
  - Fire: heat release rate
- *Scenario characteristics are the basis for model selection*
- The model may require more or less information than the one already collected.

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Fire Modeling Guide: Step 3

- Select appropriate model(s)
  - The guide provides a table that summarizes the capabilities of each zone model
  - The characteristics of the scenario are required to use the table
  - Additional description may be required based on the specific inputs to the selected model(s)

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Fire Modeling Guide: Step 4

- Estimate fire generated conditions
  - Prepare input file to the model
  - Run the model
  - Process output file

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Fire Modeling Guide: Step 5

- Verify and interpret results
  - Check if results are consistent with input parameters
  - Use the results to address the predefined objective

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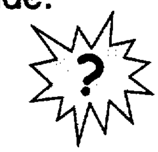
Supplemental Guidance

- In many fire scenarios, these 5 steps can not be readily implemented for reasons that include:
  - Enclosure geometry
  - Modeling capabilities
  - Input parameters



- Supplemental guidance in these areas help analyst perform fire modeling studies without compromising technical validity.
- Supplemental guidance is also provided in the area of interpreting fire modeling results

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Research Results

- Library of NPP fire scenarios
- Modeling examples of the library of fire scenarios
- Fire modeling guide
- Excel template: Five-Rev1

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Conclusions

- Understanding of fire dynamics is essential:
  - Physical phenomena
  - Assumptions in the development of each model
  - Capabilities and limitations of each model
- Combination of modeling tools is usually necessary to evaluate complex situations in nuclear power plants
- The fire modeling guidelines help engineers to organize information and select appropriate models
- EPRI is preparing a two-day training course on compartment fire behavior and the use of the FM guide

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Conclusions

- Areas where fire modeling can be applied
  - Thermal effects of plumes, ceiling jets and radiation
  - General room heat up, and hot gas layer
  - Elevated fires and oxygen depletion
  - Multiple fires
  - Multi-compartments: corridors and multiple elevations
  - Generation, migration and density of smoke
  - Partial barriers and shields
  - Detection

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Conclusions

- Areas for future research
  - High energy fires: explosions
  - Hydrogen or liquid spray fires
  - Fire growth within main control board
  - Fire propagation between control panels
  - Fire suppression
  - Cable fires
- EPRI method uses empirical models based on a combination of operating experience and applicable fire tests to estimate consequences of such fires

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Acknowledgments

- Duke Power
- Exelon
- Public Service Electric & Gas
- Pacific Gas & Electric
- EDF
- NIST
- NRC

SAIC 8/19/2002 Slide: 36 EPRI

IRSN

FLAMME_S code qualification

- 4 series of tests for qualification :
  1. Centred Pool fires (IPSN tests)
  2. Pool fires against a wall (IPSN tests)
  3. Multi- room tests ; centred fire (Cooper and al.) ;
  4. Multi rooms tests ; fire against a wall (Peacok and al.)

- *Objectives of IPSN tests*
  1. *To study the development of a pool fire in a semi-confined compartment with forced or natural ventilation*
  2. *To study the interaction between the wall and the fire*

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IRSN

FLAMME-S qualification

Fuels	Chemical formula
TPH	$C_{12}H_{26}$
70% TPH - 30% TBP	70% ($C_{12}H_{26}$) – 30% ($C_{12}H_{27}O_4P$)
Ethanol	C_2H_6O
Mineral Oil (DTE medium)	$C_{31,34}H_{63,9}$
Domestic fuel	$C_{15,55}H_{29,3}$
Methane	CH_4

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IRSN

FLAMME-S code qualification

FLIP tests

- fire pool against the south wall
- PLUTON facility : V = 400 m3, L×l×H 9 m×6 m×7,6 m concrete walls
- the normal ventilation flow rate of the room : 3 volume changes per hour.

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IRSN

FLAMME_S code qualification

Area of the pool (m^2)	Mean HRR kW	Kind of fuel	Test
0.4	360	TBP/TPH	FLIP1
0.4	215	Ethanol	FLIP1A
1.0	645	TBP/TPH	FLIP2
1.0	510	Ethanol	FLIP2A
1.5	910	TBP/TPH	FLIP7

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IRSN

FLAMME_S code qualification

Experimental data

Experimental cell :

- Liquid fuel mass
- Plume temperature
- Gas temperature
- Wall temperature
- Total and radiative thermal fluxes on the walls
- Gas pressure
- Flow velocity in the plume
- Species concentrations : O_2, CO_2, CO, soot (C)

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FLAMME_S code qualification

Ventilation network

- Admission and extraction flow rates
- Pressures at different location (ex : up and down stream of the filters)
- Gas temperature
- Species concentrations : O_2, CO_2, CO, soot (C)

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IRSN

FLAMME_S code qualification

- Data used to qualify FLAMME_S code

Imput data :

- ✓ Mass Combustion rate : *measured mass loss rate in function of time*
- ✓ Soot fraction : *mean experimental value* (mass balance after the test)

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FLAMME_S code qualification

Test Data used for the comparison with code results

- ✓ Gas temperature : mean temperature , lower zone temperature, upper zone temperature
- ✓ Gas pressure
- ✓ Gaseous species fractions : O_2, CO_2, CO
- ✓ Wall temperatures
- ✓ Ventilation network : gas flow rates (admission and extraction)

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FLAMME_S qualification

Comparison of the experimental and calculated values

- Experimental and calculated values plotted on graphes
- Determination of the relative variations between the maximum values
- Determination of the largest deviations

Qualification criteria :

Relative deviation between experimental and calculated values **less than 20%** for the main variables

gas mean temperature, gas pressure, oxygen concentration, wall temperature

lower and upper zone temperatures interface height
admission and extraction gas flowrates

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FLAMME_S code qualification

Domain of qualification

- room walls : concrete or of steel.
- height of the room : equal or greater than the smallest horizontal dimension of the room.
- room : sealed or connected to the outside with vertical openings or with a ventilation network (flow rate : 3 to 5 volume changes per hour).
- fire pool : centered in the room or against a wall (see FLIP tests).
- fuel : mineral oil or of an organic liquid.
- the pool area to the area of the horizontal surface of the facility ratio : less than 5%
- combustion rate of the fuel : input data
- heat release rate to the volume of the facility ratio is less than $5 kW/m^3$

IRSN

FLAMME_S code qualification

Future steps for qualification

- Electrical cabinets fires tests (CARMELA, CARMELO tests) :
  - ✓ to develop a model for describing the heat release rate evolution for this material
  - ✓ First series of tests is achieved ; an empirical model is proposed ; complementary analytical and global tests are planed in 2002
- Multi room tests :
  - ✓ DIVA tests (first preliminary campaign : 2002) : study of smoke and heat spreading in multiroom configurations (natural and mechanical ventilation)

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FLAMME_S code qualification

- Comments :
  - ✓ Results are not satisfying for calculation of large pool fires (ex : 2 MW, 400 m^3)
  - ✓ Limitation of zones model to simulate fires with large vertical thermal gradient into the gaseous volume

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Area of the pool (m^2)	Fuel	Facility : Volume m^3 (L×l×H) ou (S×H) wall material	Ventilation conditions	Test
0,0314	Mineral oil (DTE medium)	4,35 m^3 (0,856 m^2×5,35 m) (steel wall)	confined	LPI 7
0,0314	Mineral oil (DTE medium)	4,5 m^3 (2,011 m^2×2,24 m) (steel wall)	confined	LPI 9bis
0,0629	Mineral oil (DTE medium)	4,5 m^3 (2,011 m^2×2,24 m) (steel wall)	confined	LPI 10
1	70% TPH - 30% TBP	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (3 V/H)[1]	LIC 2.3
1	70% TPH - 30% TBP	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LIC 2.8.1
1	70% TPH - 30% TBP	3600 m^3 (20 m×15 m×12 m) (concrete wall)	confined	LIC 2.CA
1	TPH	3600 m^3 (20 m×15 m×12 m)	confined	LIC 2.CB

[1] The value indicated corresponds to the ventilation flow rate at the start of the fire.

		(concrete wall)		
1	Mineral oil (DTE medium)	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (5 V/H)	LPI 11A LPI 11 PEPSI 1
1	ethanol	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (5 V/H)	LIC 1.14
2	Mineral oil (DTE medium)	400 m^3 (9 m×6 m×7,6 m) (concrete wall)	mechanical (5 V/H)	LPI 12
5	70% TPH - 30% TBP	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LIC 2.8.5
5	Mineral oil (DTE medium)	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LPI 13
5	Domestic fuel	2000 m^3 (10 m×10 m×20 m) (concrete wall)	Natural	LPI 19

Q (kW)	½ corridor	¾ corridor	corridor	Corridor and lobby	Corridor 1/2 door	Corridor 1/4 door	Corridor 1/8 door
25	x	x	x	x			
100	x	x	x	x	x	x	X
225	x	x	x	x			
Ramp fire	x	x	x	x			

List of Cooper tests ↑

↓ *List of Peacock's tests*

Test number	Q (kW)	Door (corridor)	Third room
1	100	Open	No
4	100	Open	Yes
5	300	Open	No
6	300	Closed	Yes
7	300	Open	Yes
8	500	Open	No
9	500	Open	Yes

International Collaborative Project to Evaluate Fire Models
for Nuclear Power Plant Applications
Gaithersburg, MD, May 2-3, 2002

ZONE MODEL VALIDATION OF ROOM FIRE SCENARIOS

O. Keski-Rahkonen and S. Hostikka
VTT Building and Transport

VTT

Contents

- Introduction
- Overview of scenario B
- Experimental data reduction for fire model validation
- Participants
- Results
- Godness determination of the results
- Conclusions

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Introduction

- Performance based code usage
- Zone model technology evaluation
- Round robin within CIB W14
- NIST codes considered here
  - CFAST
  - FIRST
- Excerpt of a full report

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Scenarios

	Test label	Room size (m^3)	Fire load (kg)	Fire load density (MJ/m^2)	Peak RHR (MW)	Test time (min)
B1	SF83-3	$15 \times 7.2 \times 3.5$	1989	330	11	100
B2	SF85-10	$20 \times 7.2 \times 3.6$	1815	220	14	180
B3	SF86-10	$7.4 \times 7.2 \times 3.6$	2×500	330	5.2	120

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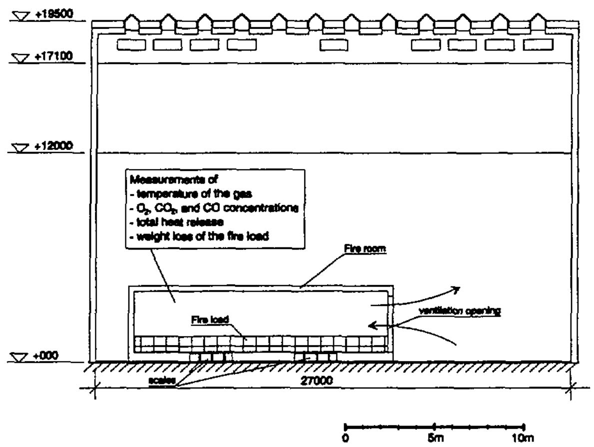
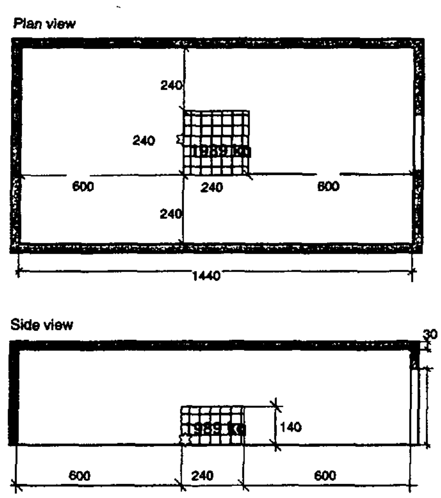
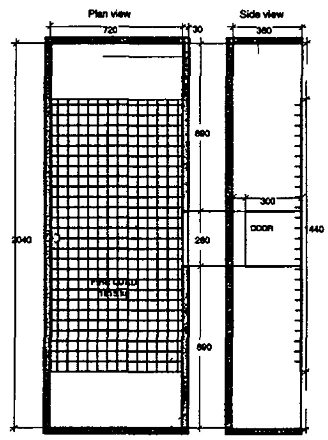
Testing hall



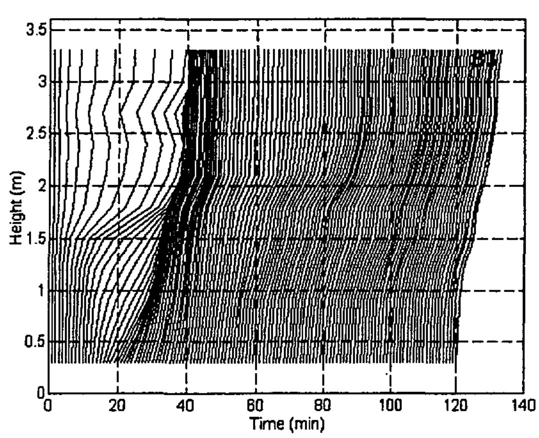
Subscenario B1



Subscenario B2



Temperature profiles



$$T(z_i,t)=T(z_{min},t)+t$$

Layer definitions

$$\frac{T(z_i,t)-T_{amb}}{T(z_{top},t)-T_{amb}}=\frac{N}{100}$$

N-percent rule

$$\int_0^H T(z)dz=(H-z_i)T_U+z_iT_L$$

$$\int_0^H \frac{dz}{T(z)}=(H-z_i)\frac{1}{T_U}+z_i\frac{1}{T_L}$$

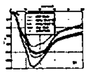
Quintiere et al. 1984 (DIM)

Density integral method (DIM)

$$z_i=\frac{T_L\left(I_1\cdot I_2-H^2\right)}{I_1+I_2T_L^2-2T_LH}$$

$$I_1=\int_0^H T(z)dz$$

$$I_2=\int_0^H \frac{dz}{T(z)}$$



Layer height

Temperatures

'Goddness of fit'

$$E = \frac{100\%}{t_0} \cdot \int_0^{t_0} \frac{|\theta_s(t) - \theta_m(t)|}{\theta_m(t)} dt$$

$$E_{max} = 100\% \cdot \frac{\frac{1}{t_0} \int_0^{t_0} \frac{|\theta_s(t) - \theta_m(t)|}{\theta_m(t)} \cdot \theta_m(t) dt}{\frac{1}{t_0} \int_0^{t_0} \theta_m(t) dt}$$

$$= 100\% \cdot \frac{\int_0^{t_0} |\theta_s(t) - \theta_m(t)| dt}{\int_0^{t_0} \theta_m(t) dt}$$

Mean relative errors

Code Variable	ARG	CFA	MRF	FIG	FW	FST	FLS	FIS	Average
T_{up} B1	25	13	14	14	21	21	48	26	23
T_{up} B2	27	27	25	26	NA	15	36	33	27
T_{up} B3	32	10	20	12	NA	NA	41	35	25
Average	28	17	20	17	21	18	42	32	24
h_{smoke} B1	72	23	14	27	20	19	25	19	27
h_{smoke} B2	69	62	81	88	NA	86	70	65	74
h_{smoke} B3	54	36	10	28	NA	NA	51	32	35
Average	65	40	35	48	20	52	49	39	43
ΔO_2 B1 [a]	3.3	2.7	2.0	3.0	7.4	1.7	1.1	1.8	3
ΔO_2 B2	37	38	36	31	NA	54	53	38	41
ΔO_2 B3	31	34	42	43	NA	NA	175	67	65
Average	24	25	27	26	7	28	76	36	31

VTT BUILDING AND TRANSPORT

Conclusions

- Results improved from blind to open simulations
- Selection of alternative submodels important
- Deviations from experimental data 10% ... factor of 2
- The user the most critical factor
- CFD calculations was not superior to zone models

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Fire models for NPP Applications

Fire zone model MAGIC : The validation and verification principles

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EDF

2

SUMARY

- **Discussion on the zone model validation :**
  - » Validation of the submodels (classic laws, empirical correlation,..)
  - » Validation of the global model
- **Short presentation of the MAGIC validation :**
  - » principles
  - » list of references
  - » examples
  - » future prospects

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Zone model approach of fire

A zonal model results from the association of various sub-models :

- Integration of classical physics laws
  - »energy and mass balance on different layers (homogeneous T and concentrations, hydrostatic P, Perfect Gas assumption , etc..
  - »simplified conduction in walls (1, 2 or 3D) or some targets
  - »simplified radiation (semi-transparent assumptions in concave rooms)
- Semi-empirical models
  - »fire source
  - »Plume, ceiling jet
  - »Convection heat exchange coefficient
  - »Openings and vent
  - »Detection, suppression etc..

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Validation of the sub-models

General laws are accepted by the scientific community.

Empirical models have most of the time been directly obtained from specific experiment, and have been qualified according to it.

Both have shown a certain accuracy and validity domain.

ex: Alpert correlation for ceiling-jet was studied for r/H<3.

The control of the right use of it must be done inside the code (for instance : produce "warnings" when getting out of a validity domain).

The sub-model validation is so considered during the zone-model conception, but :

- » A sub-model used outside of its validity domain does not necessarily mean that the global code results will not be acceptable.
- » Deduce the accuracy of a code from its component ones is not possible.

The validation of the global model remains always a necessity.

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Validation of the global zone-model

The objectives of the Zone model validation are the accuracy of the result data and the validity domain. Both are linked : the acceptable accuracy domain is the validity domain.

Accuracy of the code seems impossible to determine theorically, but it can be displayed by confrontation to experimental fire, and estimated by this means.

The accuracy of a fire model, observed by comparison to experimental fires, remains quite rough :

- too many parameters are involved in the fire process
- some complex phenomena (combustion, mass flow, etc..) cannot be completely described.

Furthermore, when using the model in a real life risk study, the input control will be much worse and will interfere with accuracy.

So, it is not necessary to seek a very high level of accuracy when confronting experimental and numerical results.

.../...

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Aims of the validation

.../...

The most important is to show that the code:

1- gives realistics quantitative results in its current application field

2- respects the qualitative tendancies in the fire dynamics and the effect of input variations

The validation process is demonstrative : it has to proove that, when the input parameters are efficiently controlled, the code results are sufficiently realistic, in the range of the code current application field.

The way of using the code in this process must be similar to the way it is used for typical fire risk studies.

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Validation "code of ethic"

Quality of the reference tests :

To be demonstrative, the tests must be well known, approved and accepted by the scientist community. Of course, the quality of the experiment is the main factor of this acceptance, and has been discussed a lot (ex: ASTM e603)

Conditions of the code use:

To enhance the confidence and decrease the user effect, the input of the code during the test must be clearly identified.

Any user modeling choice (fixed exchange coeff., plume model,etc..) specific to the calculation must be identified, or, as much as possible, avoided.

Field covered by the tests :

The tests should cover the field of application of the code. First building configuration : mall to medium scale compartment configuration, multi-compartment and large scale tests, opened or confined condition for instance. Also, fire parameters: kinds of combustible, heat release rates, etc..

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The validation File of MAGIC

- Validation of Magic is based on comparison to real scale fires. About 60 real scale fire tests are available in the base.
- The file is used to define the validation domain of the code:
  - Volumes from 10 to 1300 m^3 (200 000 m^3 case at work)
  - Heat release from 100 kW to 2.5 MW (60 MW case at work)
  - Ventilated and post-flashover fires
  - Mono-compartment and multi-compartment varied configurations
  - Liquid fires, solid fires
  - Pool fires, linear fires

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MAGIC : A large validation file

- **Main data available :**

Semi-natural fires in a room: Hognon B. CSTB/ DGRST-CSTB 1980
and Carmier, Curtat, Hognon, Bertin - CNRS - CSTB 1984
Semi-natural fire in a commercial hall corridor : N. C. Markatos, M.R. Malin "Int J Heat transfer" Vol. 25 n° 1 p. 63-75 BRE/FRS 1986
Fires in ventilated rooms: (Alvares N.J., Hasegawa H.K., Lipska.Quin A.B.) Report UCRL-53179, LLNL, Univ. of California, Livermore 1982
Fire in a compartimented building (Cooper L.Y& al.) J. of Heat Transfer vol. 104 pp 714-749 NBS (1982)
Real-size tests in multi-compartimented buildings : R.D Peacock, S. Davis, V. Babrauskas "Data for room Model Comparisons", Journal of research of the NIST, vol 96, N°4, 1991.
Control-room tests FM/SNL : S. Nowlen NUREG/CR-4681 1987
20-foot separation tests UL/SNL : NUREG/CR-3192 1983
Large cable fire tests (2 compartments) EDF-CNPP : CNPP TR 96 5045 P1 -1997
CTICM Hotel-room : H. Leboigne Test reprt 96S511 (1996) Linen-room (2 compartiments, post-flashover): H. Leborgne TR 97S031 (97) Large hall tests : TR 98-x-406 (97) ; TR 94-R-242 (94)

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Code quality assurance

- The validation file is used systematically to guarantee no regression of new versions (~20 selected tests). Any difference between versions must be justified.
- The code is always in standard conditions when launching the reference tests (Quality Assurance Process). The validation file is part of the documentation and can be easily re-played by the user.

<u>note: Verification of code Specification :</u>

Verification of code specification (respect of sub-model specifications, running of the different part of the code, etc..) is a different task than validation, which is done through an Assurance Quality process.

This aspect must not be neglected because the validation tests are not necessary covering all the code functionalities.

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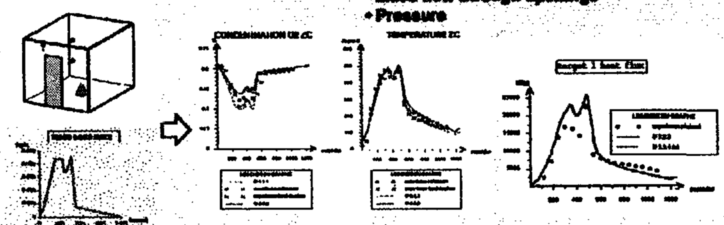
Direct comparison of num. and exp. data

Model necessary input :
- Building materials and configuration, boundary conditions
- Combustible properties and location
- Mass loss rate scenario

Commonly available data for comparison :
- Local temperatures, average temperatures
- Heat exchanges on targets (fluxmeters)
- Interface height
- Gaz velocities
- Species concentrations (O_2, CO_2, CO, CnHm NOx, SOx,...)
- Mass flow through openings
- Pressure



Mono-compartment test (CSTB 84)

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What and how to compare ?

What :

The first comparison is generally done on gaz temperature and fluxes, considering at less the range and delay of the peaks.

Those variable represent the thermal boundary condition for the materials to protect. Nevertheless, they are not easy to obtain, being very unstable, linked to mass flows and radiation. In somecases it seem that internal temperature of targets could be an interesting alternative to develop.

The other measurements are less frequent, some like pressure or mass flows are rarely provided.

How:

The comparison is first a "visual" analysis of differences.

Numerical analyse can be done, based on relative difference :

ex: (Tmes-Tcalc)/ (Tmes-To) as a error percentage.

Sensitivity to input variation has been done in the process of qualifying the physic model adjustments.

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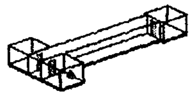
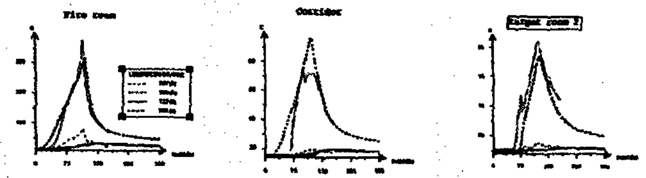
Multi-compartment validation : example

- Thermal conditions in the fire room
- Propagation of smoke and hot gas to the secondary compartments





ex: test n°30 from NIST 4 room series , 210 m³, 1 MW (in 120 s)

International Collaborative Project to evaluate fire Models for NPP applications 8-9 may 2002
Research & Development Division

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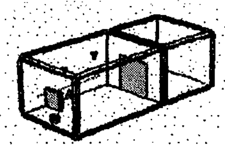
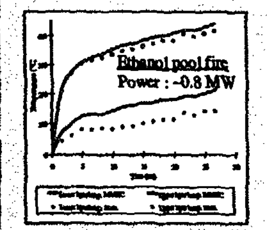
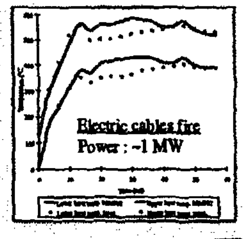
Large cable fire (CNPP 1997)

- 2 room "NPP-like" configuration
  - 7 superposed PVC cable tray fire (~300kg burnt)
  - Pool fire







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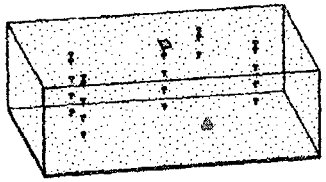
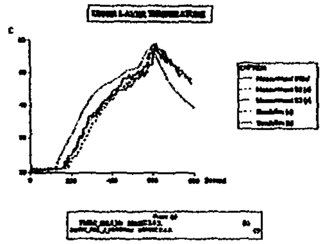
Control-room fire (SNL/FMRC 87)

650 kW gaz burner, 1361 m³





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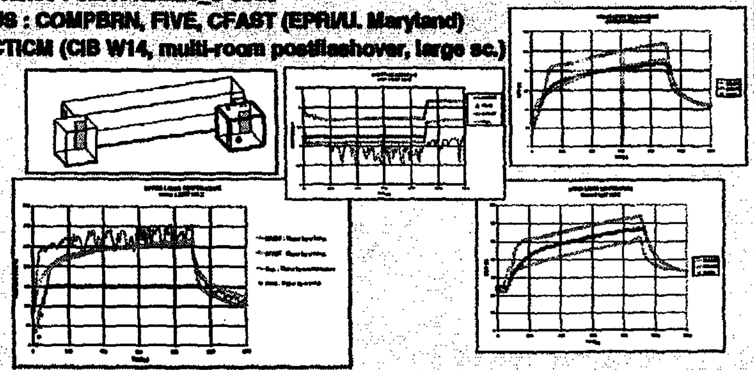
Comparison to other codes

- •France : CEA Flamme_S code
- •US : COMPBRN, FIVE, CFAST (EPRI/U. Maryland)
- •CTICM (CIB W14, multi-room postflashover, large sc.)



ex: test n°M100Z from NIST 3room series, 100m³, 100kW

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Future prospects

Enhancement of the validation file :

- Targets temperature : fluctuate less than gas temp. and more relevant for risk studies (dysfunction, ignition) (2002).
- Pressure measurment and interaction with ventilation system (2002)
- Fire suppression effect
- Complex multi -room configurations : horizontal openings and duck-board.

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Conclusion of EDF experience

- The validation File is the key of code acceptance
- Real-size and a large field of experiment data is important.
- Tests must be of good quality, available and accepted by the scientific community.
- The process of code validation must be independent of modeling choices and available to the final user.
- The results obtained with MAGIC on a selection of experimental data has allowed us to get confident for its use in a large range of volumes, heat release and configurations.

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Enhancements to the FIVE Methodology

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University of Maryland

Acknowledgements

- The "heavy lifting" for this project was performed by Francisco Joglar-Billoch, currently with SAIC
- Partial support for this project was provided by Brookhaven National Laboratory and the USNRC

FireMD - Slide 2

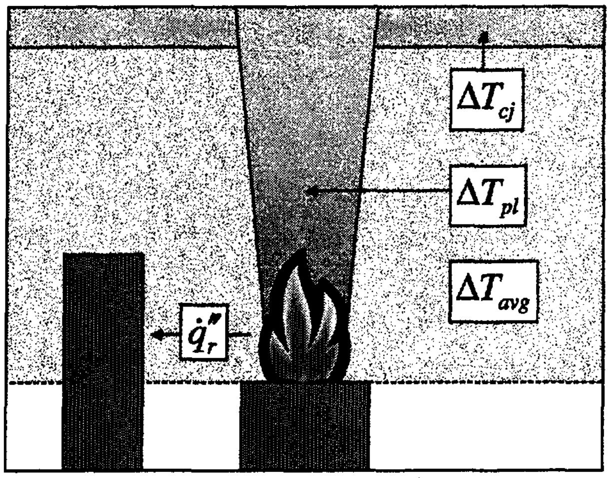
Background on FIVE

- Developed by EPRI in early 1990s for nuclear utilities to use in IPEEEs
- Included two parts
  - Overall methodology developed by PLC
  - Methods of quantitative fire hazard analysis developed by Mowrer
- Fire hazard analysis methods intended for screening purposes
  - Widely used for qualification purposes

The FIVE methodology

- Developed as series of lookup tables for one-zone one-room analysis
  - Average gas temperature
    - Unventilated enclosure (base case)
    - Naturally ventilated enclosure
    - Mechanically ventilated enclosure
  - Fire plume sublayer
  - Ceiling jet sublayer
  - Thermal radiation

The FIVE methodology



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The FIVE methodology

- Average hot gas layer temperature

$$\Delta T_{avg} = T_o \left[exp(Q_{net} / Q_o) - 1 \right]$$

- Plume temperature

$$\Delta T_{pl} = \Delta T_{avg} + 25 \frac{\dot{Q}_c^{2/3}}{z^{5/3}}$$

- Ceiling jet temperature

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.32}{(r / H)^{2/3}}$$

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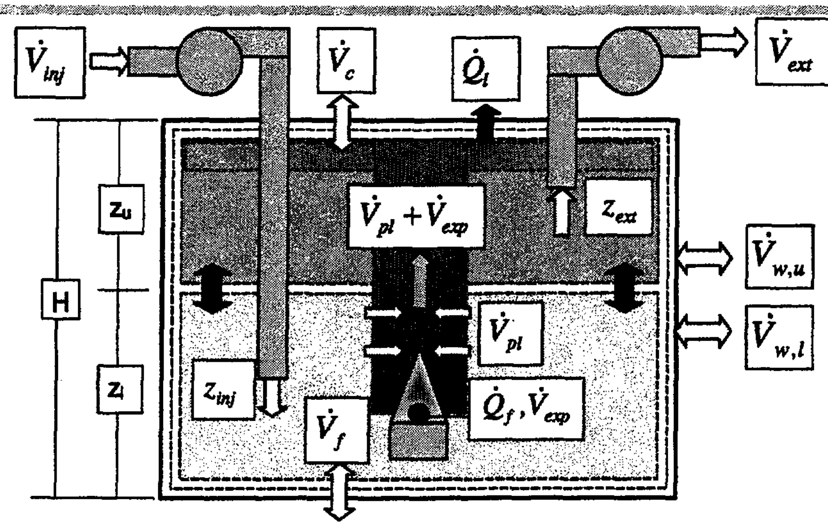
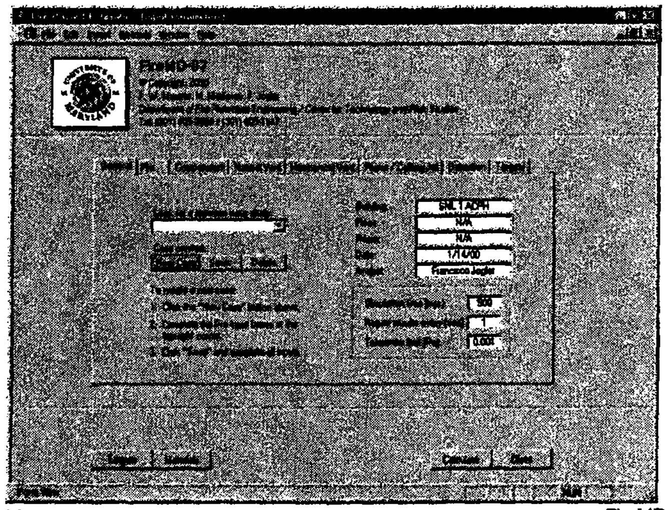
FireMD features

- A one-room two-zone fire model with the following features:
  - Implemented in Access and Excel (97 / 2000)
  - Natural and mechanical ventilation
    - Floor / wall / ceiling vents
    - Specified injection / extraction rates
  - Plume / ceiling jet sublayers
  - Detection algorithm with RTI / conduction
  - Target / boundary heating

FireMD diagram



FireMD - General



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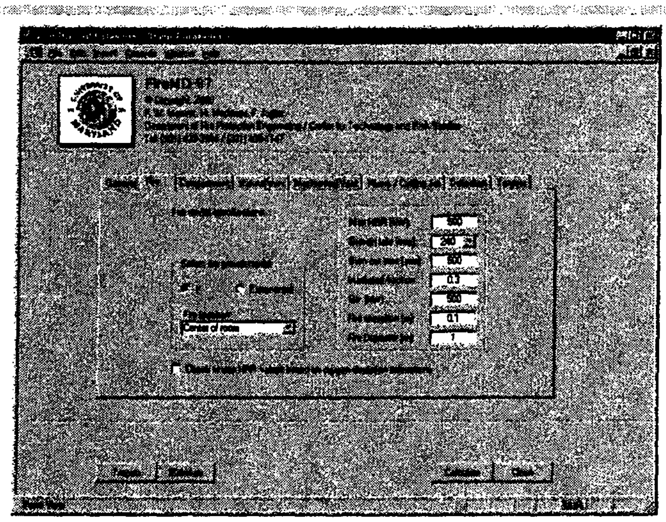
FireMD - Slide 9

FireMD - Fire



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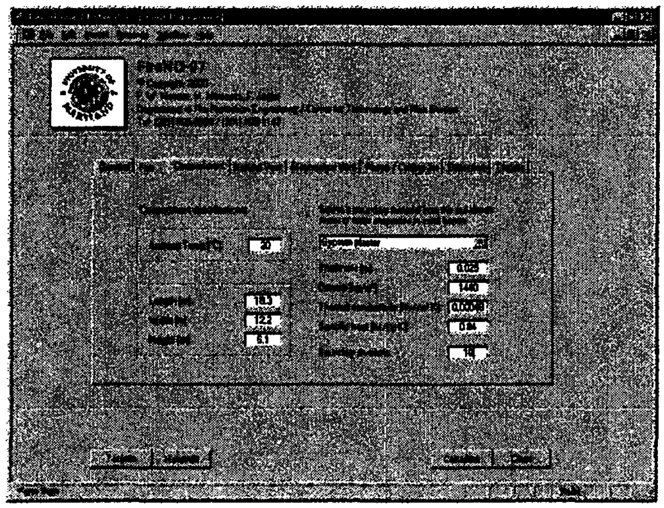
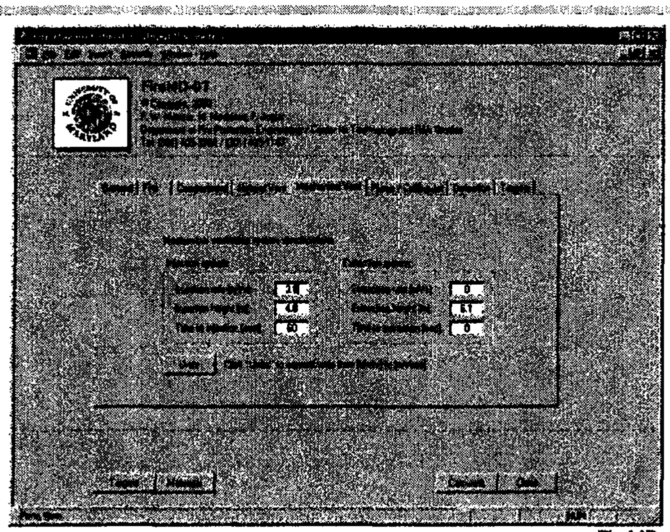
FireMD - Slide 10

FireMD - Compartment



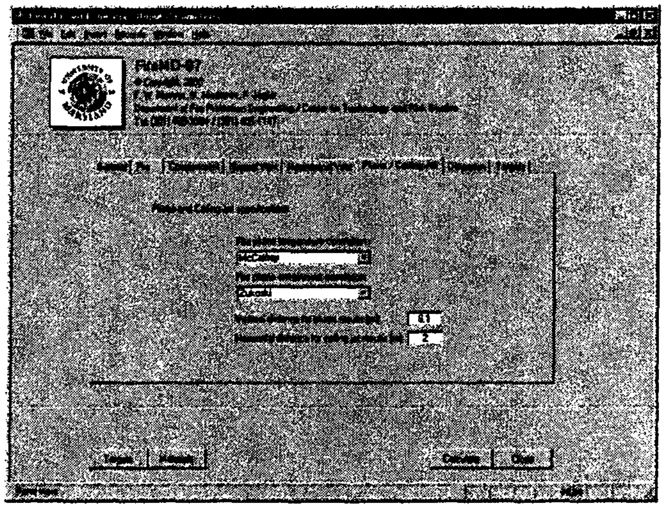
FireMD - Slide 11

FireMD - Ventilation



FireMD - Slide 12

FireMD - Plume / CJ



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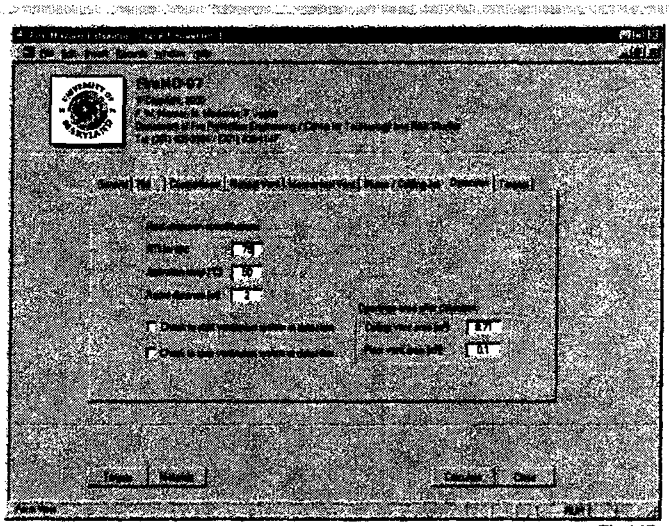
FireMD - Slide 13

FireMD - Detection



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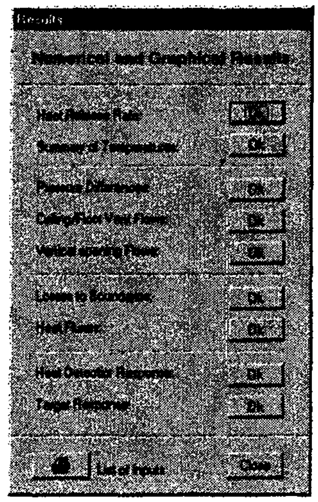
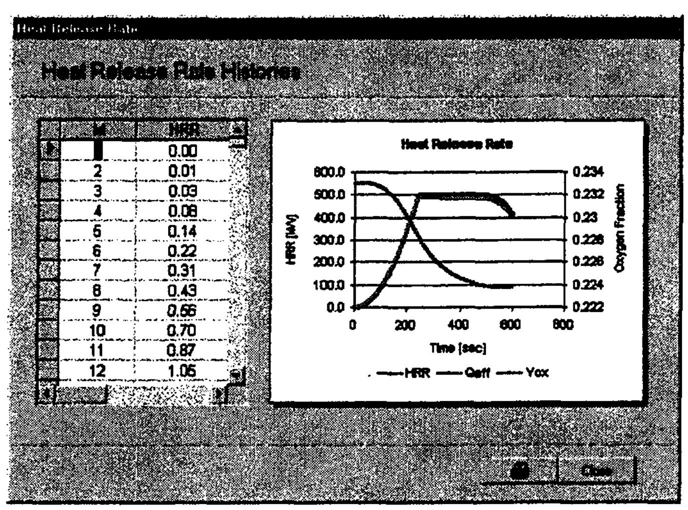
FireMD - Slide 14

FireMD - Results



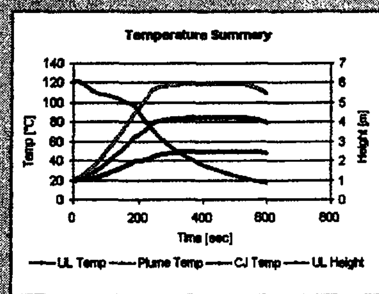
FireMD - HRR



FireMD - Temperatures

Temperatures and Smoke layer height

Id	UL Temp	Plume
1	20.00	20
2	20.03	20
3	19.92	20
4	20.21	20
5	19.86	20
6	20.14	20
7	20.06	20
8	20.09	20
9	20.12	20
10	20.14	21
11	20.16	21
12	20.19	21

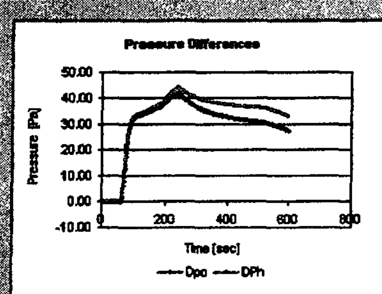


Close

FireMD - Pressures

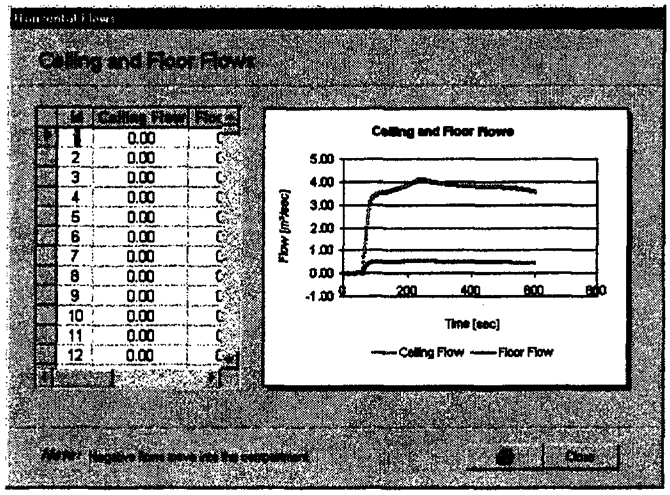
Pressure Difference at Floor and Ceiling

Id	Dpo	DPh
1	0.00	0.00
2	0.00	0.00
3	0.00	0.00
4	0.00	0.00
5	0.00	0.00
6	0.00	0.00
7	0.00	0.00
8	0.00	0.00
9	0.00	0.00
10	0.00	0.00
11	0.00	0.00
12	0.00	0.00

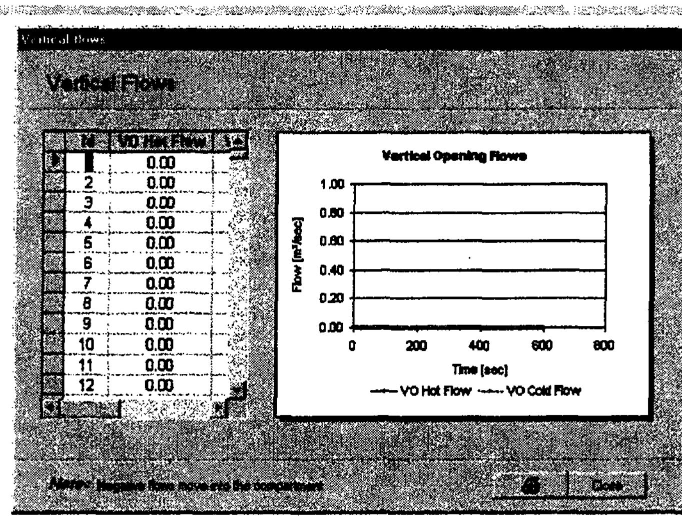


Close

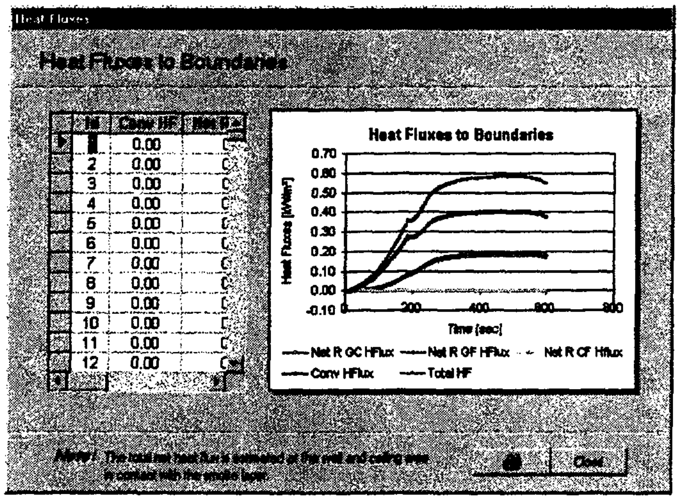
FireMD - Ceiling/floor



FireMD - Vertical flows



FireMD - Heat fluxes



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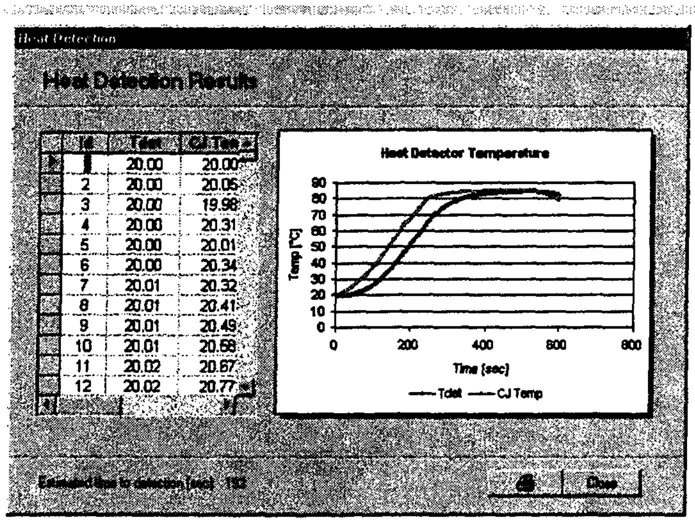
FireMD - Detection



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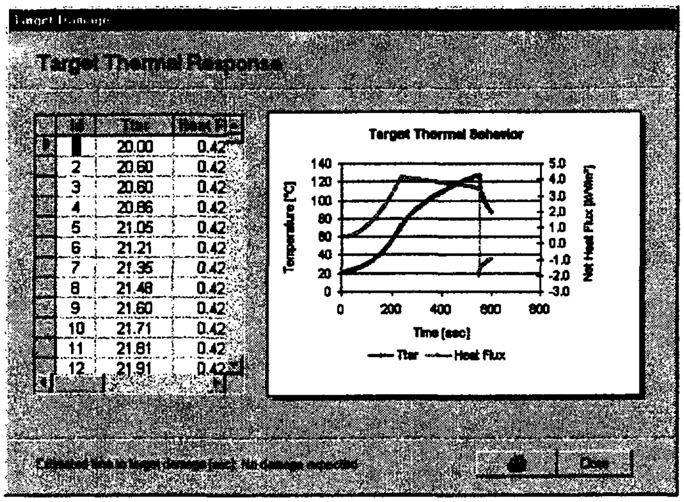
FireMD - Target



FireMD validation studies

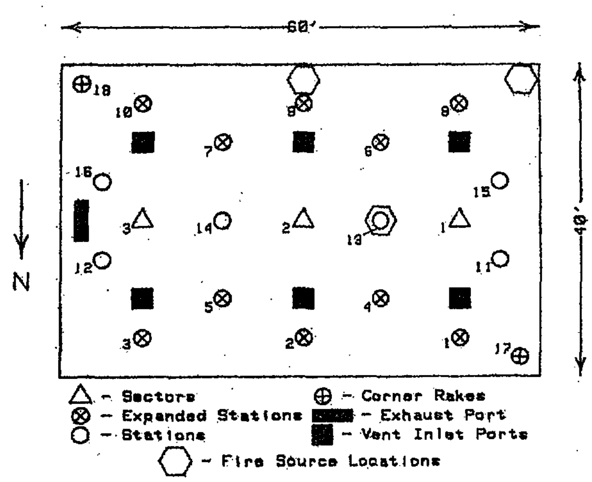
- FMSNL baseline validation enclosure fire tests
- LLNL mechanically ventilated enclosure fire tests

FMSNL series

- Enclosure
  - 18.3 m (60') x 12.2 m (40') x 6.1 m (20') high
- Fire sizes / durations
  - 500 - 2000 kW / 10 - 20 minutes
- Ventilation
  - Mechanical injection through 6 vents located 1.2 m (4') below ceiling
  - 0.4 - 3.8 m^3/s (1 - 10 changes/hour)

FireMD - Slide 25

FMSNL instrumentation

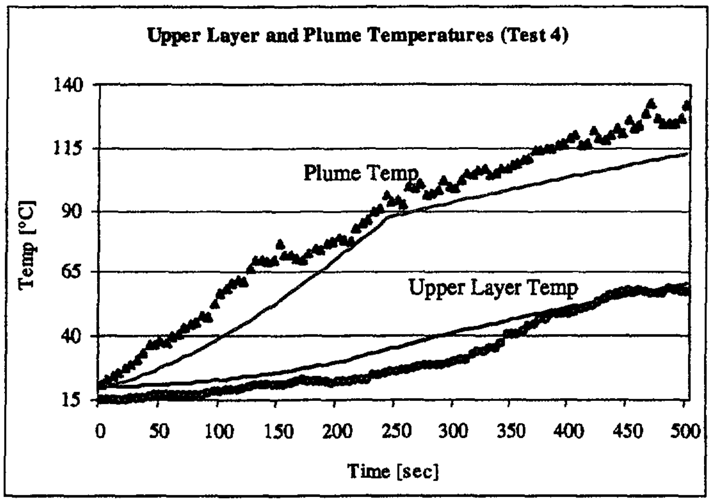


FireMD - Slide 26

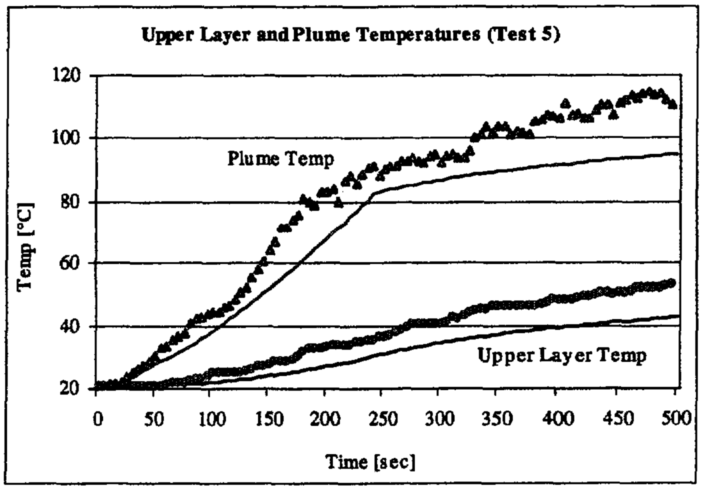
FMSNL series

- Test 4:
  - 1 air change per hour (0.38 m^3/sec)
  - Peak HRR = 500 kW, Growth time = 240 sec.
- Test 5:
  - 10 air changes per hour (3.8 m^3/sec)
  - Peak HRR = 500 kW, Growth time = 240 sec.
- Test 9:
  - 8 air changes per hour (3.3 m^3/sec)
  - Peak HRR = 1000 kW, Growth = 480 sec.

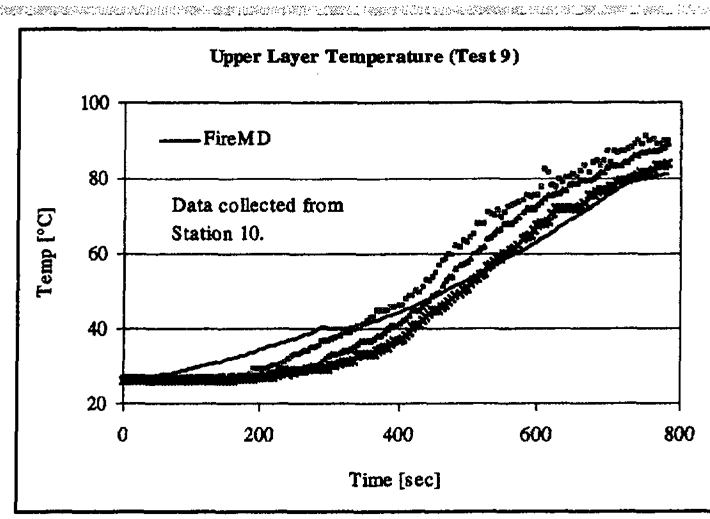
FMSNL Test 4



FMSNL Test 5



FMSNL Test 9



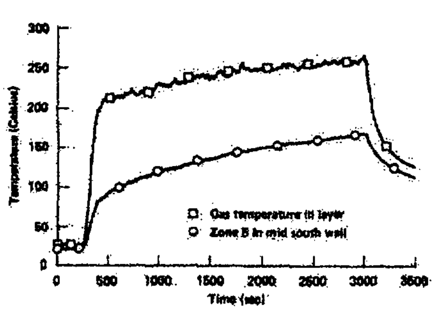
LLNL series (Mod27B)

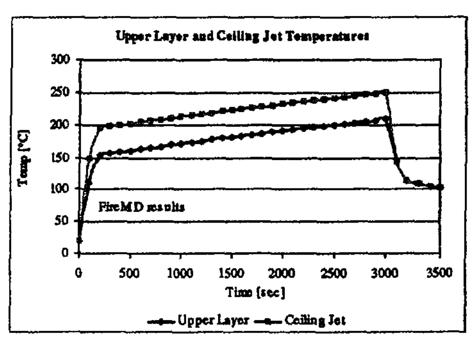
- Enclosure
  - 6.0 m (20') x 4.0 m (13') x 4.5 m (15') high
- Fire size
  - Steady 400 kW fire
- Ventilation
  - Mechanical extraction at 0.25 m^3/s through vent located 0.36 m (1.1') above floor
  - Makeup air through 0.24 m^2 inlet 0.1 m above floor

FireMD - Slide 31

LLNL Mod27B

- Upper layer temperature

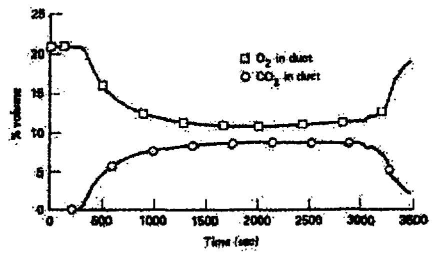


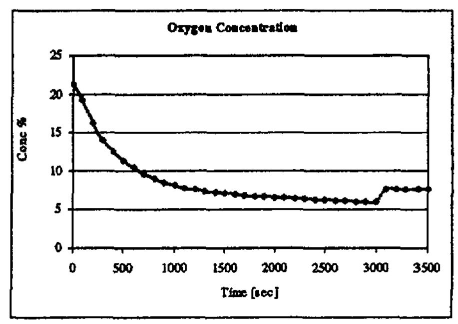


FireMD - Slide 32

LLNL Mod27B

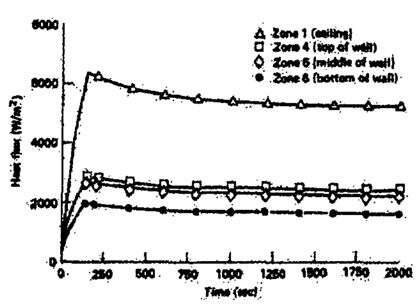
- Oxygen concentration

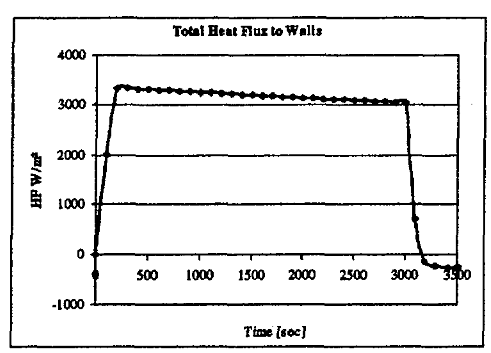




LLNL Mod27B

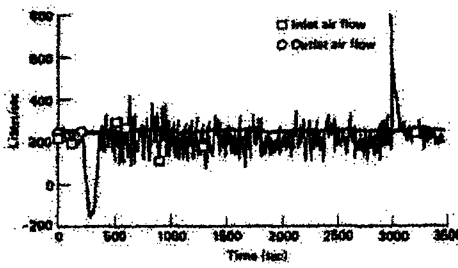
- Wall heat flux

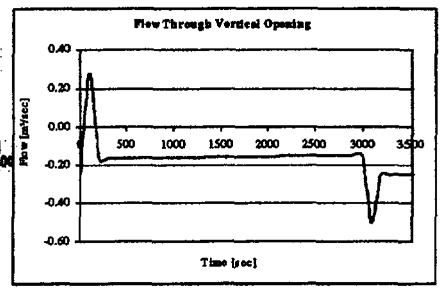




LLNL Mod27B

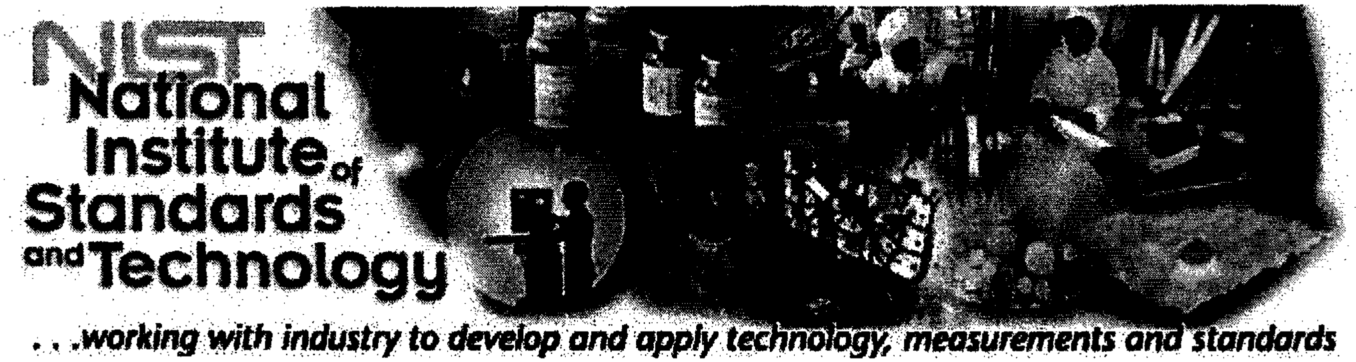
- Inlet / outlet air flow





Summary

- FireMD provides useful enhancements to FIVE
- FireMD predictions compared with experimental measurements for a range of enclosure sizes, fire intensities and ventilation conditions
- FireMD predictions are generally within ~20% of measurements for temperatures and flow rates
- Further work needed on O2 concentration and higher temperature fire conditions
  - No work currently being done on the model



Verification and Validation of CFAST

Walter W. Jones
Analysis and Prediction Group
Building and Fire Research Laboratory

5th Meeting of the International Collaborative Fire Model Project

May 2-3, 2002

NIST

The Three Legs of Modeling for Public Safety

- Zone Modeling
  - **CFAST (and the GUIs)**

- Validation and Verification
  - **Through statistical analysis**

- Data for comparisons
  - **FASTData database development**

Modeling

- CFAST - zone model
  - Large (complex) building simulation
  - Input/model/output
- FAST/FASTLite/FireWalk/FireCAD
  - GUI interfaces for fire models
  - Includes simple back of the CRT calculation

NIST

Concept of a Zone Model

Each compartment is subdivided into "control volumes," or zones. Conservation of mass and energy is applied to each zone.

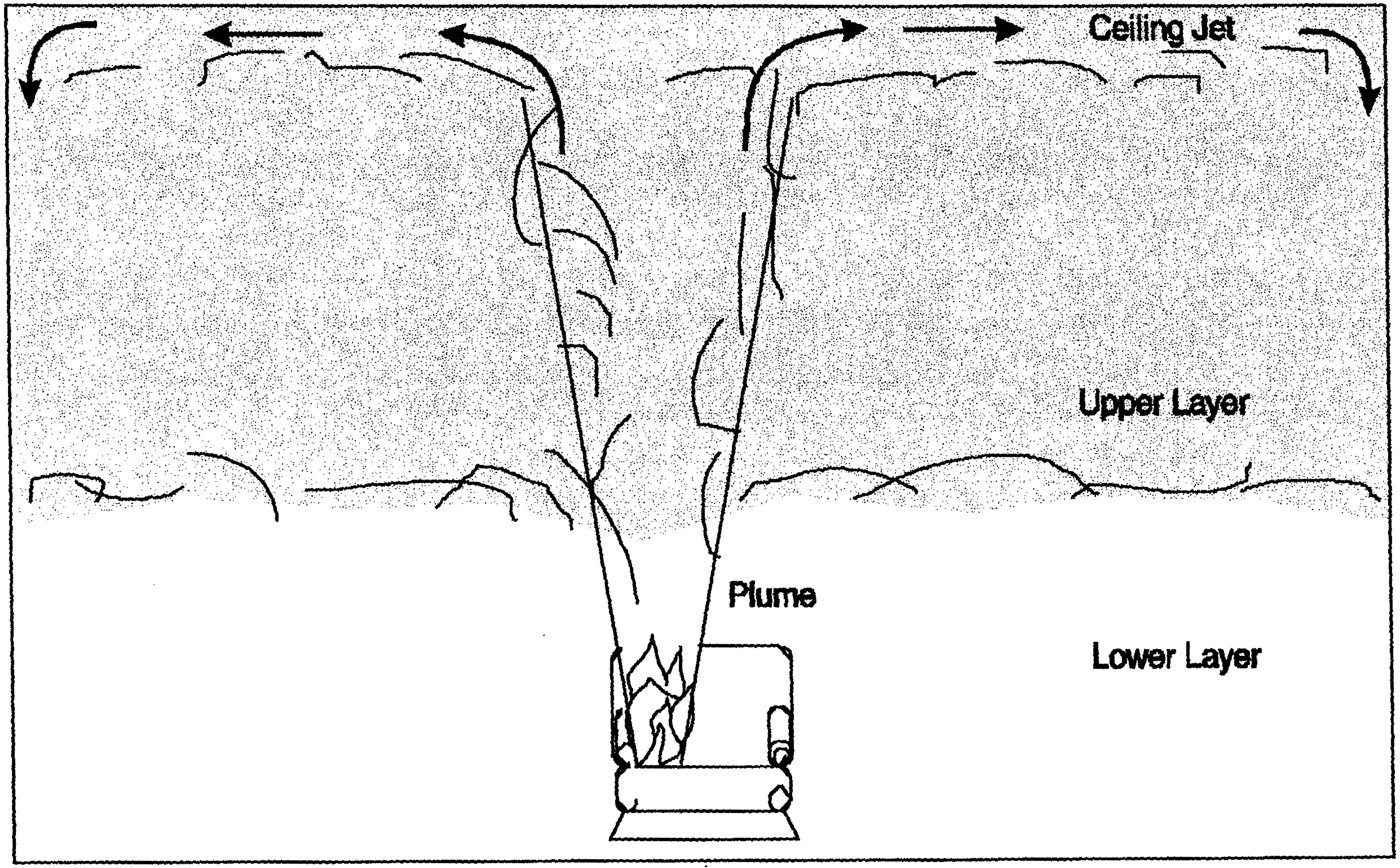
A few zones (2 to 10)

Predictive equations are derived from conservation of energy and mass (momentum at boundaries)

Use ordinary differential equations rather than partial differential equations

Adding phenomena is *relatively* easy

Concept of a Zone Model



Why Is this Modeling Important?

- Speed – algorithm implementation is very important

- Do parameter studies of complex buildings
  - Complex and numerous connections

- Predict (small variations do not matter)
  - Environment (CO, ...)
  - Insult to the structure

NIST

Zone Models in the U.S.

CFAST - 2.0.1 - HAZARD I version 1.2

CFAST - 3.1.5 being used in fire reconstruction

Compbrn III - UCLA - consulting with EPRI

BRI2 (Japan) - Factory Mutual Risk Analysis

Many specialize tools such as FPETool (ASET, ASCOS, ...)

Phenomena

Multiple compartments (60->~100)

- Variable geometry

Multiple fires

- Ignition: time, flux or object temperature

Fire plume and entrainment in vent flow

Vitiated or free burn chemistry

Four wall and two layer radiation

Four wall conductive heat transfer through multilayered walls, ceilings and floors

Wind effects

3D specification of the location of the fire and non-uniform heat loss thru boundaries

Phenomena

D-123

Generalized vent flow

- Horizontal flow (doors, windows , ...)
- Vertical flow (holes in ceilings/floors)
- Forced flow (mechanical ventilation)

Intercompartment heat transfer

Ceiling/floor

Horizontal - compartment to compartment

Horizontal smoke flow

Detection - smoke, heat

Suppression - heat release knockdown

Separate internal and external ambient(s)

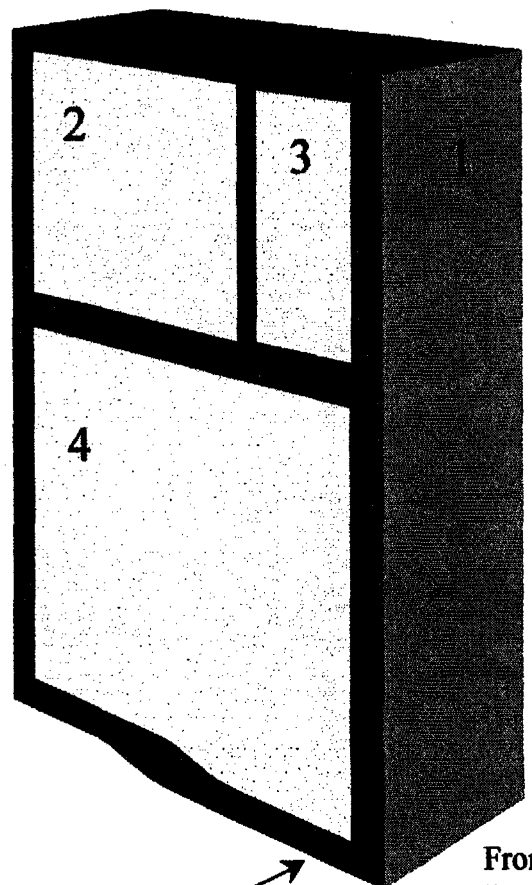
Intercompartment Heat Transfer (Horizontal Conduction)

Flux at rear of room 1 = weighted average of fluxes from front of rooms 2, 3 and 4 or ...

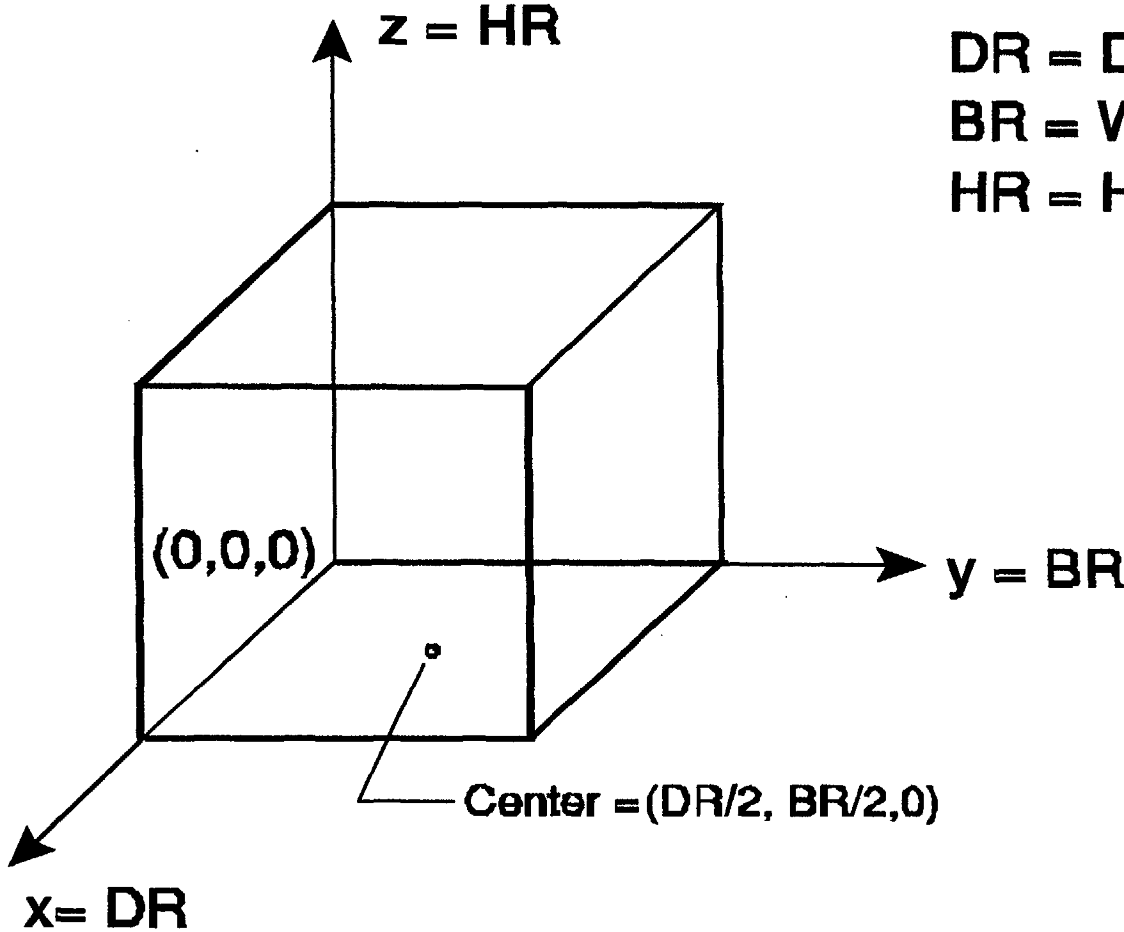
$$q''^{r}_{i,avg} = \sum_j F_{ij} q''^{f}_j$$

$q''^{r}_{i,avg}$	Average flux at rear of wall i
F_{ij}	Fraction of flux from the front of wall j contributing to the back of wall i
q''^{f}_j	Flux striking front of wall j

Wall joining compartments 1, 2, 3, 4



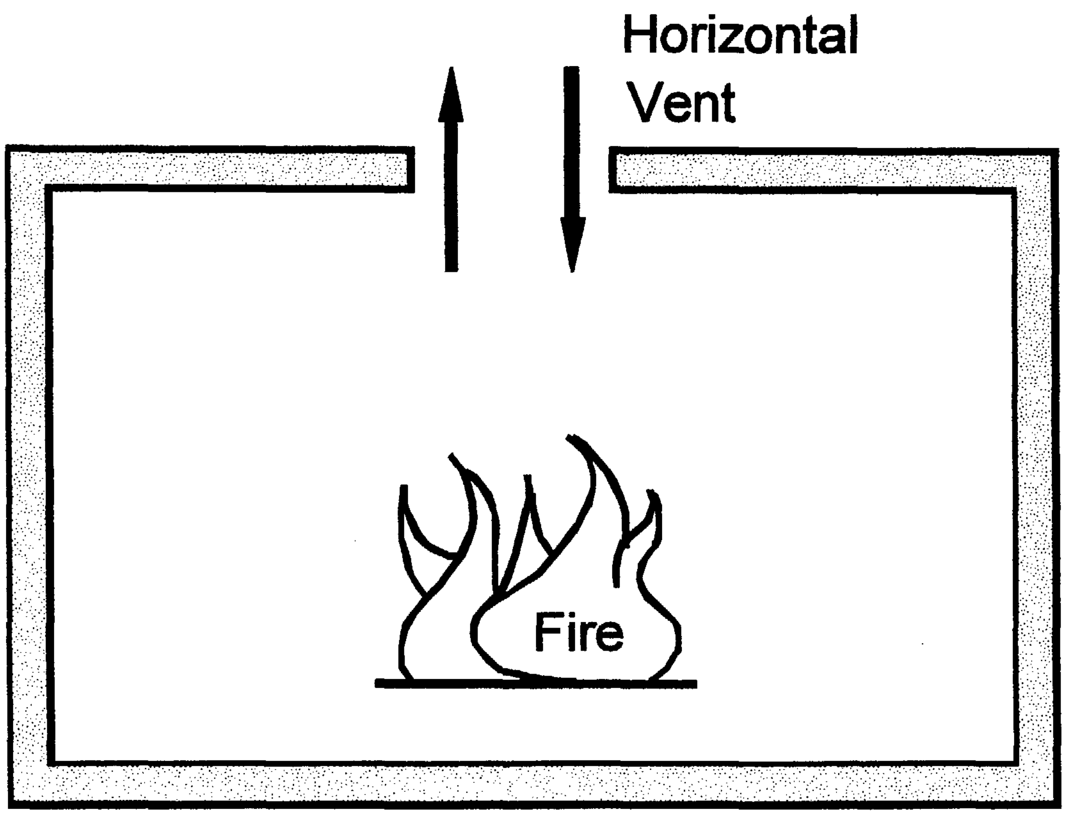
XYZ Positioning of Objects, Fires and Surfaces



DR = Depth
BR = Width
HR = Height

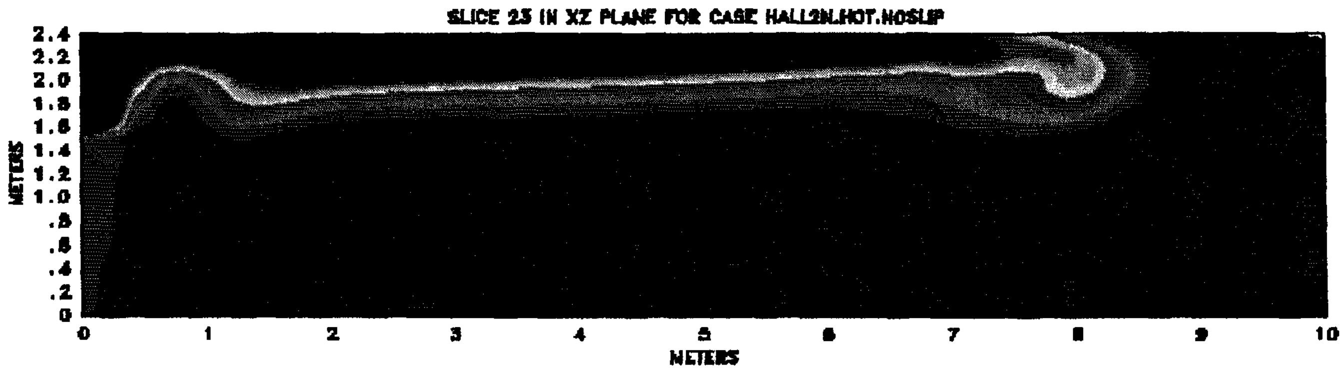
D-125

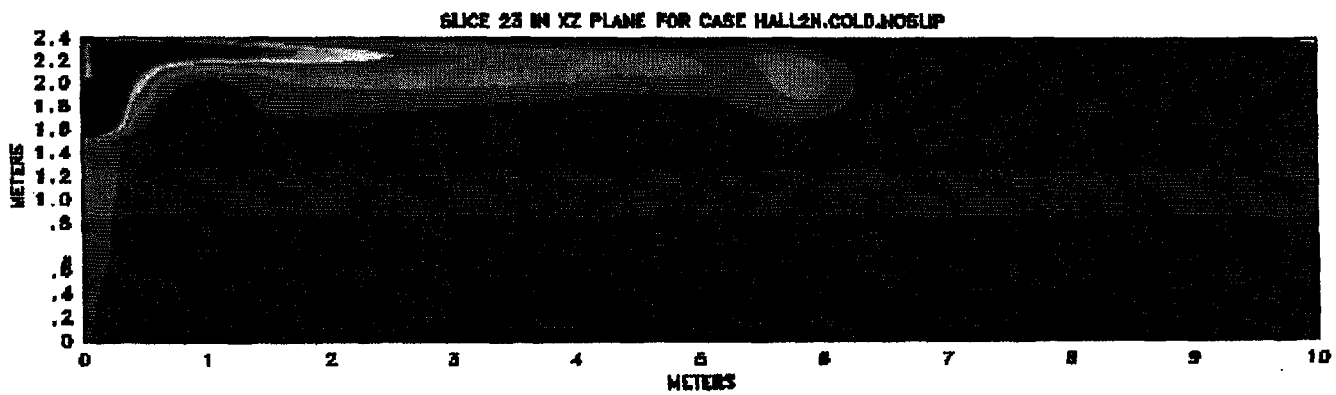
Vertical Flow
(Horizontal Vents)



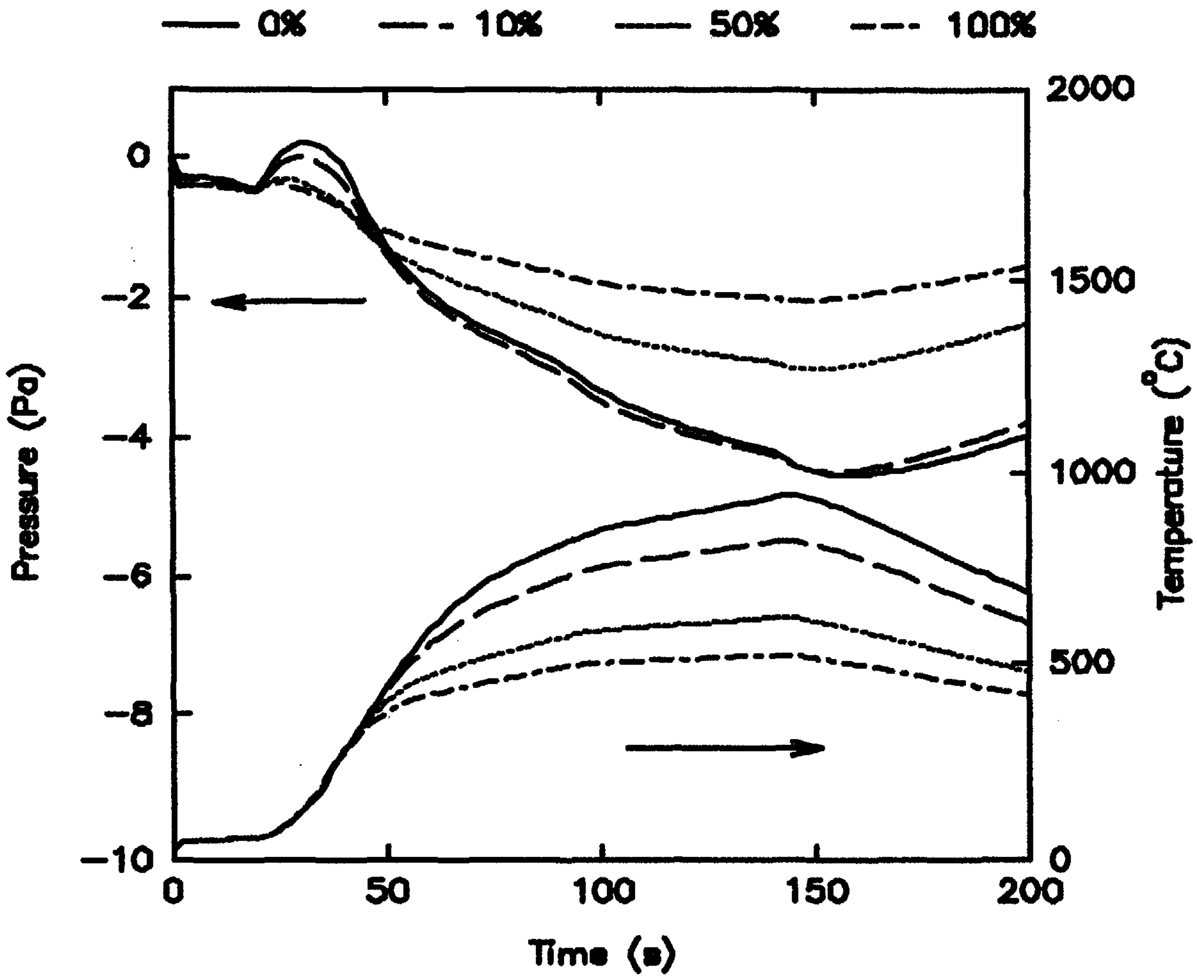
NIST

Corridor Flow



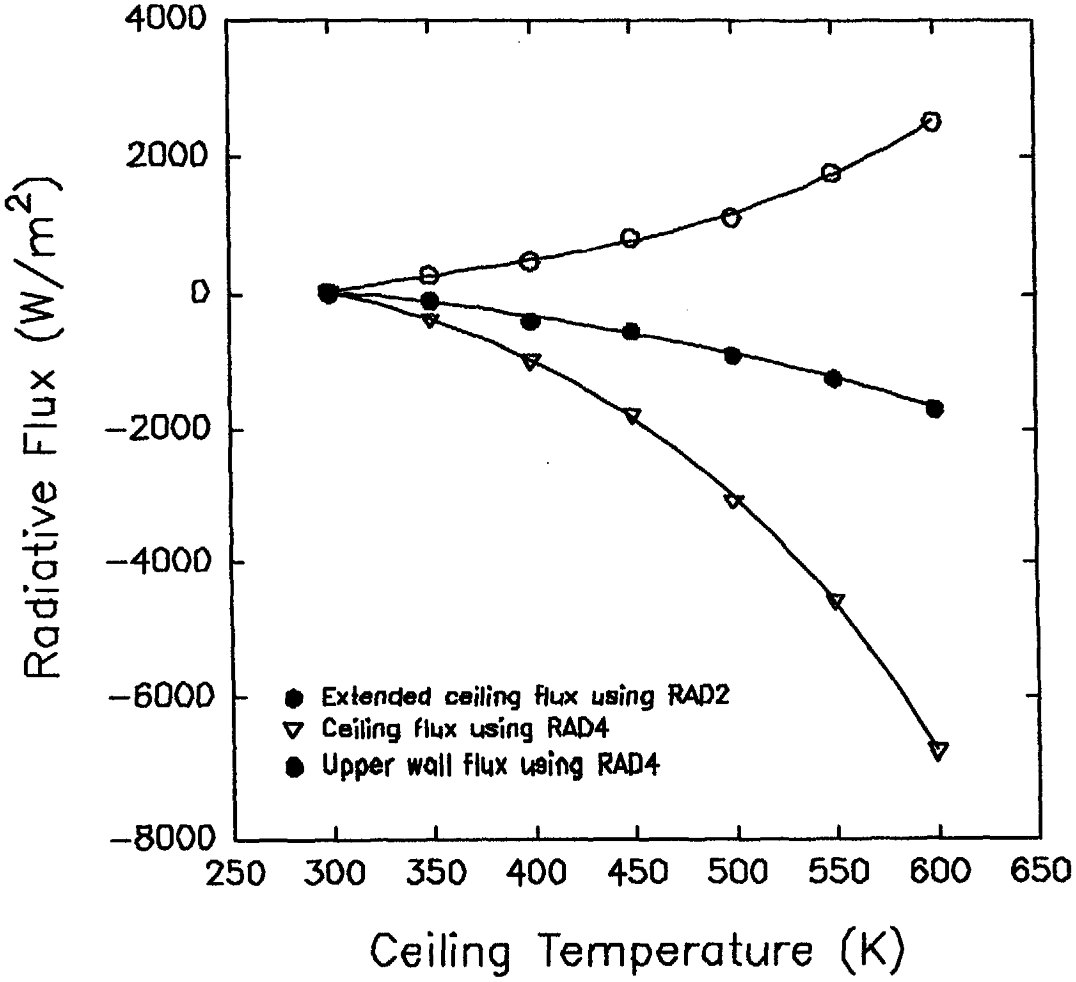


Leakage – Specification Errors



D-128

Effects we can examine closely



NIST

Verification *vs* Validation

- Verification: insuring that the phenomenology is implemented correctly in the model
- Validation: insuring that a model makes the correct (expected) prediction for a given set of input data
- For public safety and finding economies of scale, both are important

Issues Related to Verification

- Comparison with experimental data, including error analysis
- Open system - published code (verification, not validation)
- Documentation - crucial
- Sensitivity analysis (suite)

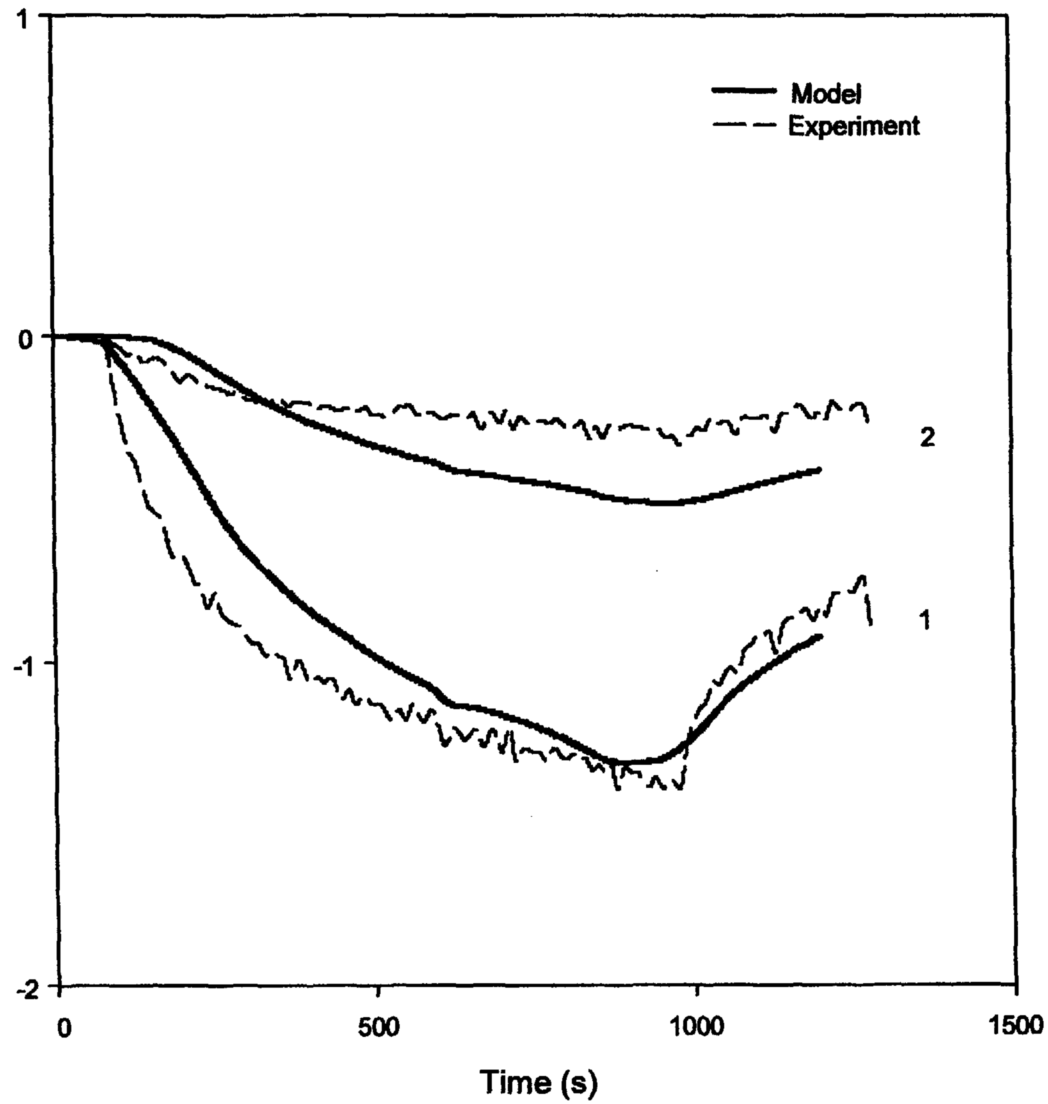
NIST

Quotes on Verification

- "The simulations generally compare favorably with the experiments"
- "Upper layer temperatures were not predicted well by either model"
- "Layer heights are well predicted by both models only in the burn room"
- "All of the models simulated the experimental conditions quite satisfactorily"
- "For the 4 MW fire size, all of the model do reasonably well"

NIST

Statistical Verification



NIST

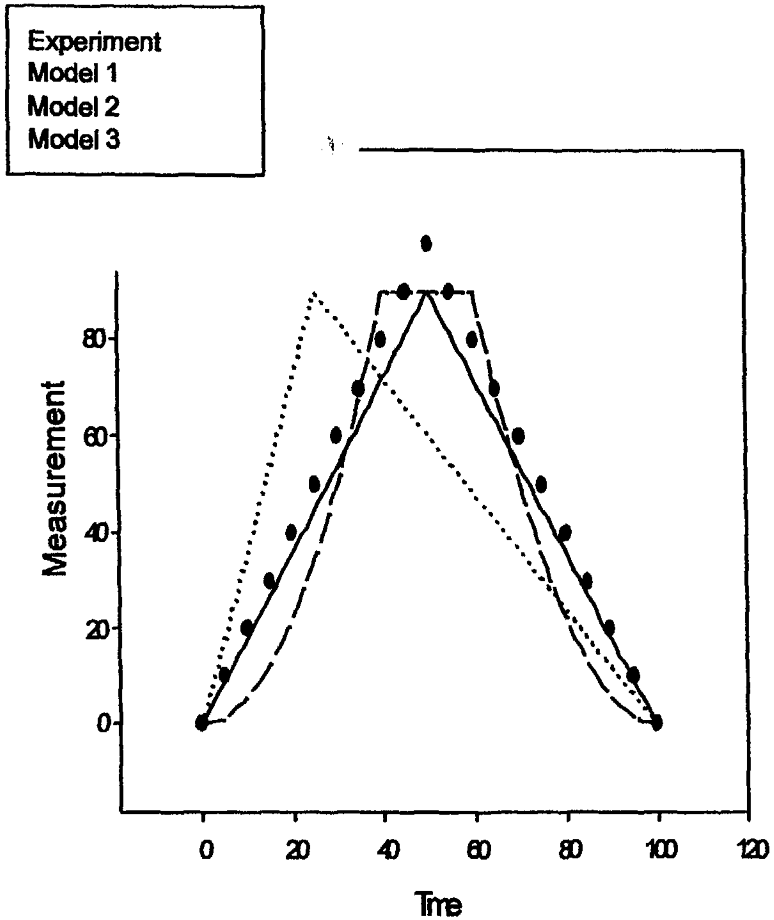
Possible "Norms"

$$\left\| \vec{x} \right\| = \sqrt{\sum_{i=1}^{n} x_i^2}$$

D-134

$$\left\langle \vec{x}, \vec{y} \right\rangle = \frac{\sum_{i=1}^{n} (x_i - x_{i-1})(y_i - y_{i-1})}{t_i - t_{i-1}}$$

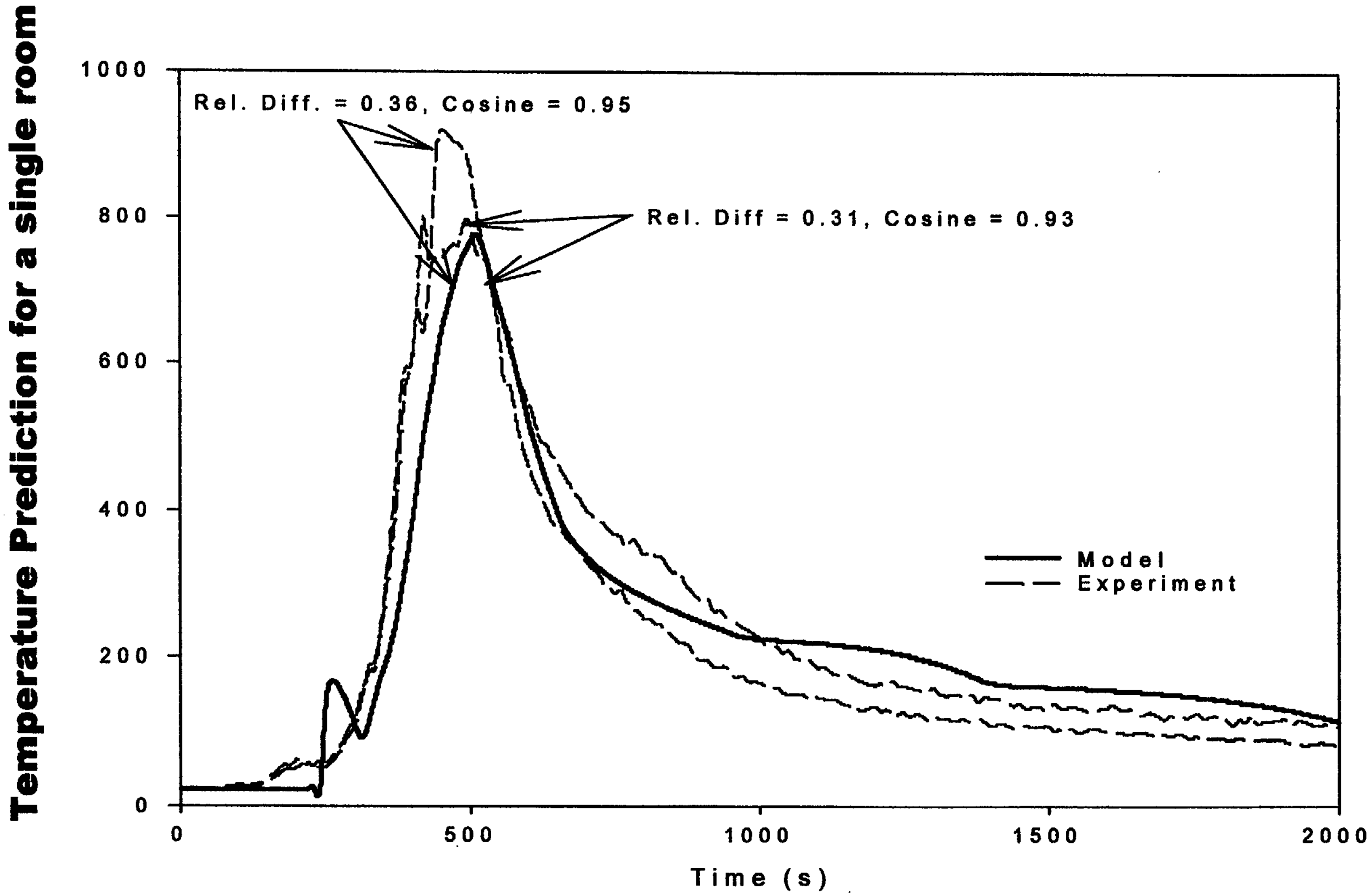
Example of Metrics



product definitions

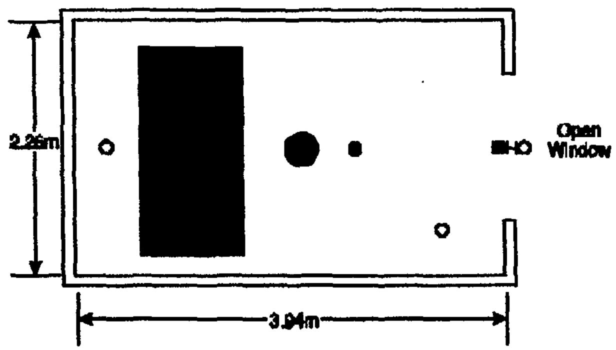
Geometry	Model	Relative Difference	Cosine
Euclidean	1	0.10	1.00
	2	0.40	0.92
	3	0.20	0.98
Hellinger	1	0.10	1.00
	2	0.94	0.58
	3	0.74	0.77
Secant	1	0.10	1.00
	2	0.92	0.58
	3	0.66	0.83
Hybrid	1	0.10	1.00
	2	0.64	0.78
	3	0.43	0.91

One of our real room comparisons

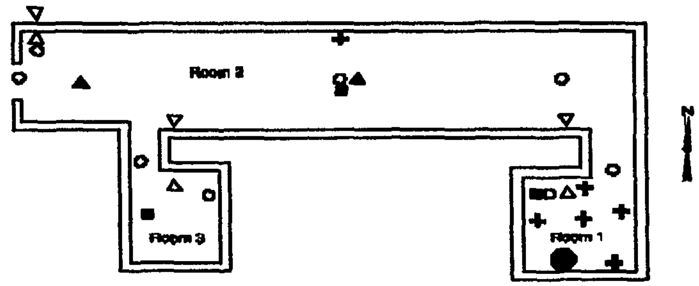


D-136

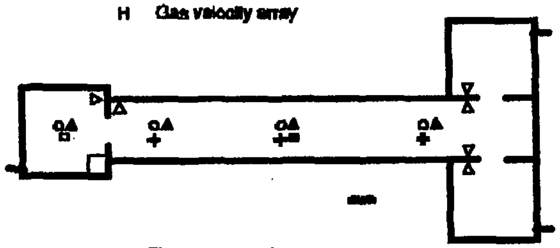
1, 3, 4 and Multistory Configurations



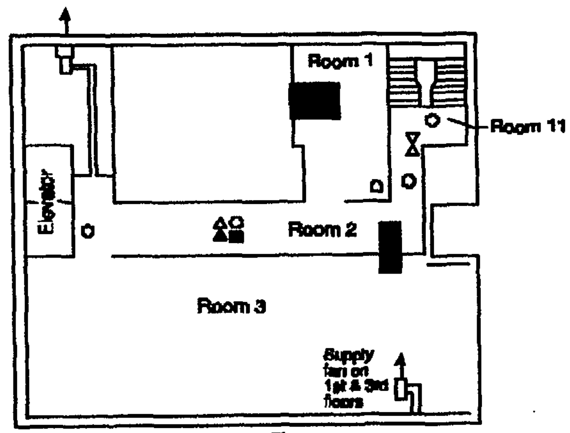
Fire source, specimen mass loss
Fire source, gas burner
Gas temperature array
Heat flux, floor level
Gas concentration (CO, CO_2, O_2)
H Gas velocity array



Fire source, gas burner
Gas temperature array
Surface temperature
Gas concentration (CO, CO_2, O_2)
Differential pressure array
Smoke obscuration, horizontal & vertical



Fire source, gas burner
Gas temperature array
Surface temperature (ceiling)
Gas concentration (CO, CO_2, O_2)
Gas concentration (CO, CO)
Differential pressure array
Smoke obscuration



Second Floor

Fire source, specimen mass loss
Gas temperature array
Gas concentration
Differential pressure (room 2 to room 4 do

An example with four real scale experiments

	Position / Compartment	Relative Difference	Cosine	Relative Difference	Cosine	Relative Difference	Cosine
Upper Layer Temperature and Interface Position							
		Upper Layer Temperature		**Lower Layer Temperature**		**Interface Position**	
Single-room furniture tests	1	0.31	0.95	0.47	0.92	1.38	-0.60
	2	0.36	0.93	0.63	0.78	0.63	0.78
Three-room tests with corridor	1	0.25	0.97	–	–	–	–
	2	0.26	0.99	–	–	–	–
	3	0.26	0.98	–	–	–	–
Four-room tests with corridor	1	0.51	0.93	0.33	0.95	2.26	0.06
	2	0.54	0.91	0.52	0.87	–	–
	3	0.36	0.97	0.78	0.86	–	–
	4	0.20	0.98	–	–	–	–
Multiple-story building	1	0.28	0.97	–	–	–	–
	2	0.27	0.96	–	–	–	–
	7	2.99	0.20	–	–	–	–
Gas Concentration							
		Oxygen		**Carbon Monoxide**		**Carbon Dioxide**	
Single-room furniture tests	1	0.48	0.90	0.93	0.66	0.69	0.93
Four-room tests with corridor	1	0.85	0.53	1.05	0.61	1.16	0.63
	2	0.93	0.39	1.02	0.57	0.90	0.63
Multiple-story building	2	0.74	0.68	0.72	0.90	0.87	0.93
Heat Release, Pressure, and Vent Flow							
		HRR		**Pressure**		**Vent Flow**	
Single-room furniture tests		0.19	0.98	–	–	0.61	0.79
Single-room tests with wall burning		0.21	0.98	1.31	0.80	–	–
Three-room tests with corridor	1	0.43	0.96	0.15	0.99	0.14	0.99
	2	–	–	0.68	0.98	0.20	0.98
Four-room tests with corridor		–	–	6.57	0.74	–	–
Multiple-story building	1	–	–	1.12	-0.41	–	–

Steps for Verification

- **1) Maintain a set of test data: small scale to real scale**
  FASTData (US), several others; not as useful as it should be

- **2) Maintain a set of data files which have given us problems in the past**
  Many of these are usability issues, but that affects predictions as well

- **3) Do are formal comparison of a "released" model with the results of past calculations**
  bintoasc, compare, compinfo - variable.dat includes allowable variance
  Appendix in technical guide
  Did through 3.1.6

- **4) Maintain a history of CFAST - earliest is March, 1989**
  In principle, one can reconstruct the executable for each release including intermediate versions. In reality this is not a practical exercise.

NIST

Conclusion

Validation and Verification are important

Statistical comparison (with metric) is possible

Needs more work

D-141

Numerical Simulation Of A Compartment Fire In A Nuclear Power Plant Containment Building

Jason Floyd

May 2002

Overview

- Multi-block FDS
- HDR facility and the T52.14 oil pool fire test
- Results

FDS

- Fire Dynamics Simulator v2 (Dec. 2001)
- Computational fluid dynamics – LES/DNS
- Building and Fire Research Laboratory, NIST
- Submodels
  - Mixture fraction combustion
  - Finite volume, gray gas radiation
  - 1D heat conduction
  - Pyrolysis (solid and liquid fuel)
  - Sprinkler dynamics and droplet evaporation

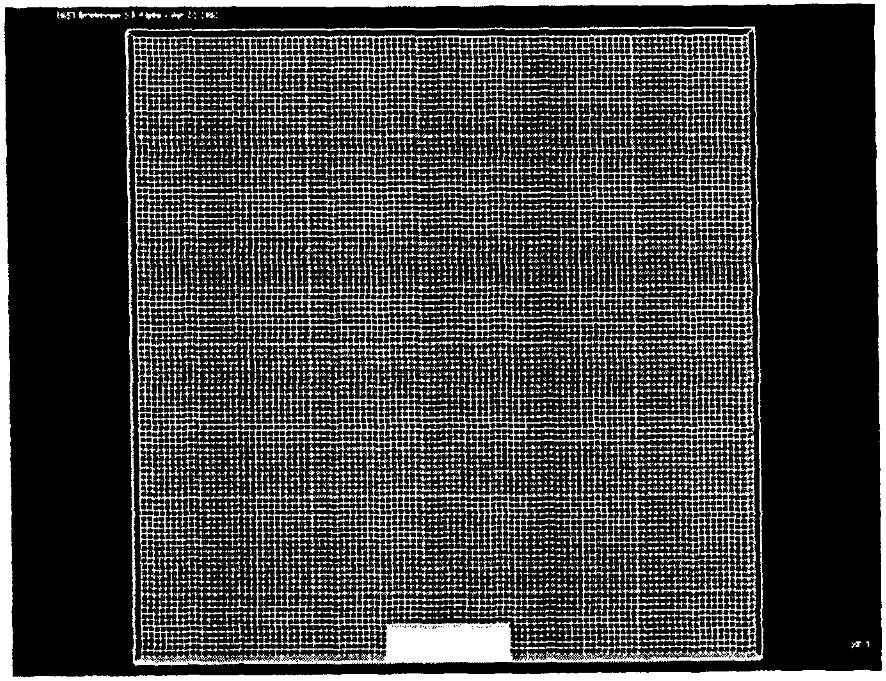
- Smokeview for data visualization

Multi-Block

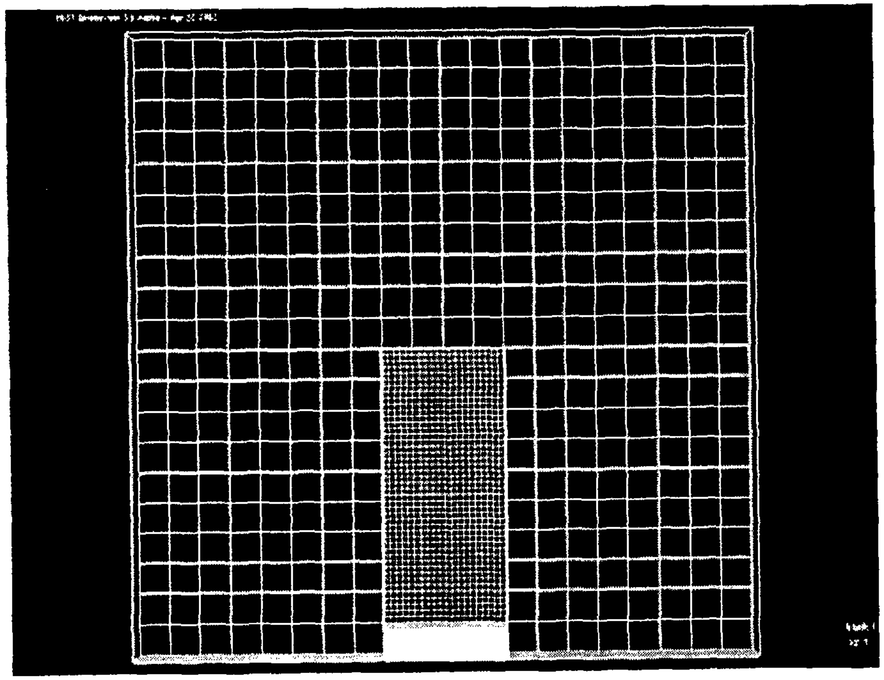
- Single-block: One grid used to span computational domain
- Multi-block: Multiple grids used
- Multi-block can reduce the number of grid cells at the expense of more complex boundary conditions
- For some problems the grid cell time savings >> boundary condition time penalty

Multi-Block Example 1

- Resolution needed for the fire > resolution needed for smoke movement



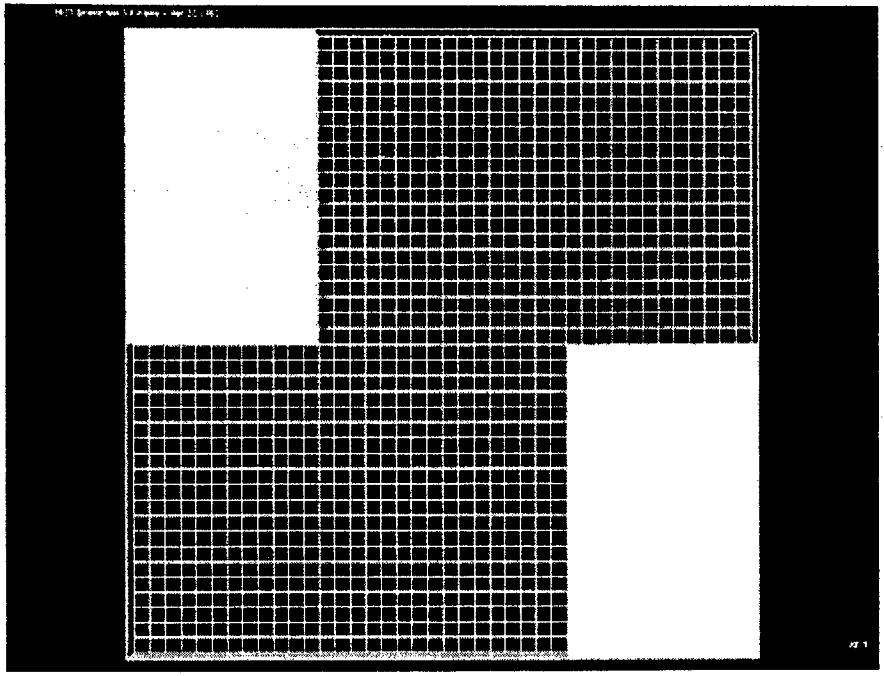
10000 Cells



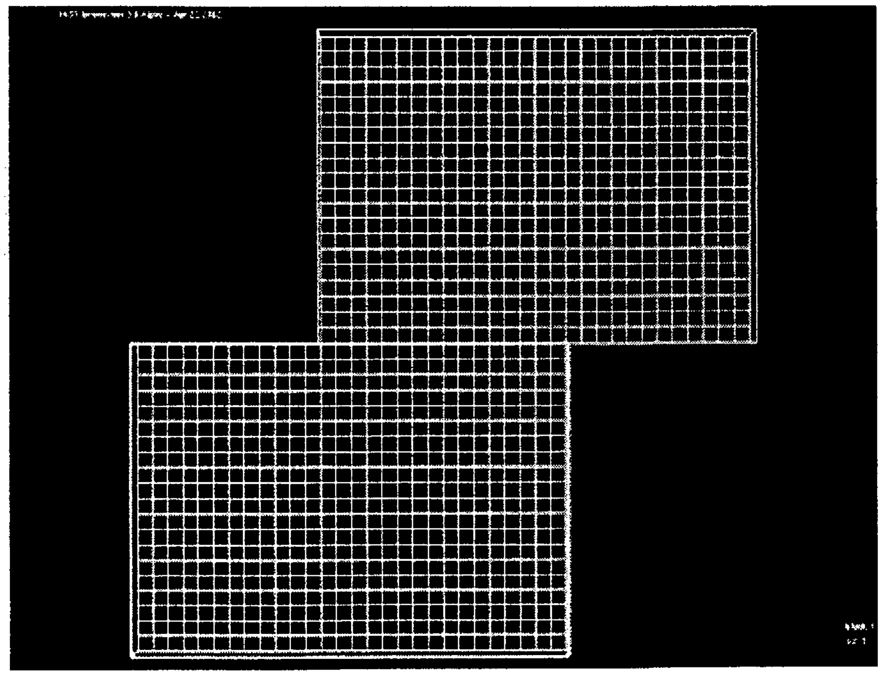
1400 Cells

Multi-Block Example 2

- Complex geometries may result in many dead cells



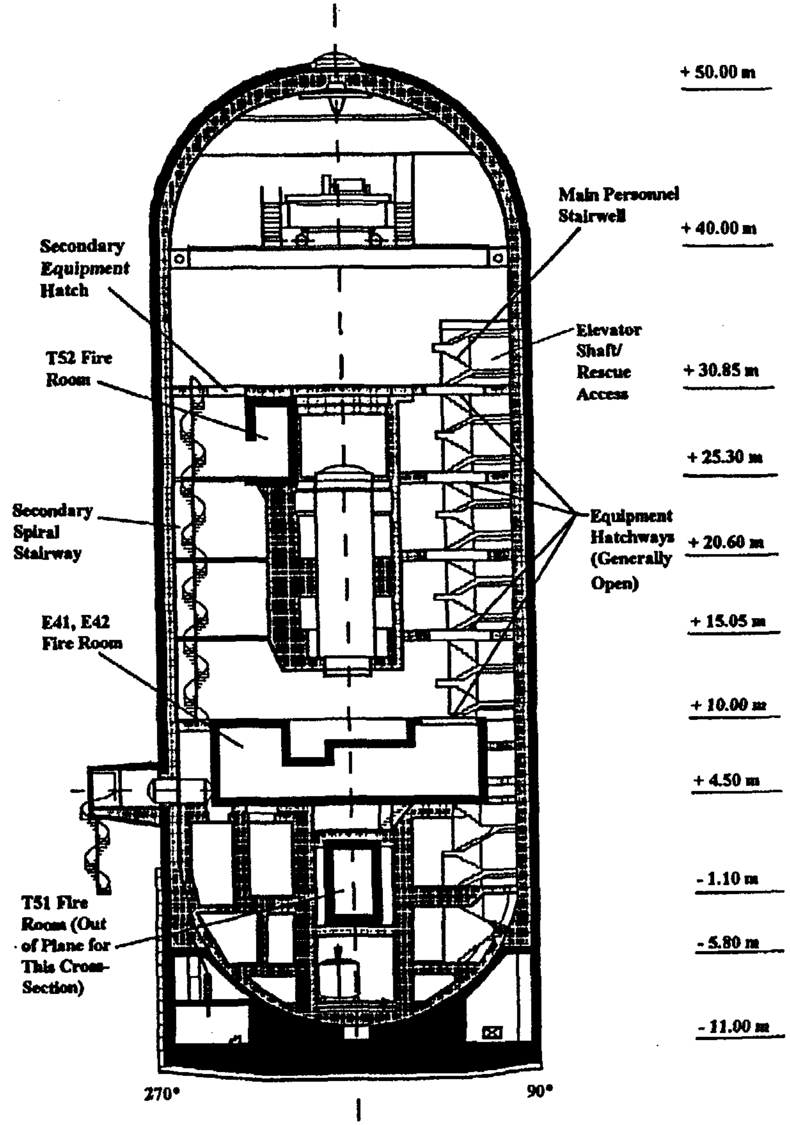
1600 Cells



1120 Cells

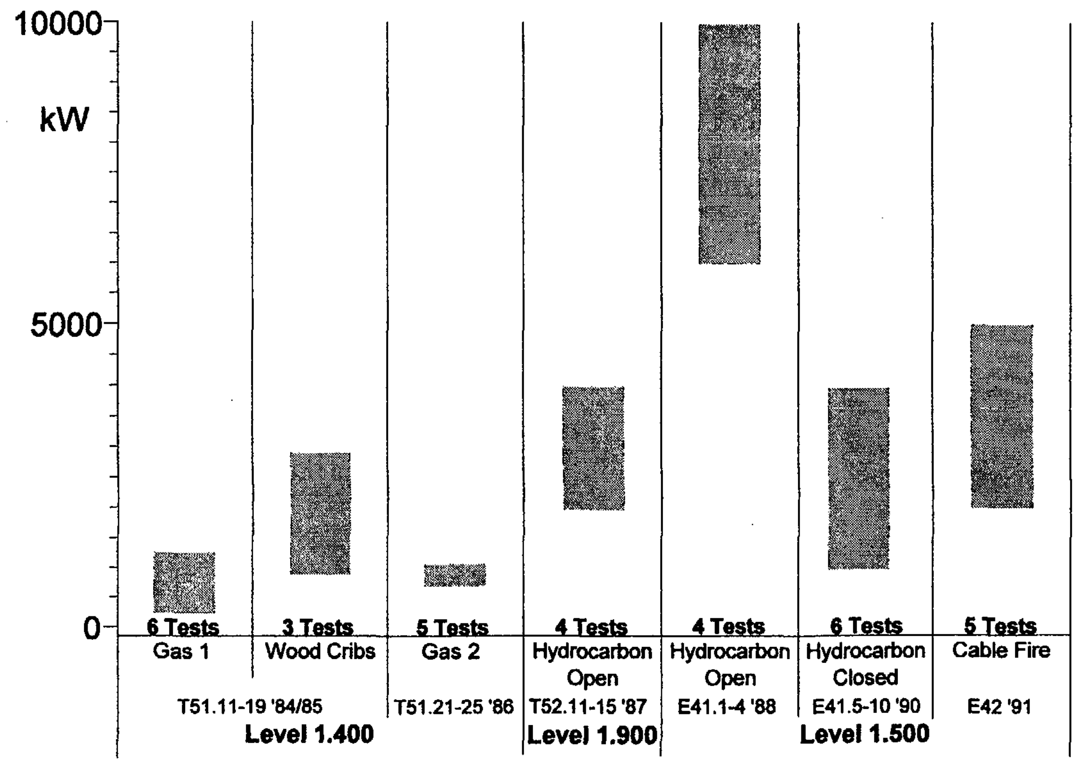
HDR Facility

- Decommissioned containment building in Karlsrhue, Germany
- 20 m diameter
- 60 m high
- 8 levels
- >60 compartments
- 11,000 m^3
- 5 vertical flow paths



HDR Fire Testing Program

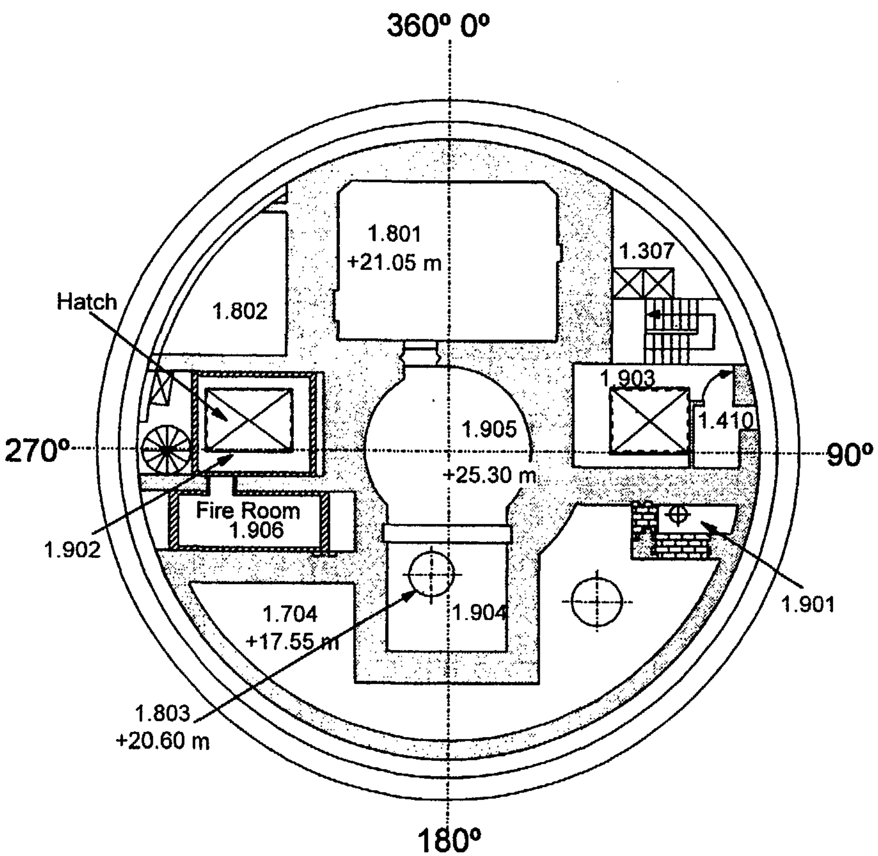
- 7 test groups
- 33 tests
- 4 fuels: propane, wood, oil, and cable
- 4 locations
- 230 kW to >10 MW

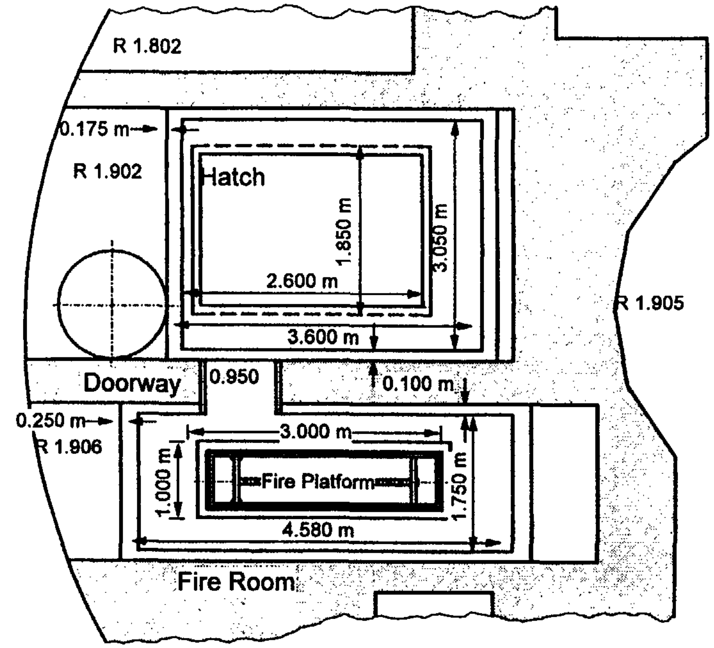


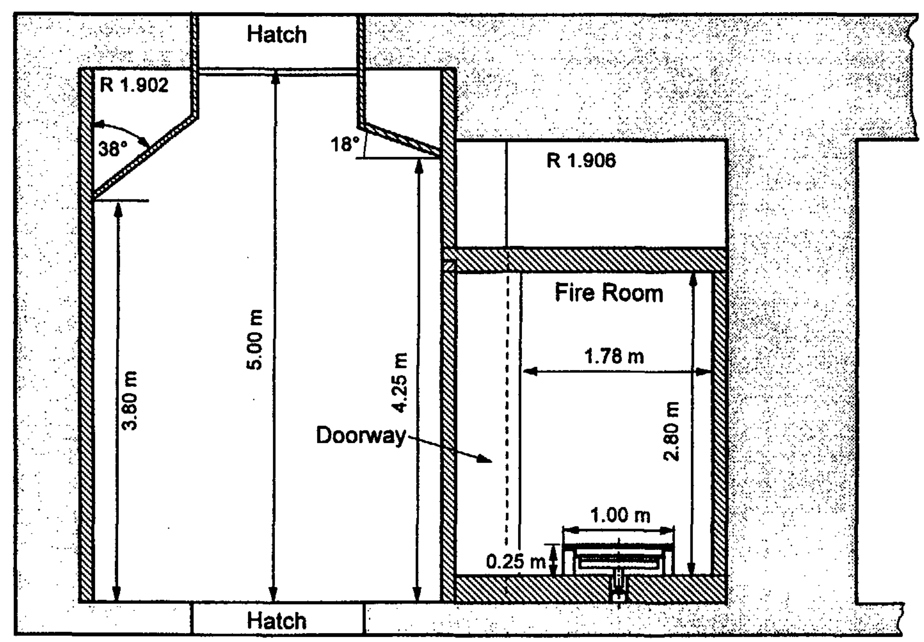
T52 Test Series

- Four tests (T52.11- T52.14)
- Liquid hydrocarbon fuel (Shellsol T)
- Level 1.9 (Below dome operating deck)
- 1 m x 1 m to 1 m x 3 m pools
- Measured temperature, velocity, CO_2 throughout facility

T52 Test Layout

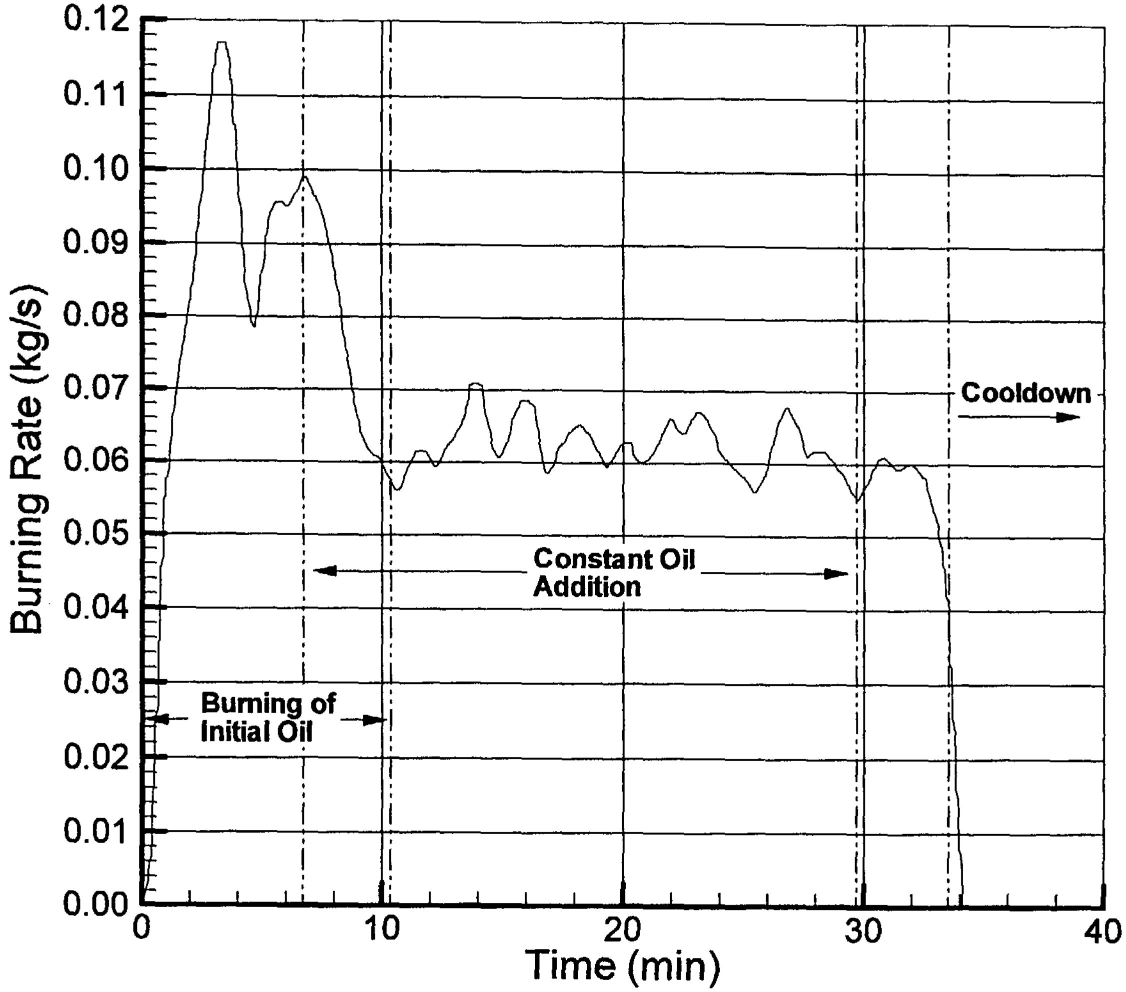






D-150

Test T52.14



0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Burning Rate (kg/s)
0
10
20
30
40
Time (min)
Burning of
Initial Oil
Constant Oil
Addition
Cooldown

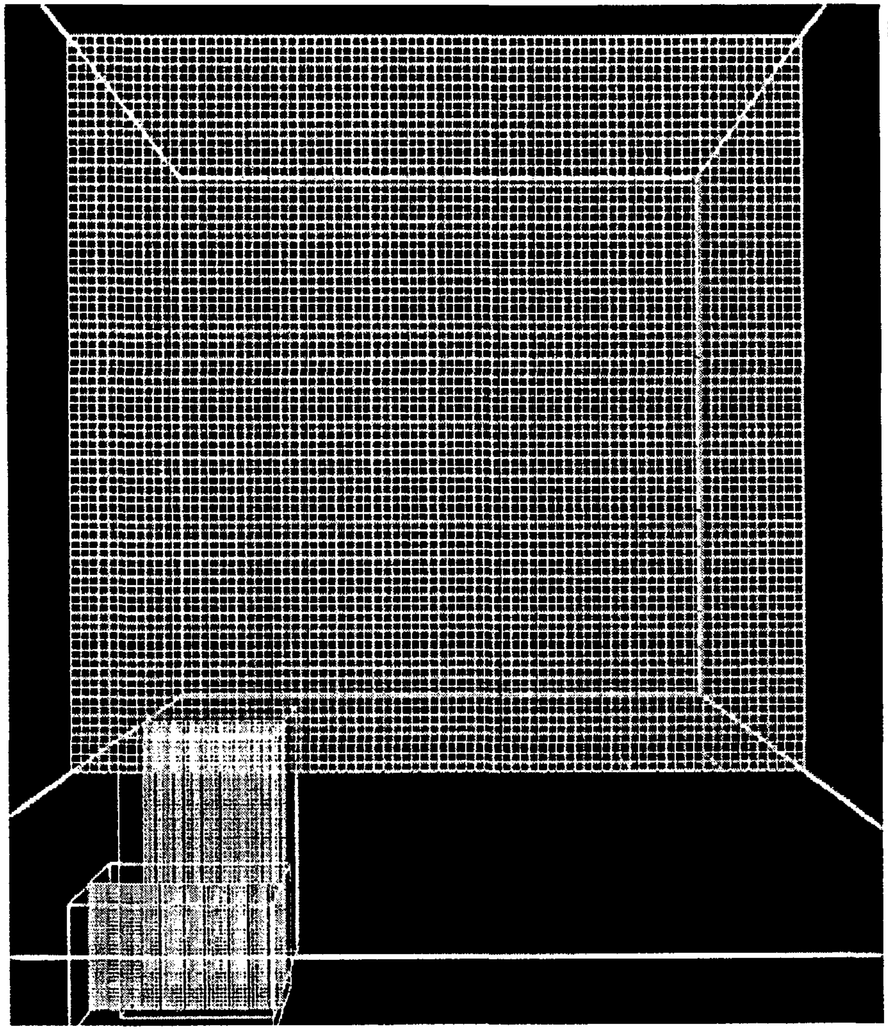
Input Parameters

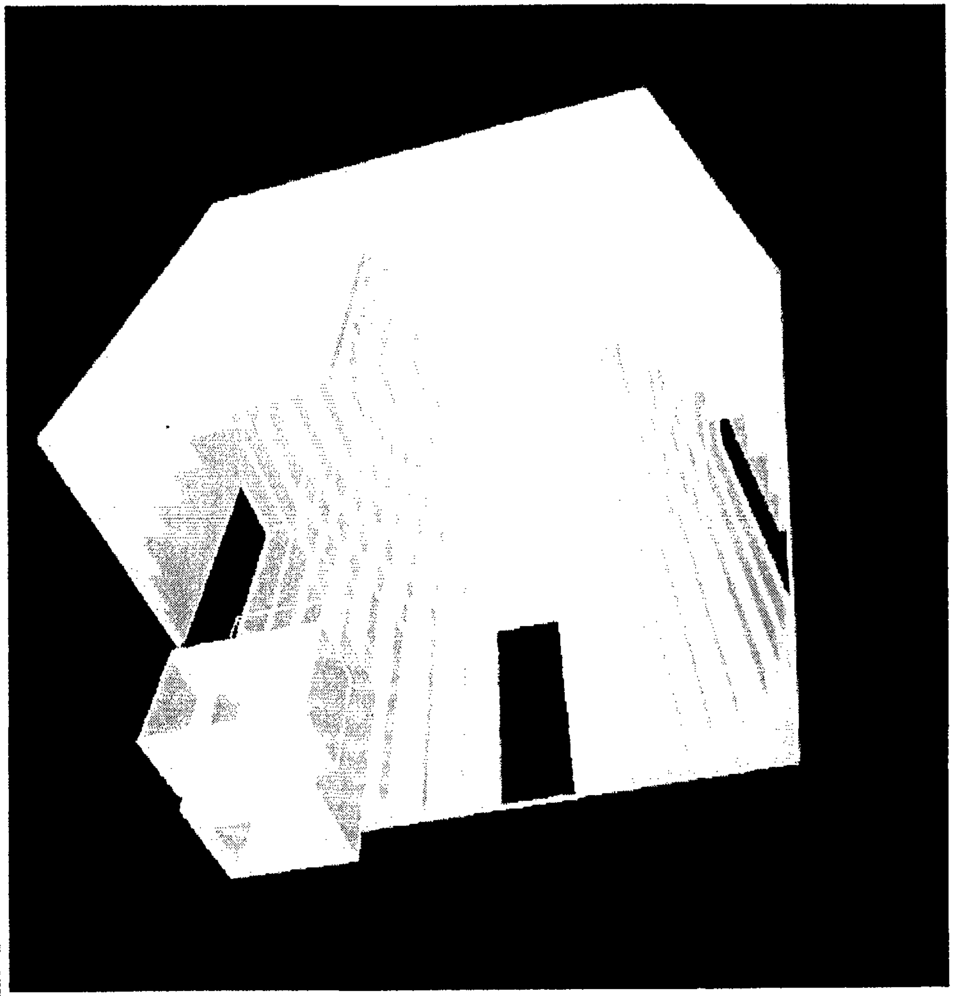
- Fire Power: 2.65 MW (Steady-state power)
- Fuel
  - $C_{12}H_{26}$: 170 g/mol, 42500 kJ/kg
- Surface definitions
  - Fire room: firebrick
  - Walls of hatch area: fire resistant fiberboard
  - Remainder: concrete

FDS Model

- Fire room, hatch room, dome
- Steady state portion
- Three grids, 650,000 grid cells:
  - Fire room, 10 cm, 48x25x32 (38 knodes)
  - Hatch, 10 cm, 40x36x72 (104 knodes)
  - Dome, 25 cm, 80x80x80 (512 knodes)
- One grid ,10 cm, 1,216,000 grid cells
- Also ran ¾ linear resolution

FDS Model





Time Required

- 2.2 GHz Pentium IV, 1 Gb RAM, Linux
  - Full resolution case (654,080 grid cells)
    - 7.5 min CPU/s realtime
  - ¾ resolution case (275,292 grid cells)
    - 2.5 min CPU/s realtime

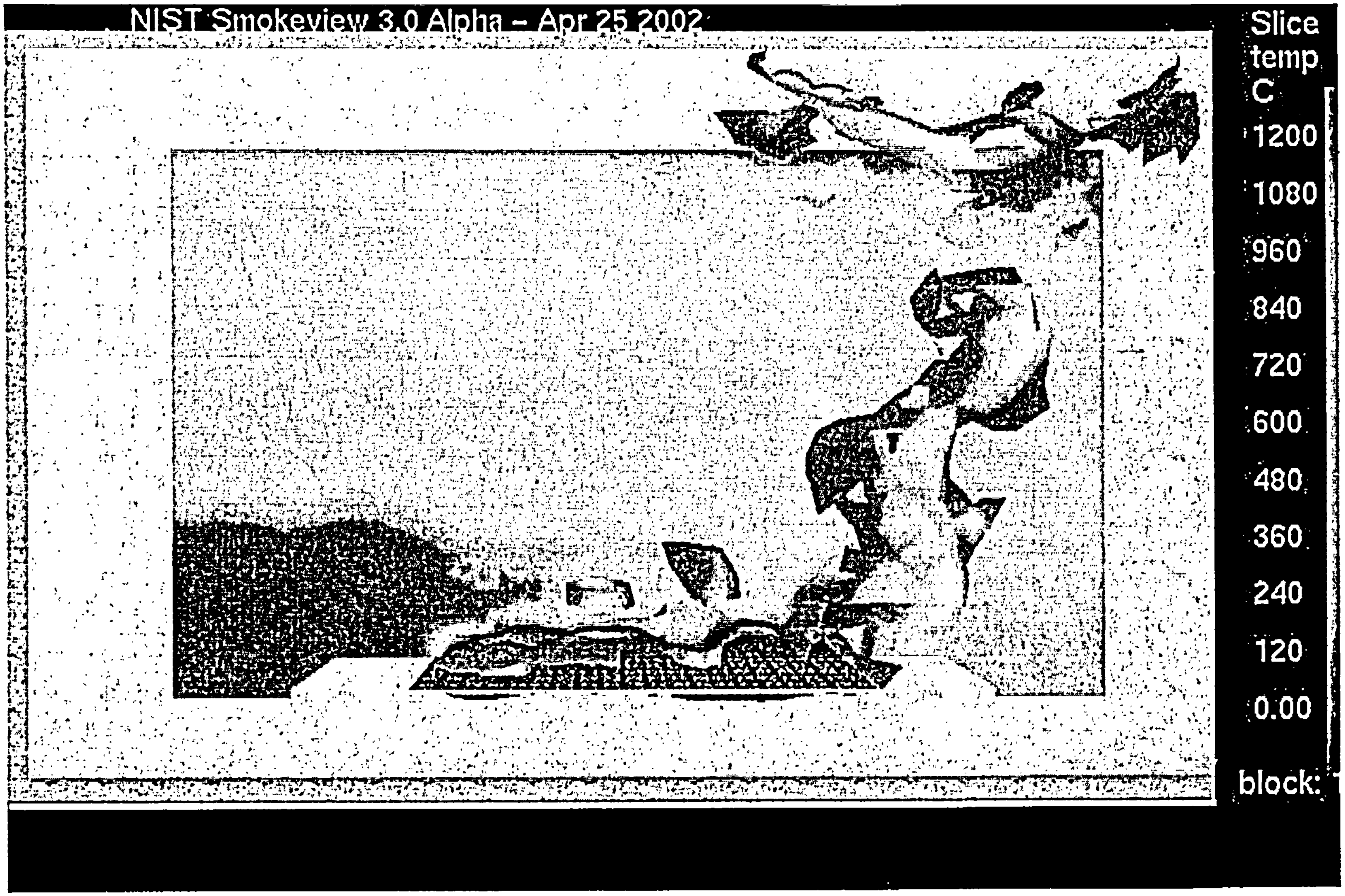
D-155

Integral Fire Room Results

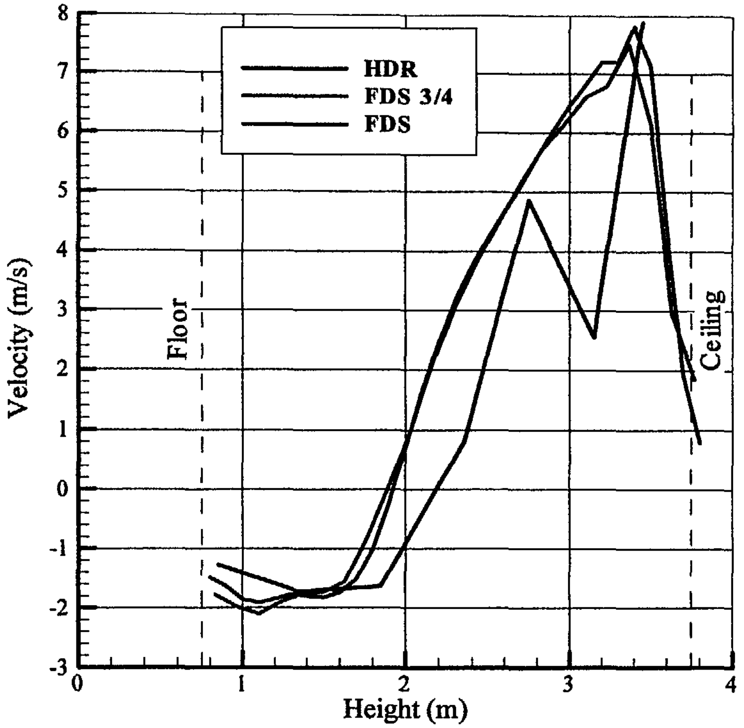
Parameter	HDR	Hand*	FDS ¾	FDS
h_n (m)	1.4	1.0	1.2	1.2
T_{out} (°C)	870	1210	793	827
(kg/s)	1.90	2.13	2.30	2.14

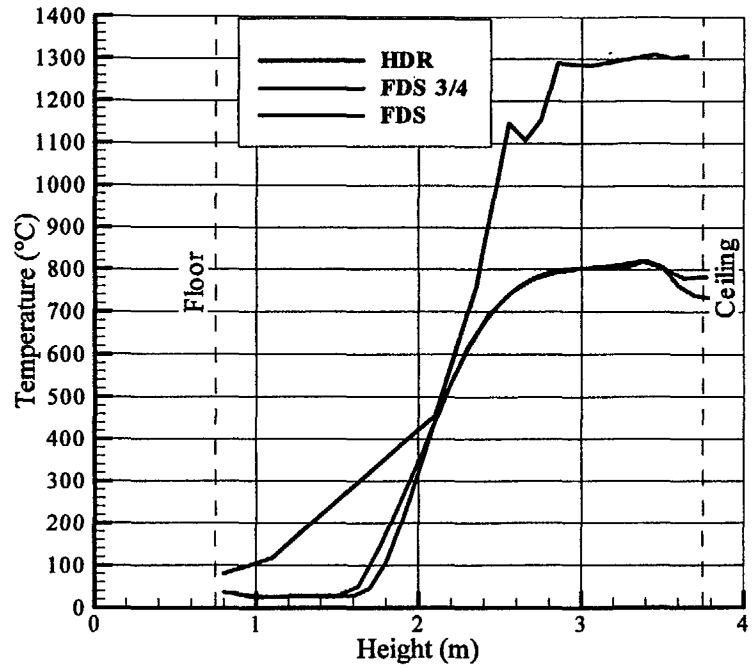
*Hand calculation following 1-layer method of Karlsson and Quintiere, 2000, Enclosure Fire Dynamics, CRC Press.

FDS Flame Surface

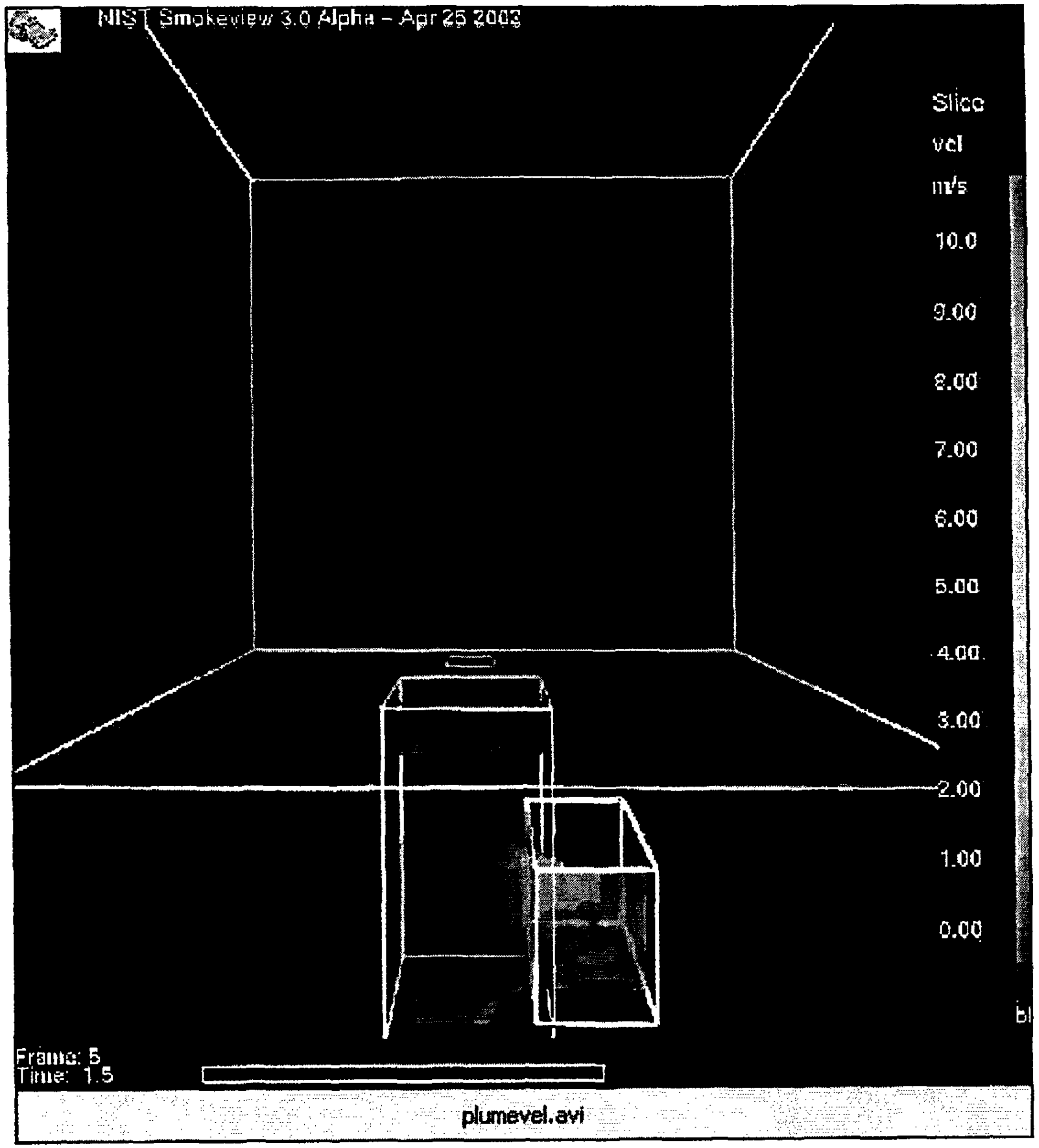


Fire Room Doorway

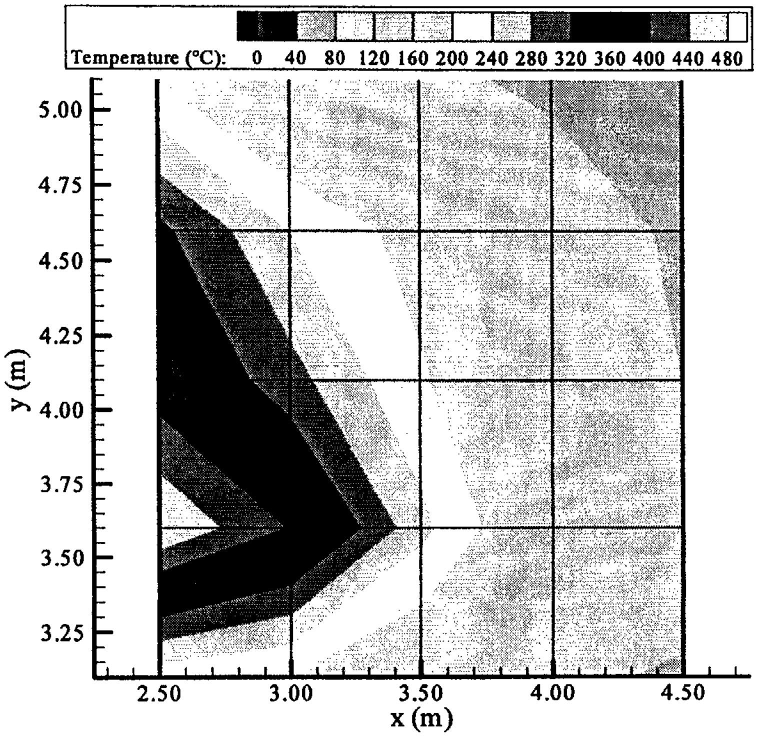


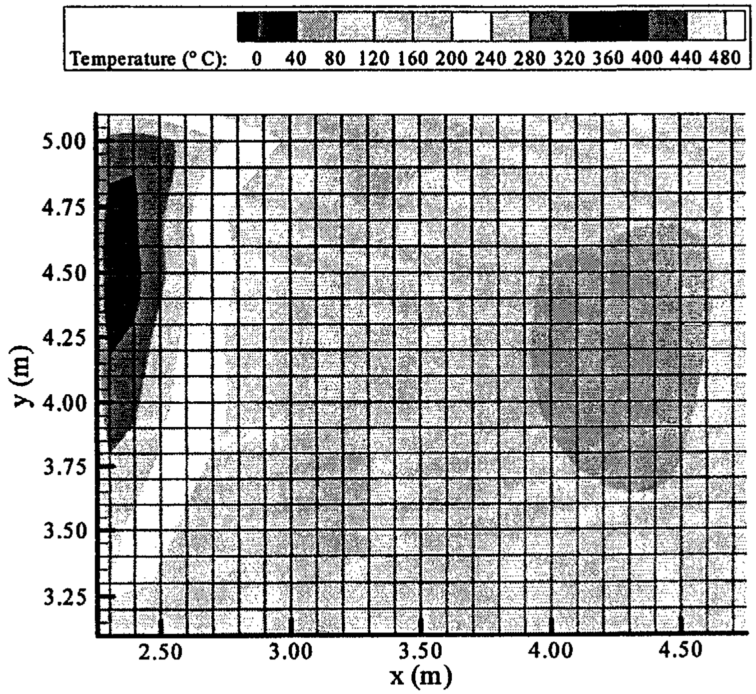


Plume Animation

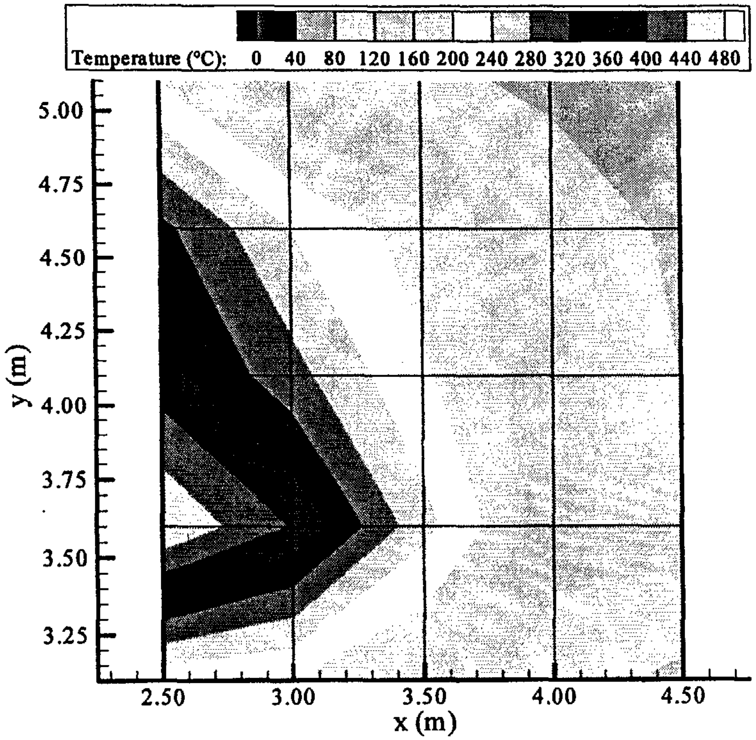


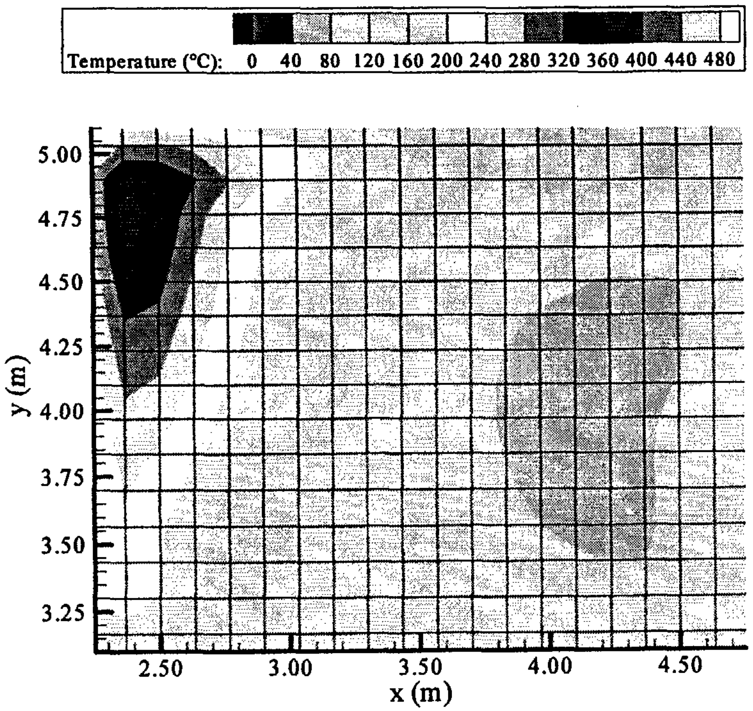
Hatch Temperature Full Grid





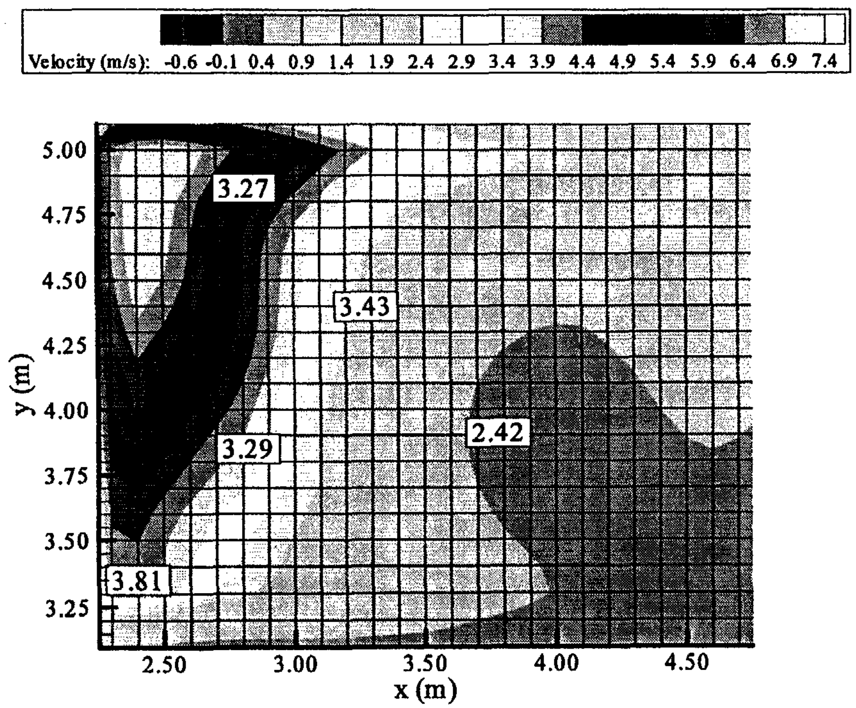
Hatch Temperature ¾ Grid



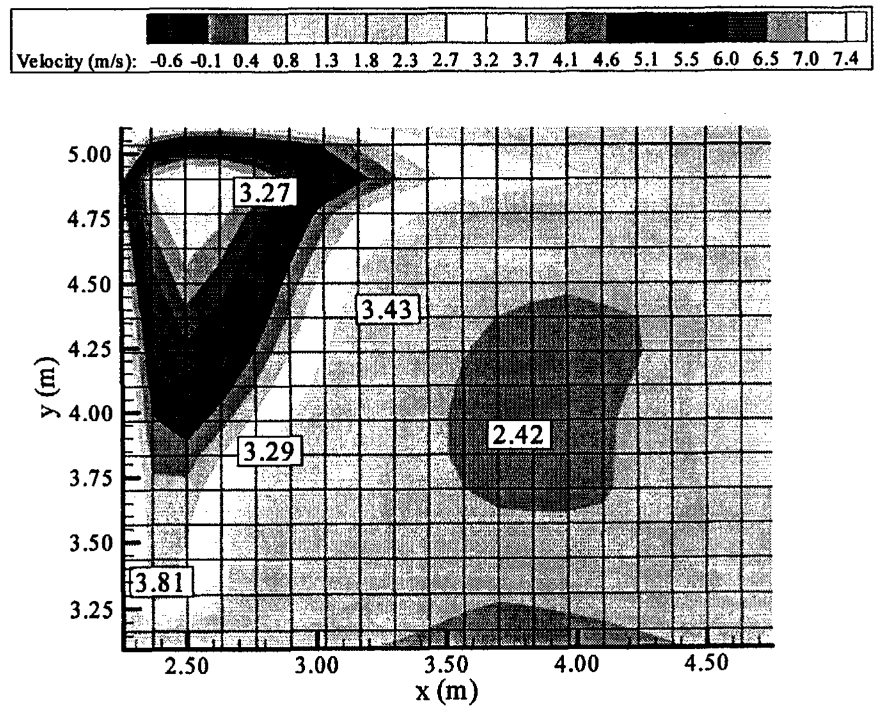


Hatch Velocity

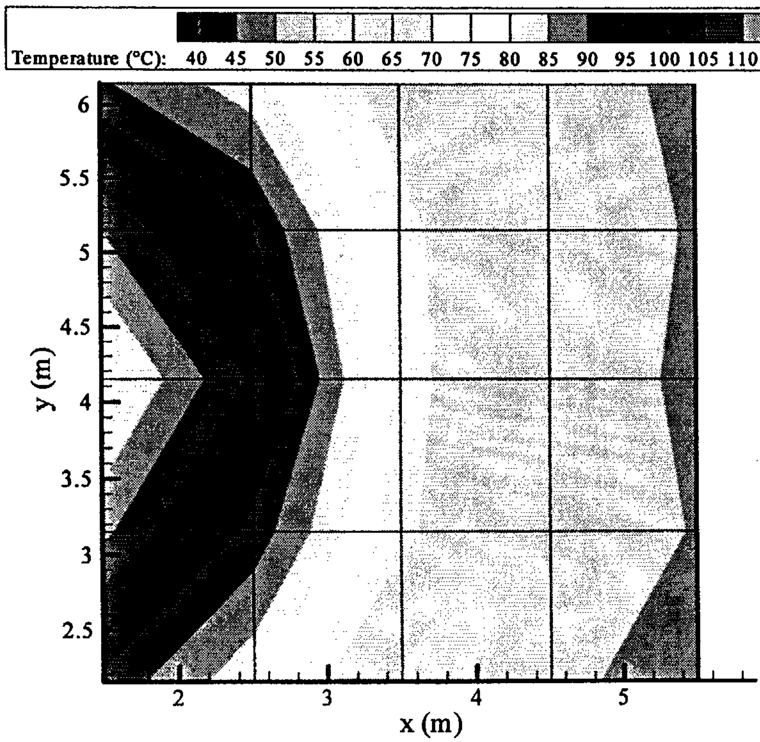
Full Grid

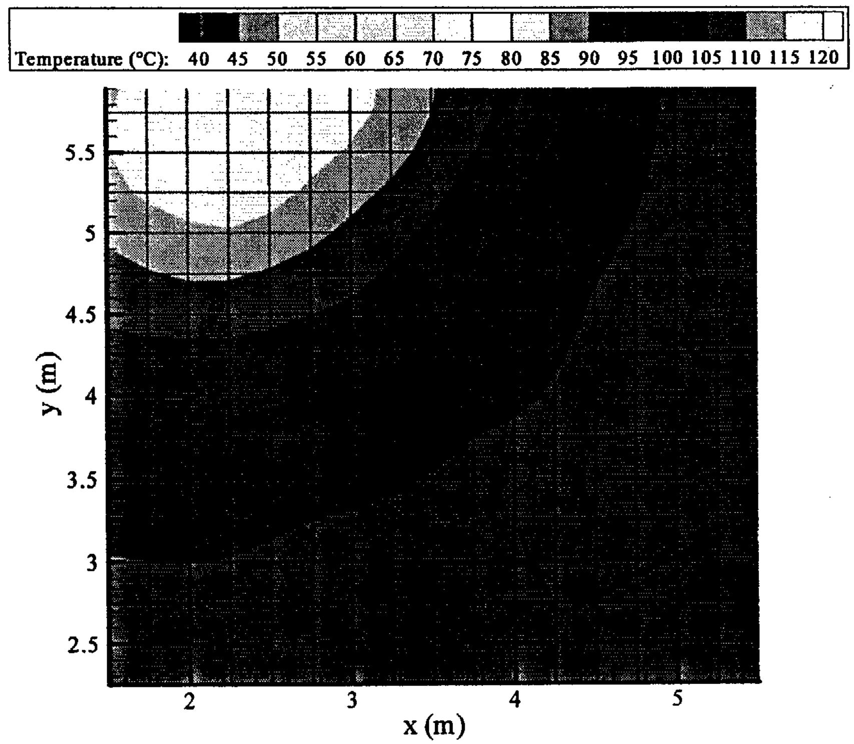


3/4 Grid

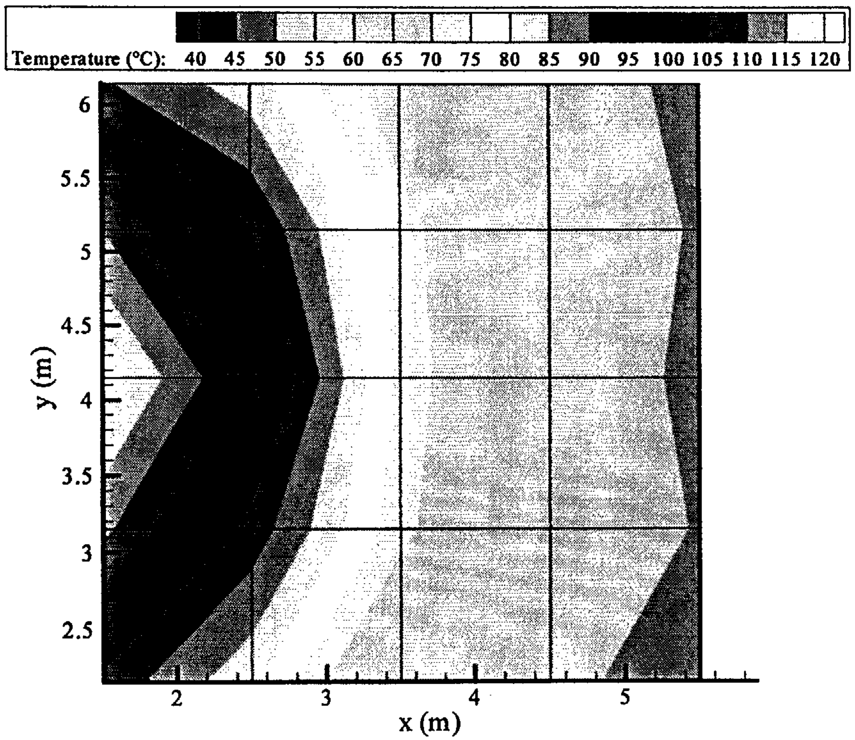


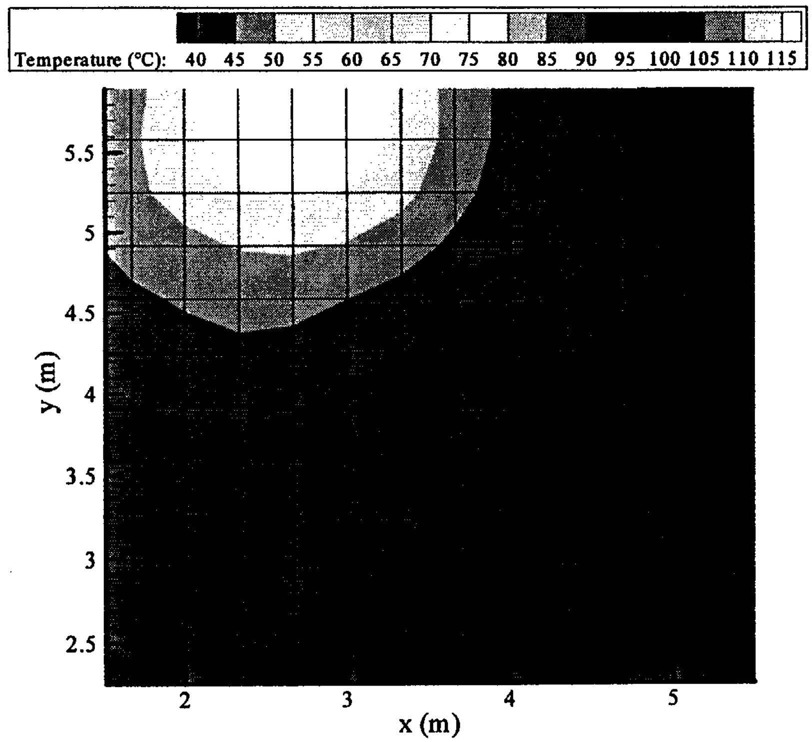
Dome Temperature Full Grid



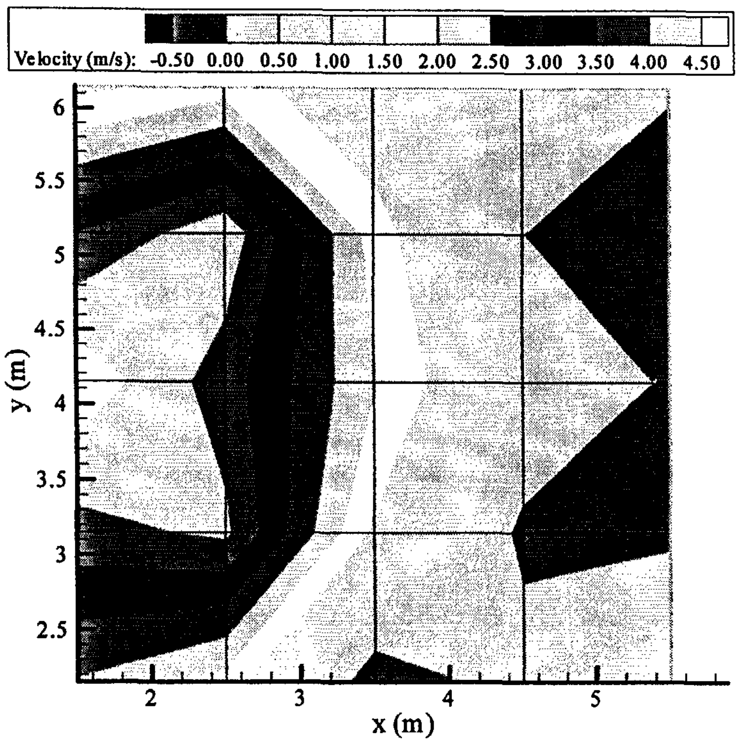


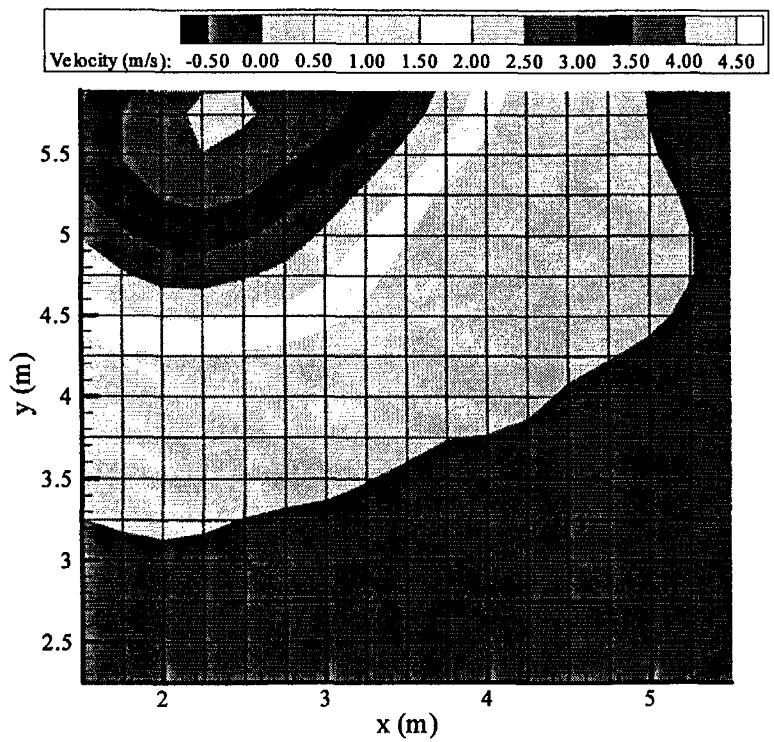
Dome Temperature ¾ Grid



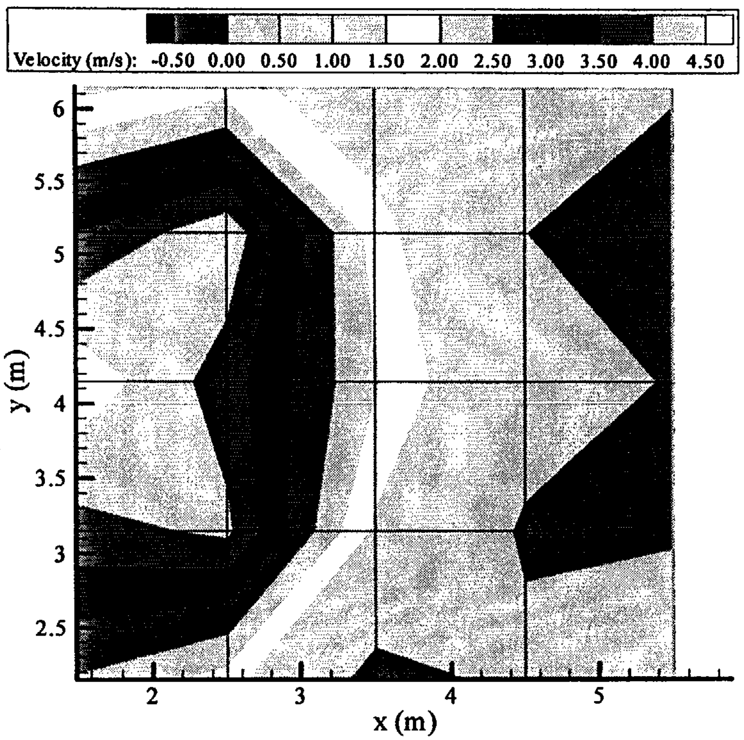


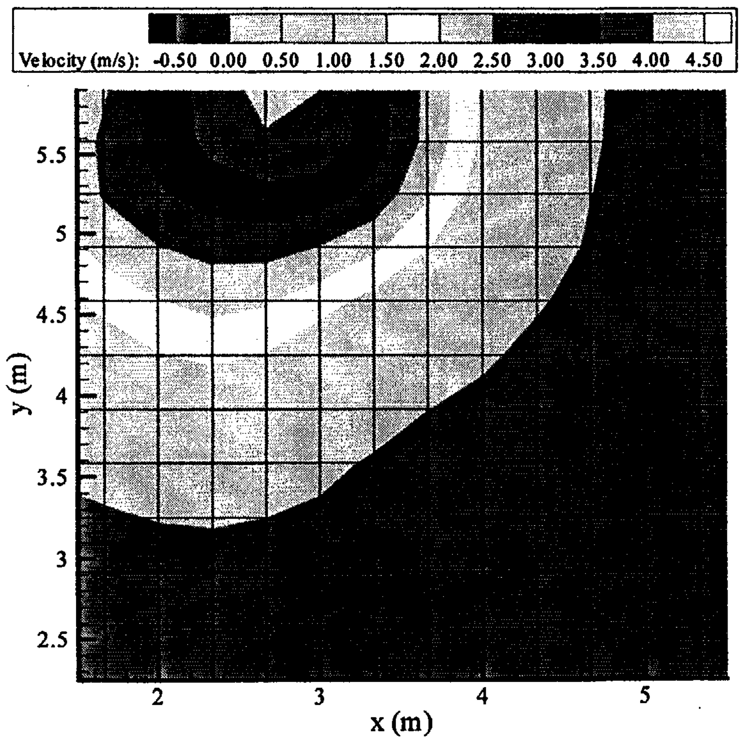
Dome Velocity Full Grid



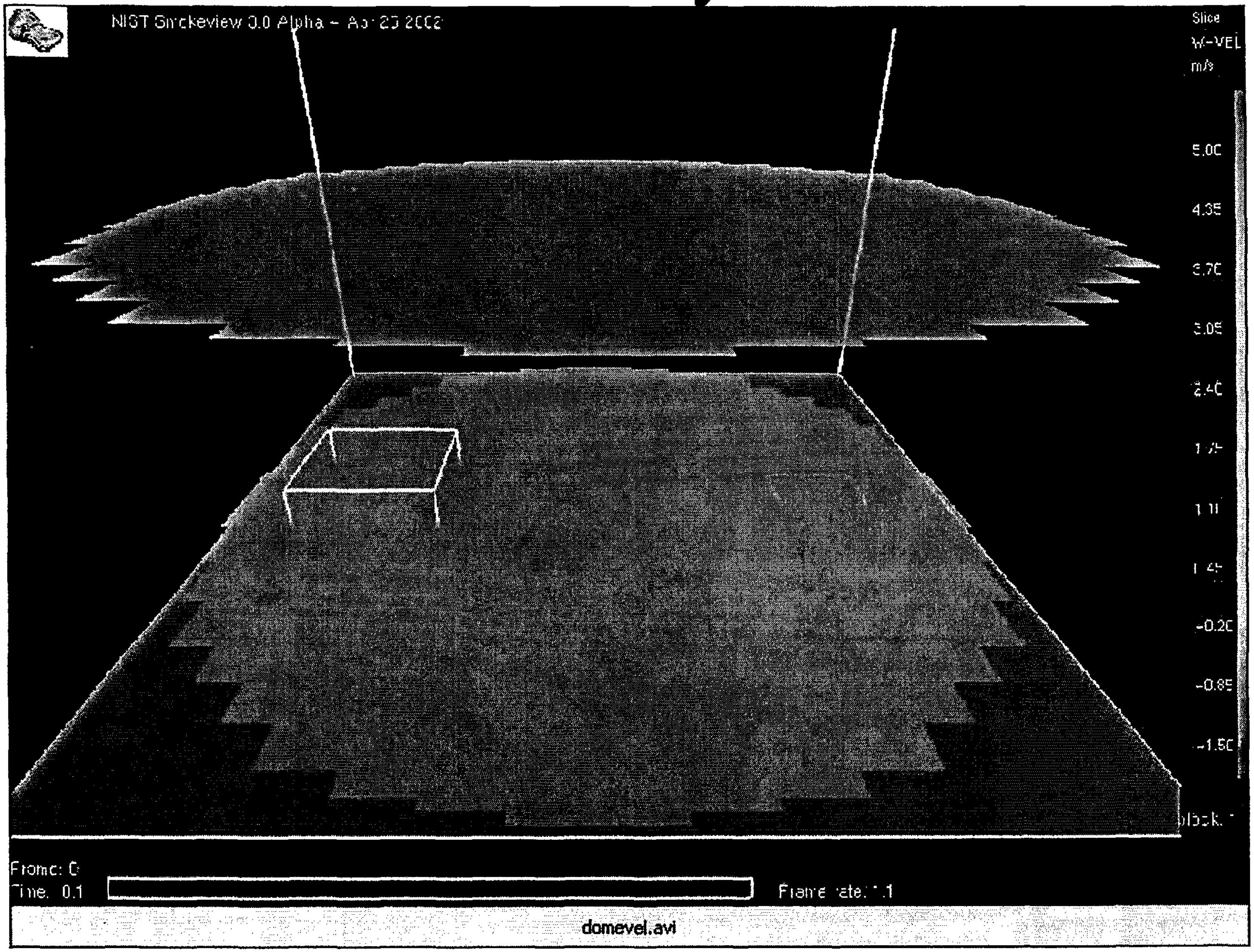


Dome Velocity ¾ Grid





Dome W-velocity Animation



Concluding Remarks

- Multi-block FDS shows great promise in enabling a user to simulate fires in very large, multi-compartment structures.
- Mass flux across grids is well maintained
- Energy flux across gris is well maintained

Verification, Validation and Selected Applications of the VULCAN and FUEGO Fire Field Models

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www.esc.sandia.gov/firescience.html

Fire Science & Technology

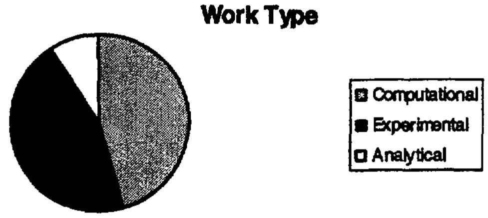
Sandia National Laboratories

Fire Science & Technology

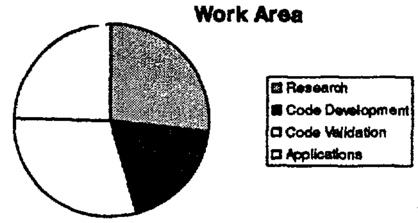
Start FY02 Fire Program Profile

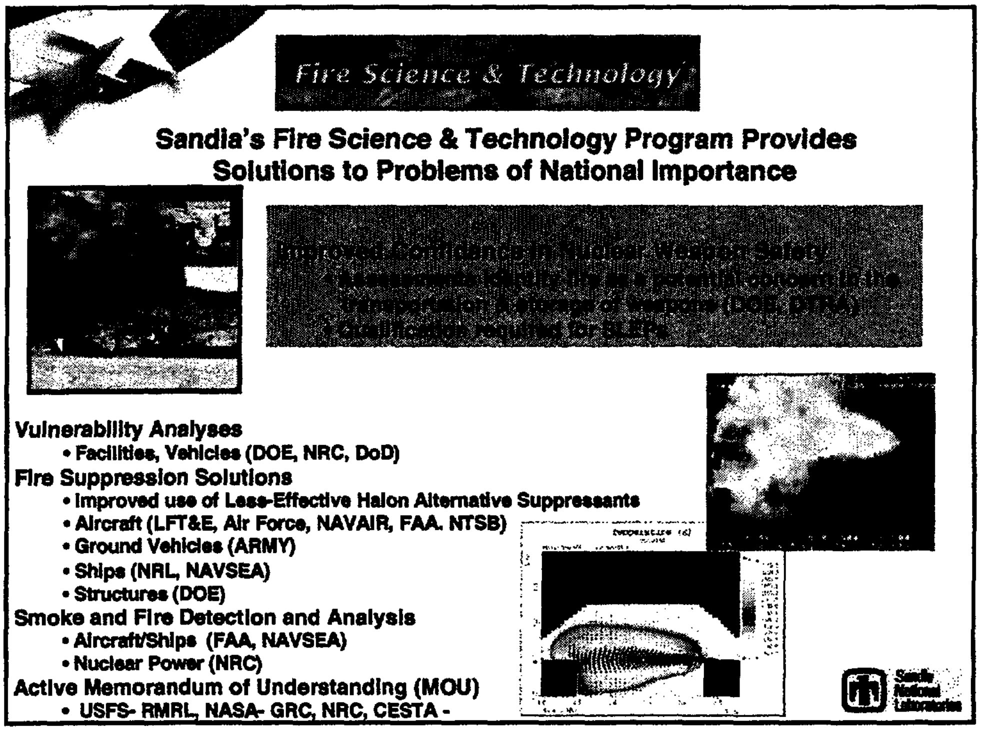
FY02 Funding Directly Related to Fire > 6.5 $million

Work Type

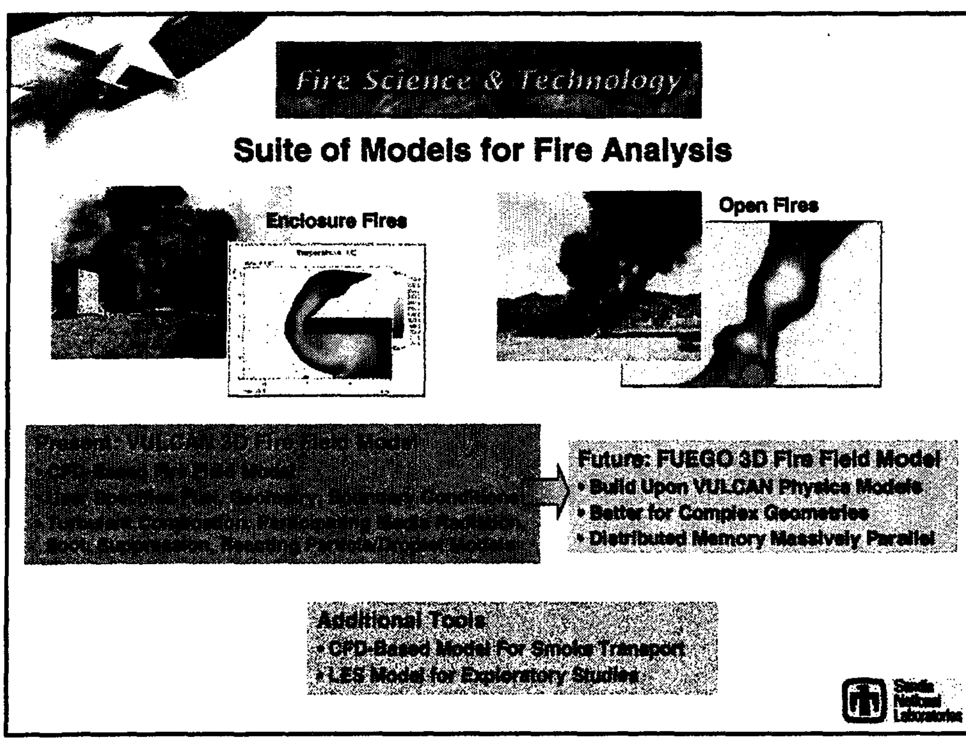


Work Area

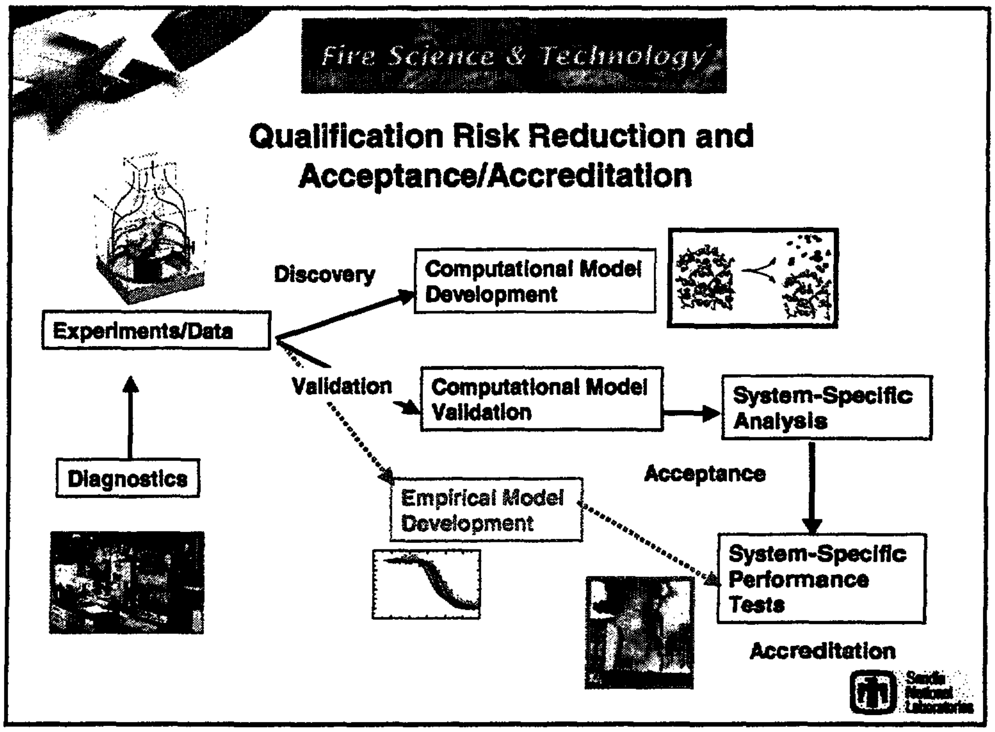


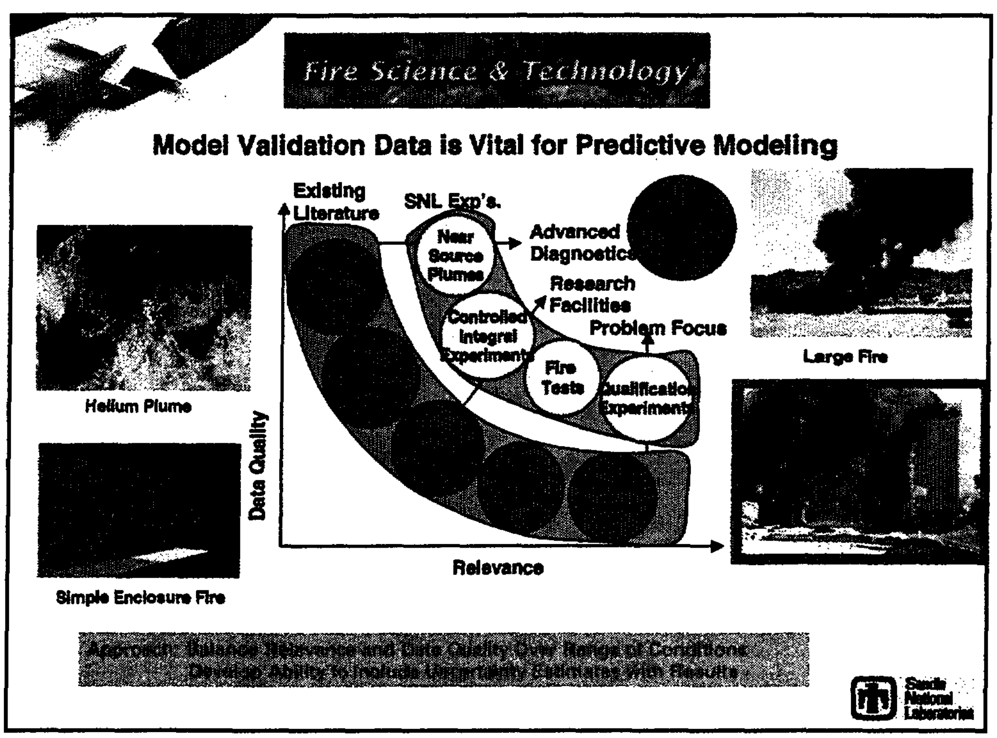


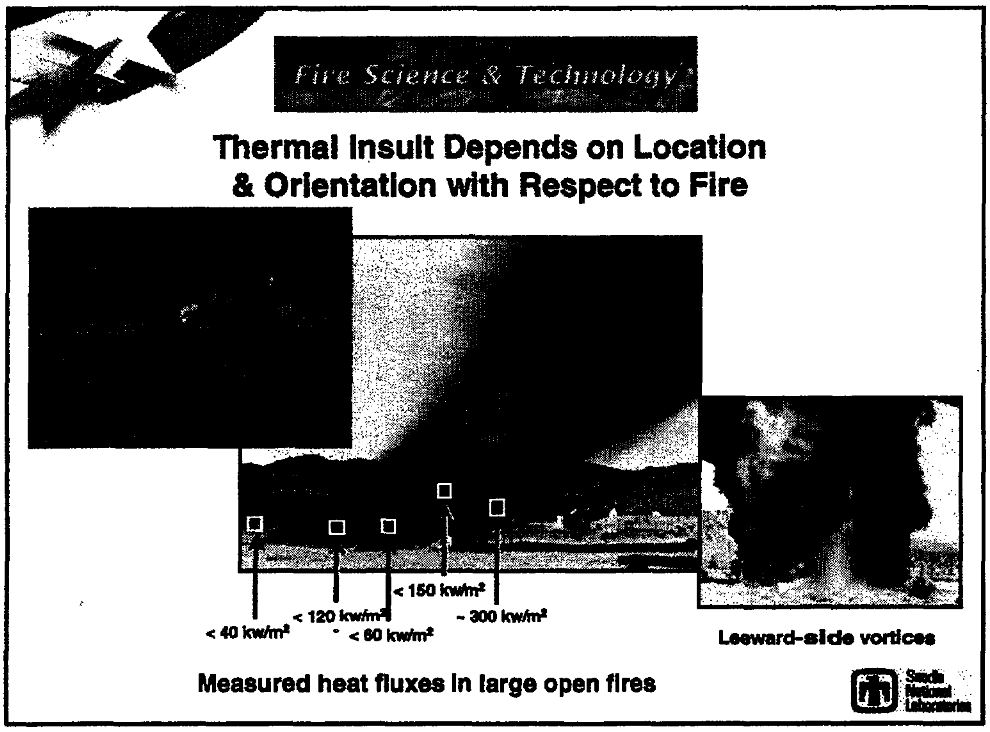
Fire Science & Technology
Sandia's Fire Science & Technology Program Provides Solutions to Problems of National Importance
Improved Confidence in Nuclear Weapon Safety
• Assessments identify fire as a potential concern in the transportation & storage of weapons (DOE, DTRA)
• Qualification required for SLEPs
Vulnerability Analyses
• Facilities, Vehicles (DOE, NRC, DoD)
Fire Suppression Solutions
• Improved use of Less-Effective Halon Alternative Suppressants
• Aircraft (LFT&E, Air Force, NAVAIR, FAA. NTSB)
• Ground Vehicles (ARMY)
• Ships (NRL, NAVSEA)
• Structures (DOE)
Smoke and Fire Detection and Analysis
• Aircraft/Ships (FAA, NAVSEA)
• Nuclear Power (NRC)
Active Memorandum of Understanding (MOU)
• USFS- RMRL, NASA- GRC, NRC, CESTA -

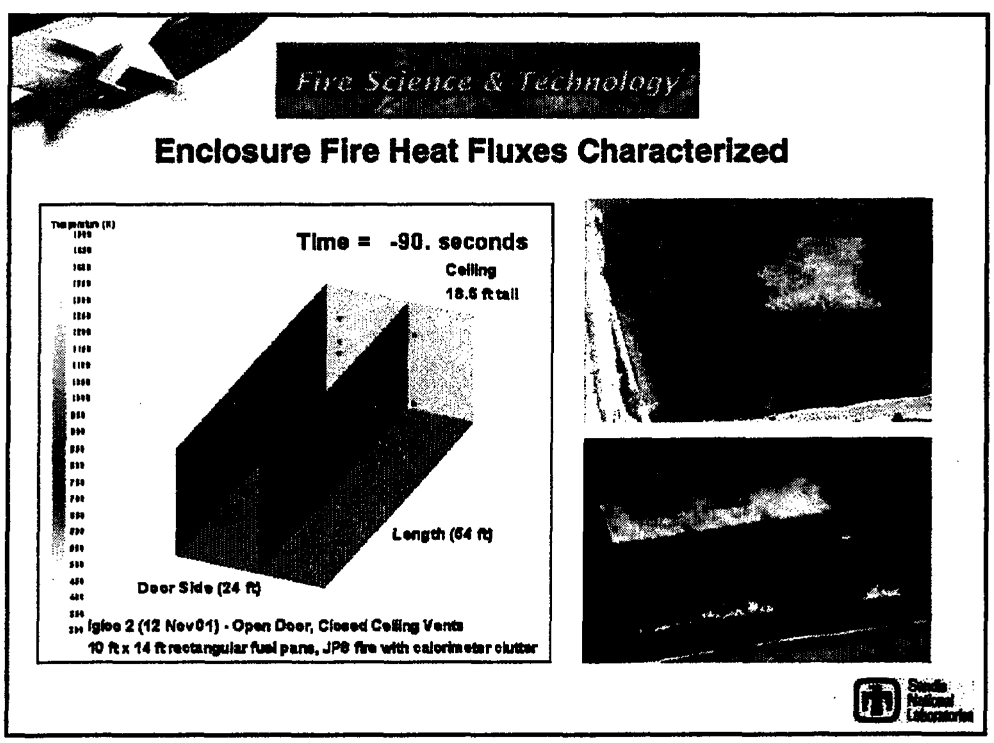


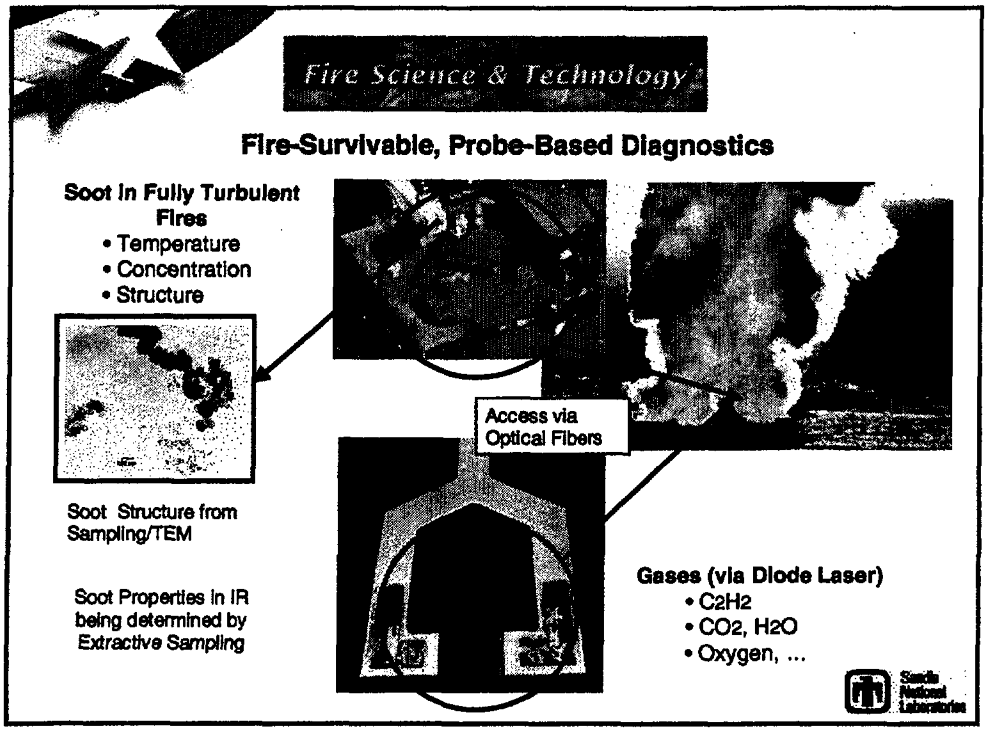
Fire Science & Technology
Suite of Models for Fire Analysis
Enclosure Fires
Open Fires
Present: VULCAN 3D Fire Field Model
Future: FUEGO 3D Fire Field Model
• Build Upon VULCAN Physics Models
• Better for Complex Geometries
• Distributed Memory Massively Parallel
Additional Tools
• CFD-Based Model For Smoke Transport
• LES Model for Exploratory Studies

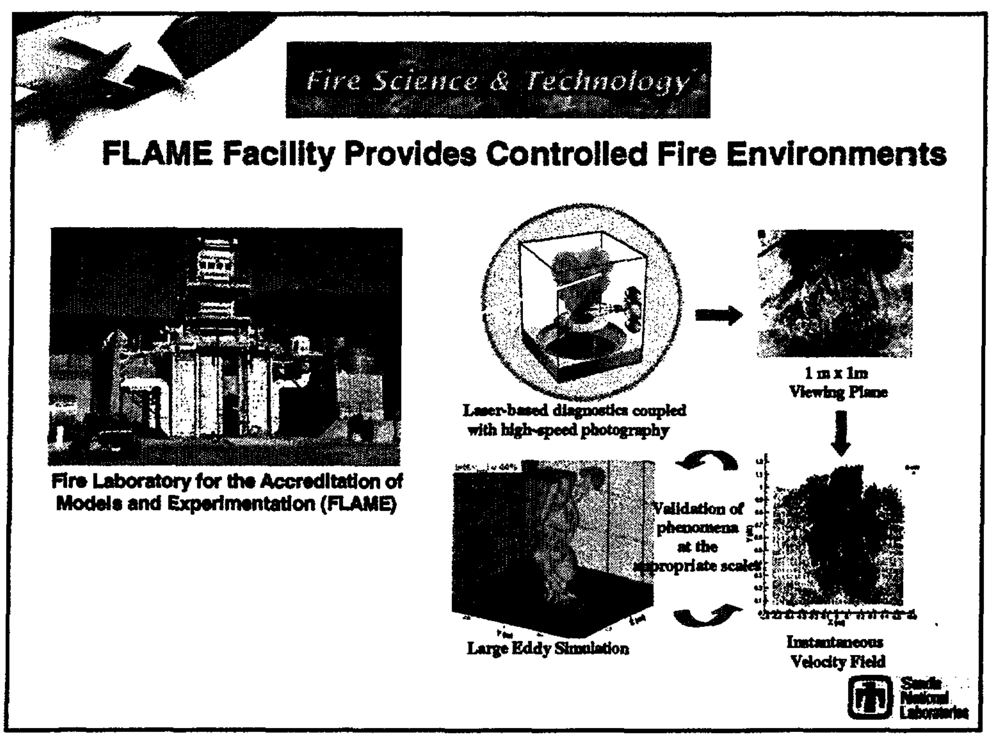

Fire Science & Technology
Qualification Risk Reduction and Acceptance/Accreditation
Discovery
Computational Model Development
Experiments/Data
Validation
Computational Model Validation
System-Specific Analysis
Diagnostics
Acceptance
Empirical Model Development
System-Specific Performance Tests
Accreditation


Fire Science & Technology
Model Validation Data is Vital for Predictive Modeling
Existing Literature
SNL Exp's.
Near Source Plumes
Advanced Diagnostics
Research Facilities
Controlled Integral Experiments
Problem Focus
Fire Tests
Qualification Experiments
Helium Plume
Large Fire
Data Quality
Relevance
Simple Enclosure Fire
Approach: Balance Relevance and Data Quality Over Range of Conditions
Develop Ability to Include Uncertainty Estimates With Results


Fire Science & Technology
Thermal Insult Depends on Location & Orientation with Respect to Fire
< 150 kw/m²
< 120 kw/m²
~ 300 kw/m²
< 40 kw/m²
< 60 kw/m²
Leeward-side vortices
Measured heat fluxes in large open fires
Sandia National Laboratories


Fire Science & Technology
Enclosure Fire Heat Fluxes Characterized
Time = -90. seconds
Ceiling
18.5 ft tall
Length (64 ft)
Door Side (24 ft)
Igloo 2 (12 Nov01) - Open Door, Closed Ceiling Vents
10 ft x 14 ft rectangular fuel pans, JP8 fire with calorimeter clutter
Sandia National Laboratories


Fire Science & Technology
Fire-Survivable, Probe-Based Diagnostics
Soot in Fully Turbulent Fires
• Temperature
• Concentration
• Structure
Soot Structure from Sampling/TEM
Soot Properties in IR being determined by Extractive Sampling
Access via Optical Fibers
Gases (via Diode Laser)
• C2H2
• CO2, H2O
• Oxygen, ...
Sandia National Laboratories

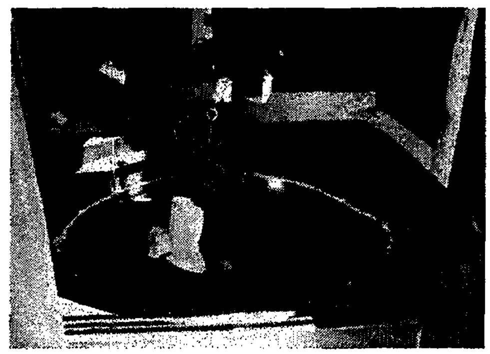

Fire Science & Technology
FLAME Facility Provides Controlled Fire Environments
Fire Laboratory for the Accreditation of Models and Experimentation (FLAME)
Laser-based diagnostics coupled with high-speed photography
1 m x 1m Viewing Plane
Validation of phenomena at the appropriate scale
Large Eddy Simulation
Instantaneous Velocity Field
Sandia National Laboratories

Fire Science & Technology

Integral Validation Experiments Underway in FLAME

Key Set of Fire Data for FUEGO Validation

- Airflow Control (<10% variation with Grid-Scale Resolution
- Temperature Distributions
- Soot Measurements
- TDL Measurements
- Fast-Scanning IR Data



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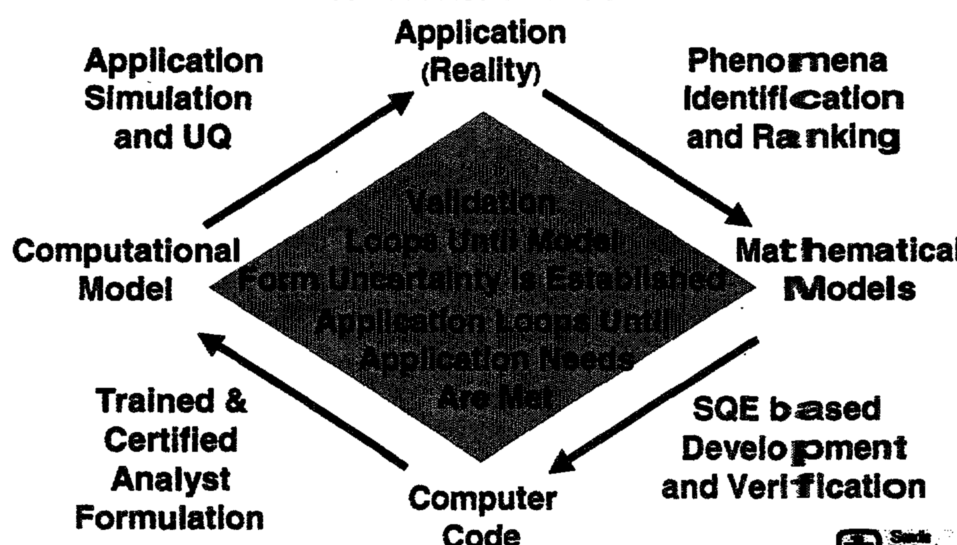
Fire Science & Technology

V&V Process Overview



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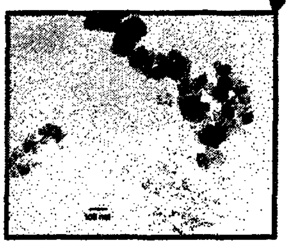
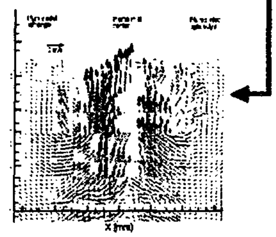
Phenomenological Identification and Ranking Table

Fire Simulations	Importance to Flux	Model Adequacy
Radiation Heat Transfer	High	Fair
• Transport	High	Good
• Radiative-Property/Turbulent-Mixing Interactions	High	Fair
• Radiation Properties	High	Poor
• Soot	High	Poor
- Temperature	High	Poor
- Mass Fraction	Medium	Poor
- Optical Properties	Medium	Fair
• Gas	Low	Fair
Convection Heat Transfer	Medium	Fair
• Boundary Layer Treatment	Medium	Poor
• Transport	Medium	Fair
• Source Terms	Medium	Fair
• Advective Closures	Medium	Fair



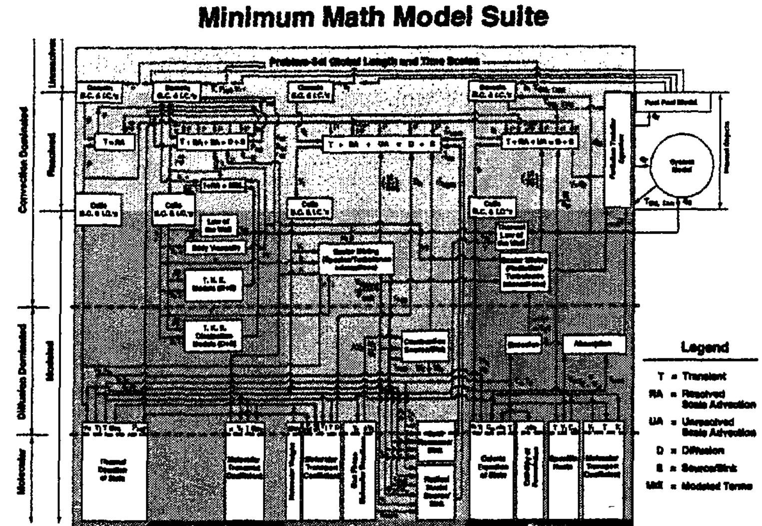
Understanding Soot



Understanding Turbulent Mixing in Fires

Fire Science & Technology

PIRT Driven Minimum Math Model Suite



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SQE and Code Verification Processes in Place

Software Quality Engineering

In use
- version control
- nightly regression testing
- requirements management
- language tools (debuggers & memory checkers)

Planned
- issue tracking
- change management

Verification

Methodology
- •Unit Testing (Subroutine level)
- •Verification Problem Testing

Approaches to Verification Problem Testing
- •Analytical & Semi-Analytical Solutions
- •Numerical Benchmark Solutions
- •Manufactured Solutions

Test Suite of 17 formal problems

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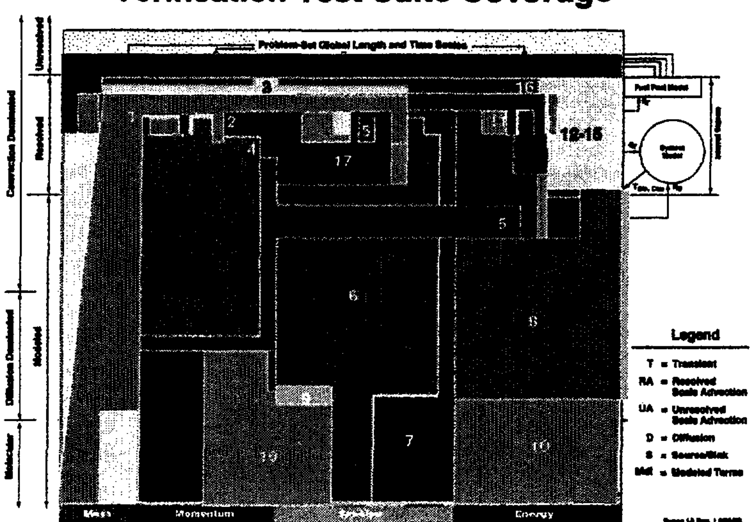
Fire Science & Technology

Verification Test Suite Coverage



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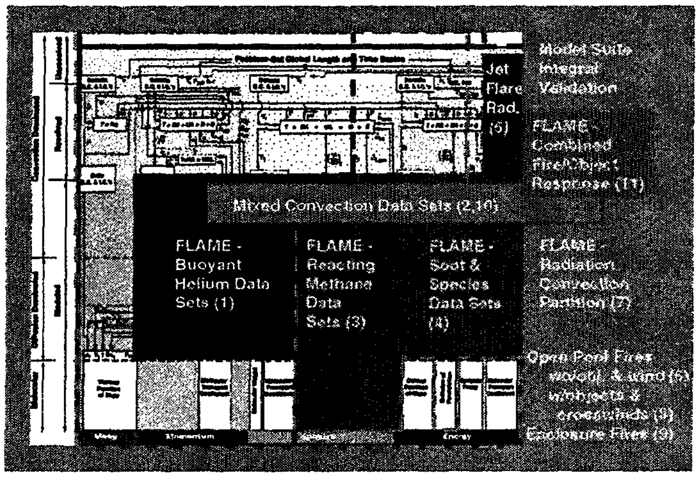
Validation Test Suite Coverage



Fire Science & Technology

Questions?

Lou Gritzo
(505) 844-8353
lagritz@sandia.gov

NIST Large Fire Facility

George Mulholland, Fire Metrology Group Leader

David Stroup, Facility Manager

5th meeting of the InternationalSub-panel for Fire Research

January 24, 2001

Purpose of Large Fire Laboratory

Apply quantified measurements, real-time analysis, and large area diagnostics diagnostics to validate models for fire phenomenon including fire dynamics, detection, and suppression.

Large Fire Laboratory Exhaust Capabilities

- Scrubber for removal of acid gases and baghouse for removal of particulate
- Variable from 0 to 42 m^3/s
- Two Fixed Exhaust Hoods
  - 6 m x 6m, 3 MW
  - 9 m x 12 m, 6 MW
- Three Connection Ports
  - 0.2 m Diameter
  - 0.5 m Diameter
  - 0.5 m Diameter

Picture of facility

Current Capabilities, 1/02

- 6 m x 6 m Hood, Heat Release Rate in real time
- Calibration burner up to 6 MW
- 9 m x 12 m Hood – Exhaust Only
- 4 m x 4 m x 2.4 m Burn Enclosure
- Data system developed with near real time analysis/presentation of results

Current Projects

- CPSC funded Smoke Detector study in manufactured home
- Fire Research Foundation study of Sub-Lethal Toxicity including flashover conditions
- STRS funded effort to plan experiments designed to support WTC fire models and fire resistance performance prediction
- STRS project to quantify the uncertainty in heat release rate calorimeter measurements

Quantify Uncertainty in Heat Release Rate Calorimeter

- Why important: Heat release rate is the single most important quantity for characterizing the hazard by a given fuel package.
- Approach:
  - Develop real-time data acquisition/analysis capbility
  - Develop calibration burner
  - Quantify the uncertainty of the measurement quantites

Heat Release Equation

$$\dot{Q} = (X_{O_2}^{0} - X_{O_2})H_C \rho_{O_2} \dot{V}$$

Where H_C is often assumed to be 13.1 kJ/kg and the duct flow, $\dot{V}$, is taken to be equal to the ambient flow.

Complications:
- **H_C is affected by CO production.**
- **$\dot{V}$ is affected by the change in stoichiometry as oxygen is consumed and CO, CO_2, and H_2O are produced.**

Illustration of Measurement System

Show sampling location, bi-direction probes and TC's, sampling line, trap, gas analyzers, "He flow system".

Data Acquisition/Analysis/Control Challenges

- Assembled dual processor workstation computer, National Instruments hardware
- Currently 192 analog input channels, 16 digital I/O channels
- Developed LabVIEW program for compensating for different measurement times to achieve near real-time analysis and display of processed data
- Typical use: 1 second averages for 60 channels scanned at 200 Hz during 1 hour test
- Capable of controlling/measuring calibration burner fuel flow rate

Calibration Burner/Flow Facility

Show the following components:

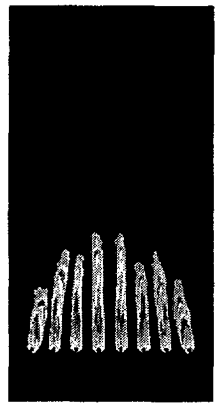
- **natural gas inlet, shut-off valve, programmable flow-controller, flow meter with pulse generator, "heat of combustion analyzer"**
- **pilot flame, flow control to various regions to maintain flame height, burner dimension, "fire-eye"**

HRR Calibration System

<u>Elements</u>
Natural Gas (daily basis)
Caloric determination of Hc of natural gas

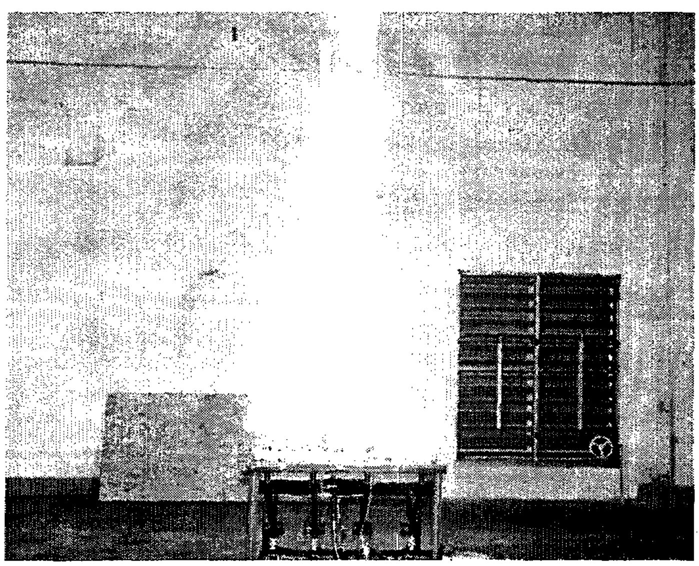
Flow Control
- Safe (industrial control design)
- Accurate (NIST Calibrated)
- Lab View Flow Control & Measurement

Tube Burner
- High turndown Ratio (50 kW-6 MW)
- Design used FDS calculations

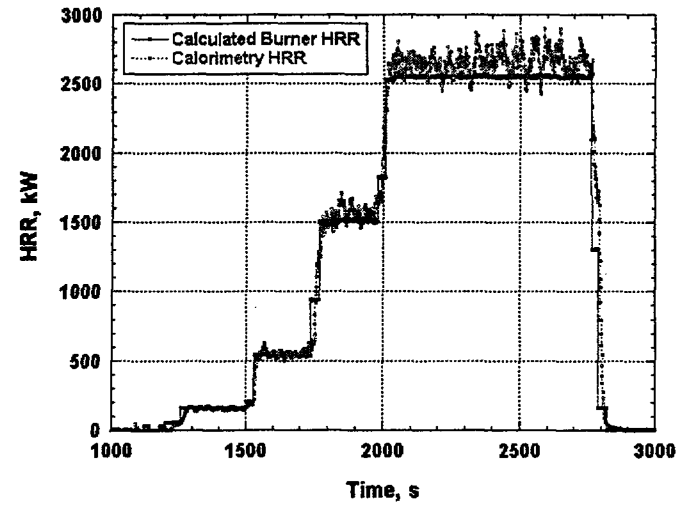


FDS Average Flame Height
4 MW Fire in Tube Burner

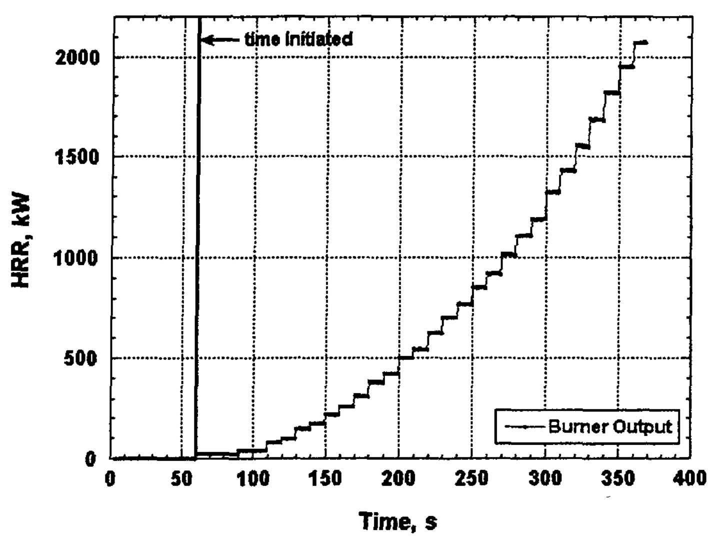
Calibration Burner, 3 MW



Comparison of the Burner Output Based on Flowrate to the Heat Release Rate

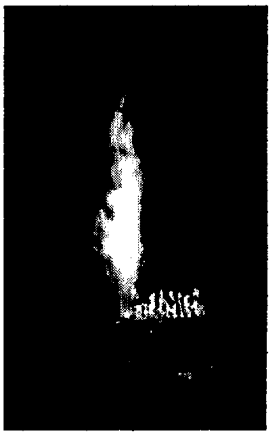


Calibration Burner t^2 Burn Designed for a Peak Heat Release of 2.04 MW

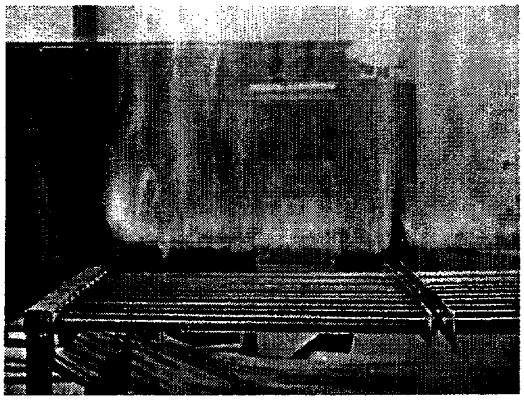


Calibration Burner Range Test

Two of 11 tubes used to see if a blowoff condition could be attained

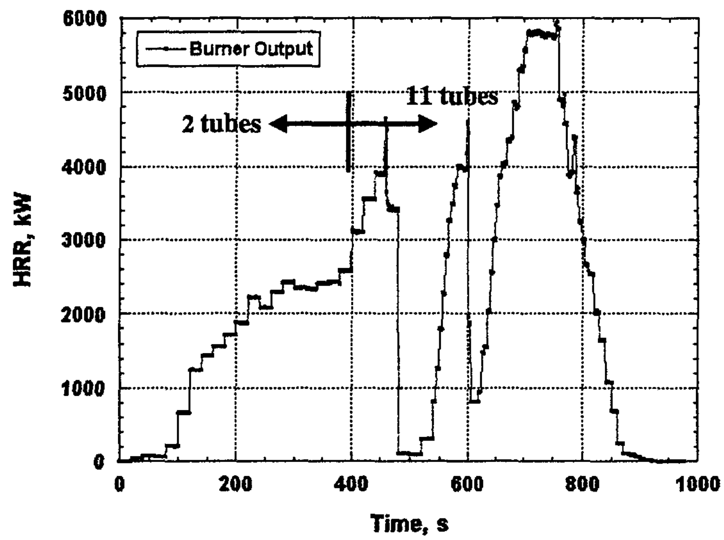


6 MW with 11 Tubes



Close-up of lower section of 1.5 MW natural gas flame (using 2 tubes). **Note low soot level**

Calibration Burner Range Test in Large Hood



Future Capabilities

- Soot volume fraction in upper layer
- Heat transfer measurements in upper layer
- Surface temperature
- Chemical analysis/FTIR
- Doorway Flow Measurements
- Water Spray Measurements
- ISO 17025 Testing Laboratory Competence
- Integrated research approach - model used for designing and interpreting results

Future Large-Scale Capability: Simultaneous Droplet Velocity and Size

Fluorescing sprinkler spray, 70 cm by 60 cm measurement area

Droplet trajectories fluoresced by laser sheets

#1

Benchmark Analysis # 2

Fire in a Large Hall

Specification for Part I

Stewart Miles
Fire and Risk Engineering Centre, BRE, UK
Tel: +44 (0)1923 664924
Fax: +44 (0)1923 664910
E-mail: miless@bre.co.uk

#2

Summary of Benchmark Ex # 2

- To further the findings from exercise # 1:
  - comparison with experimental measurements
  - fire within a large space
    - e.g. representative of a turbine hall
- To investigate the influence of modelling assumptions and approaches
  - incorporation of geometrical complexities
    - non-rectangular buildings
    - compartmentation
- Part I
  - comparison with measurements form fire tests in the VTT test hall
    - undertaken as part of a EU program
- Part II
  - 'hypothetical' simulations for a large fire in a 'real' turbine hall

#3

Schedule of Activities

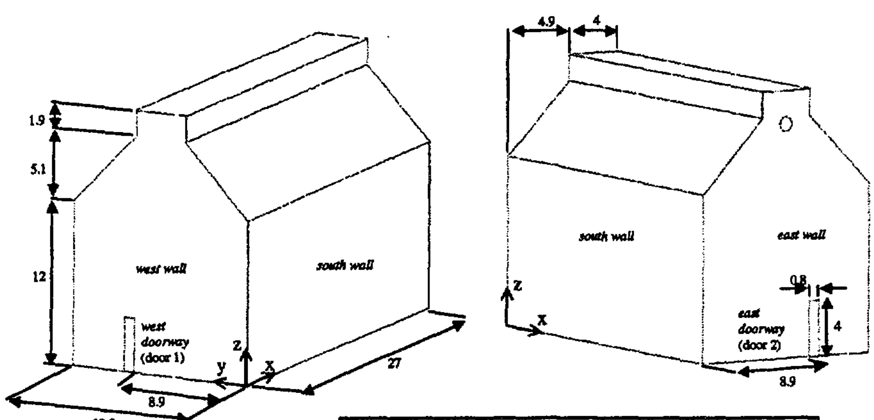
(Parts I and II)

- February 2002
  - release final specification
- February 2002 - September 2002
  - participants to perform simulations
- May 2002 (NIST meeting)
  - present preliminary findings for Part I
  - further discussion of problem definition for Part II
- Early September 2002
  - final results sent to BRE for collation
- October 2002 (BRE meeting)
  - present findings for Parts I and II

NIST, Gaithersburg | *Benchmark Analysis # 2 - Specification for Part I* | *2-3 May 2002*

#4

VTT Testing Hall



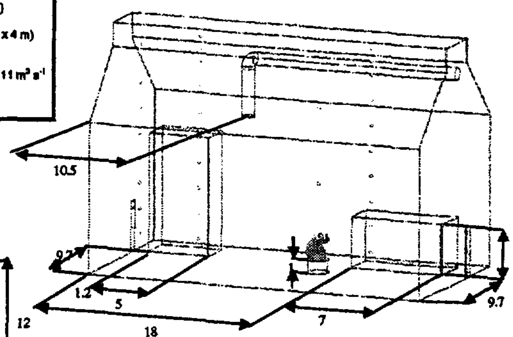
Material	Thermal properties		
	conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)
metal sheet	54	7850	425
mineral wool	0.2	500	150
concrete	2	2300	900

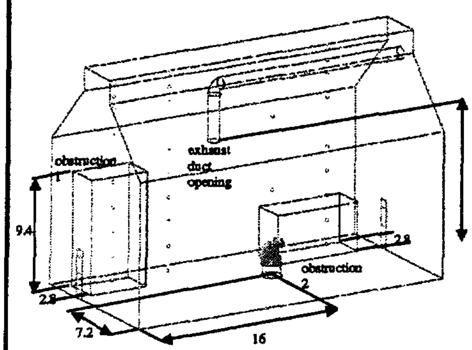
NIST, Gaithersburg | *Benchmark Analysis # 2 - Specification for Part I* | *2-3 May 2002*

\# 5

Internal Geometry and Fire Tests

Case 1	Case 2	Case 3
1.17 m fire diameter (~ 2 MW) doors closed (restricted ventilation) no mech. exhaust	1.6 m fire diameter (~ 4 MW) doors closed (restricted ventilation) no mech. exhaust	1.6 m fire diameter (~ 4 MW) two doors (0.8 x 4 m) mech. exhaust ≈ 11 $m^3 s^{-1}$





Each test lasted ~ 6 minutes

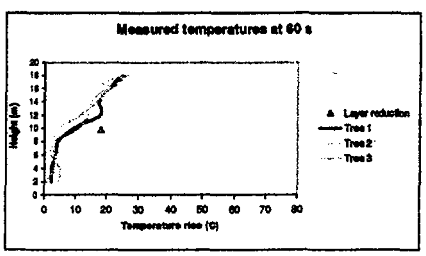
2 or 3 tests performed for each Case

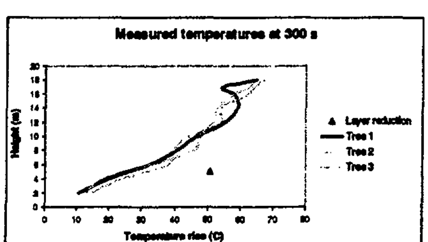
Heptane fuel - fuel mass loss rate recorded

Thermocouple readings taken

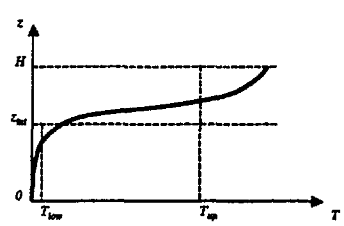
\# 6

Derived Upper Layer Temp & Height





Upper layer height and temperature derived from thermocouple readings at three locations (trees)



#7

Summary of Tasks

Zone	CFD
Heat release rate of fire	Temperatures at thermocouple trees (T1.1,...,T1.10,T2.1,...,T2.10,T3.1,...,T3.10)
Interface height	Temperatures at plume thermocouples (TG1.1 & TG.2)
Upper layer temperature	Infiltration flow rate (cases 1 & 2)
Infiltration flow rate (cases 1 & 2)	Mass flow rate in/out door 1 (case 3)
Mass flow rate in/out door 1 (case 3)	Mass flow rate in/out door 2 (case 3)
Mass flow rate in/out door 2 (case 3)	Velocities at the two doorways (case3) (V1.1,...,V1.3,V2.1,...,V2.3)
Total heat loss rate to solid boundaries	Total heat loss rate to solid boundaries
Heat loss through mech. exhaust (case 3)	Heat loss through mech. exhaust (case 3)
Plume temperature	Interface height (using reduction of thermocouple tree data)
	Upper layer temperature (using reduction of thermocouple tree data)
	Total heat release rate (within whole hall)

Lumped parameter models to include tasks as appropriate

First Results of COCOSYS and CFX Calculations for Benchmark Exercise #2 part 1 Fire in a large Hall

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)mbH

International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications

Gaithersburg, May 2-3, 2002

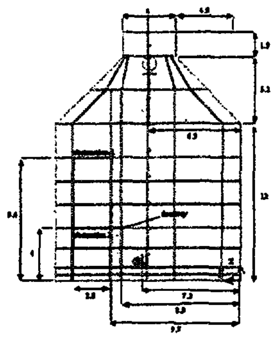
W. Klein-Heßling, M. Heitsch (CFX results)

Content

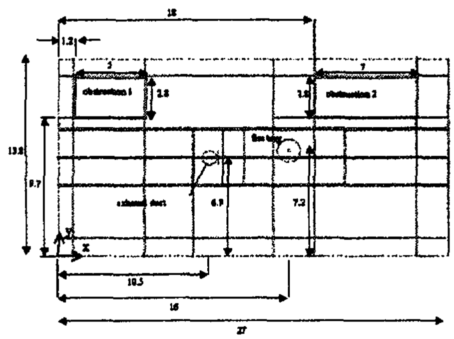
- Nodalisation and used models
- Performed calculations and variations
- First results – special aspects
- Conclusions – next steps

COCOSYS Nodalisation

- Side view

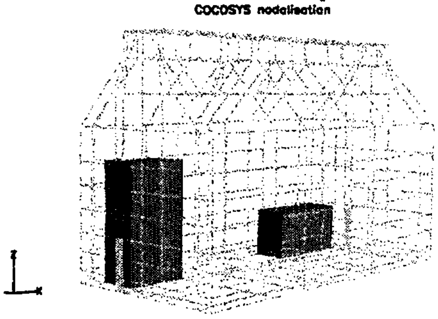


- Top view



COCOSYS Nodalisation (cont.)

- 3D view



- Characteristics
  - 543 nodes
  - 1475 connections
  - 421 wall structures

COCOSYS Model

- Pyrolysis model
  - Use of user-defined pyrolysis rate
  - Introduction of a factor for reaction efficiency of 60% above the pool
  - Use of a mixing factor of 2.4
  - Radiation fraction of 20%
- Radiation
  - Wall-to-wall radiation according specified view factors
  - Distribution of radiated heat (from reaction) according specified view factors from control volumes to wall nodes

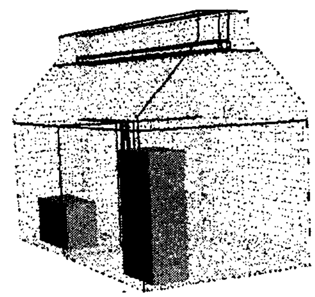
COCOSYS Model

- Heat loss through walls
  - 1D-heat conduction model
  - Use of correlations for free convection / or specified value
- Limitations
  - No plume model
  - No momentum balance
  - No soot model

CFX grid and model

- CFX model
  - Use of eddy-break-up combustion model
  - Use of Magnussen-soot model
  - Use of k-e turbulence model
  - Use of radiation model of CFX
- CFX grid

Fire Benchmark #2 part 1
CFX grid



Performed calculations - preliminary results

- COCOSYS
  - 3 variations for each case
    - full reaction of pyrolyzed heptan (*COCfull*)
    - reduce efficiency of reaction at surface to 60% (*COCbase*)
    - change boundary conditions (*COCopt*)
      - COCOSYS heat transfer models
      - non-adiabatic walls
      - move part of infiltration to top of roof
- CFX
  - variation of eddy-break-up rate constant (from 23.5 to 19.)

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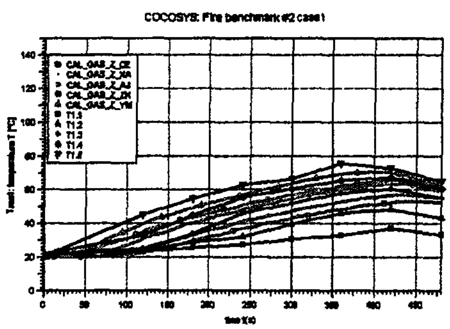
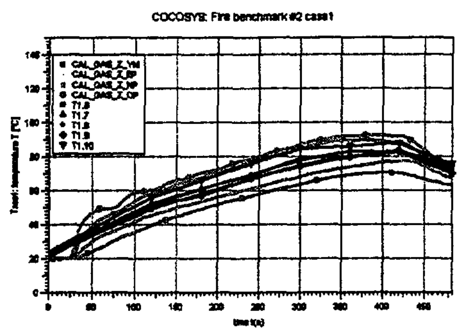
Preliminary results: Case1

- Tree 1 (lower part)



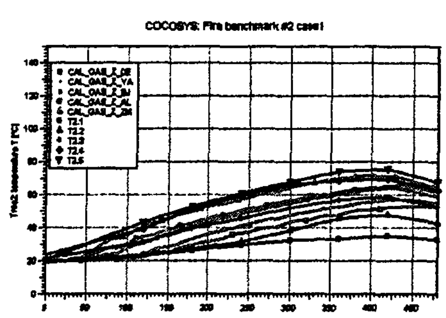
- Tree 1 (upper part)



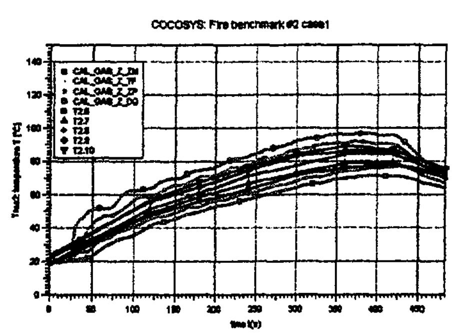
GRS

Preliminary results: Case1

- Tree 2 (lower part)

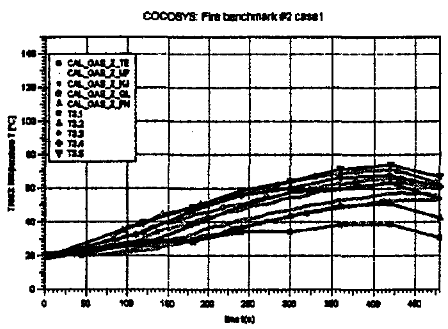


- Tree 2 (upper part)

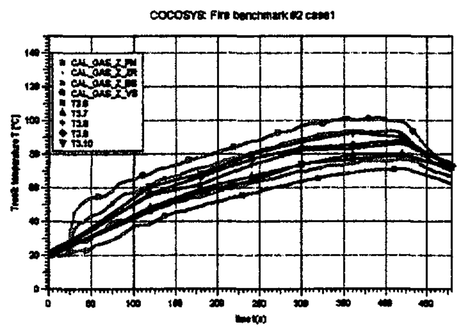


Preliminary results: Case1

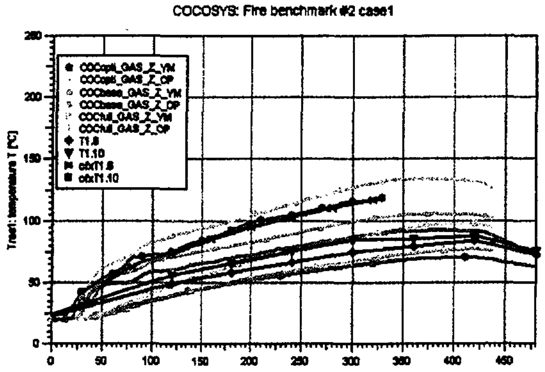
- Tree 2 (lower part)



- Tree 2 (upper part)

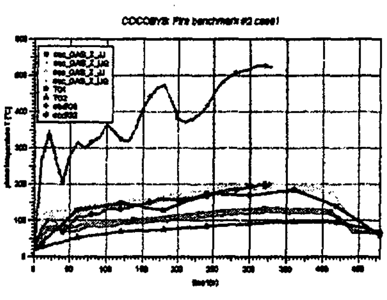


Preliminary results: Case1



- Comparable results for CFX and COCOSYS (variation *COCfull*)
- Less stratification in CFX according to meassurement
- Introduction of local efficiency of 60% leads to good temperatures

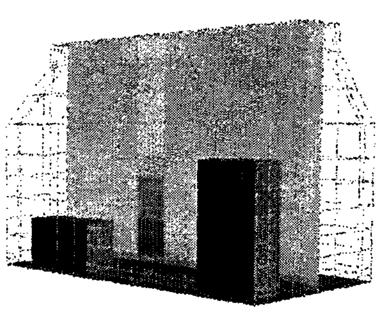
Preliminary results: Case1

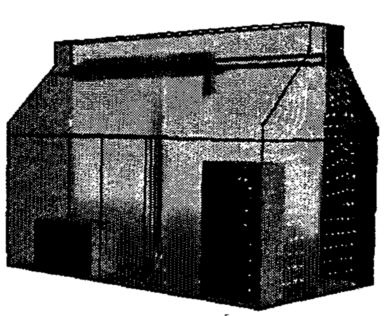


- ‚Average' temperatures inside plume
- No plume model in COCOSYS
- Temperatures inside CFX calculations much higher

Preliminary results: Case1

- Plume in COCOCSYS
- Plume in CFX

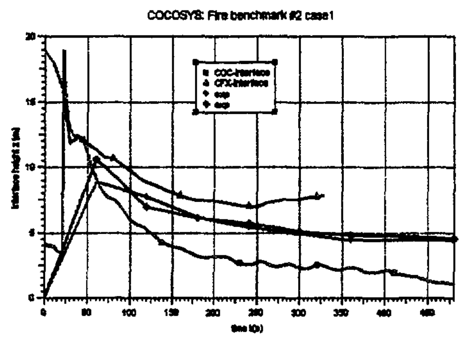


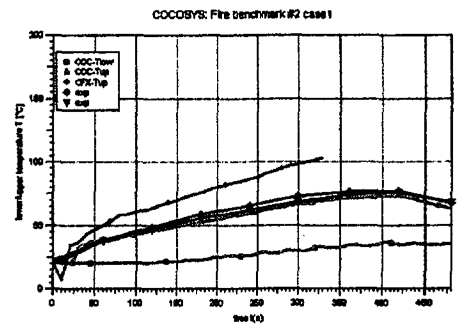


GRS

Preliminary results: Case1

- Interface height
- Upper layer temperature

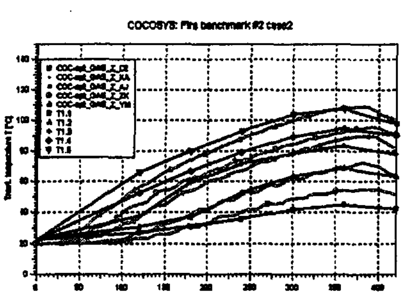


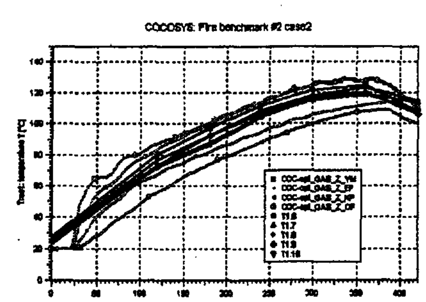


GRS

First results: Case 2

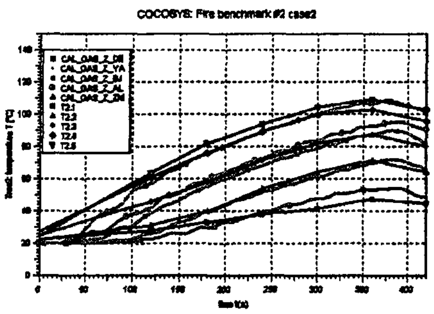
- lower part of tree 1
- upper part of tree 1

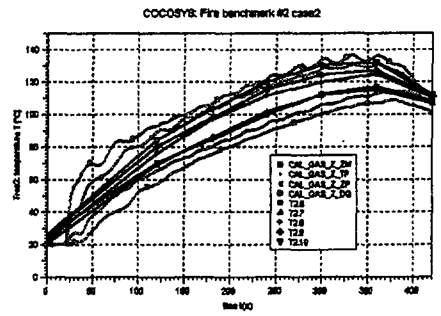




First results: Case 2 (cont.)

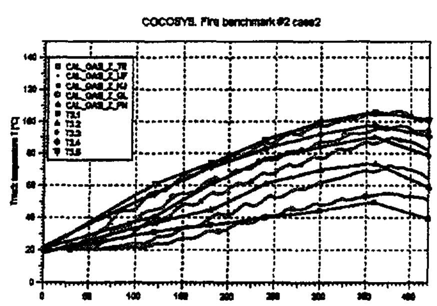
- lower part of tree 2
- upper part of tree 2

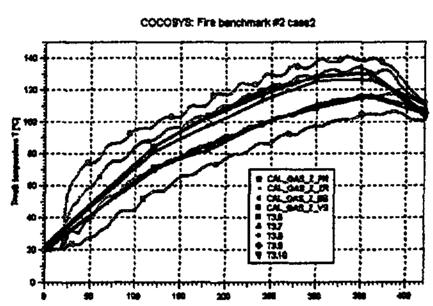




First results: Case 2 (cont.)

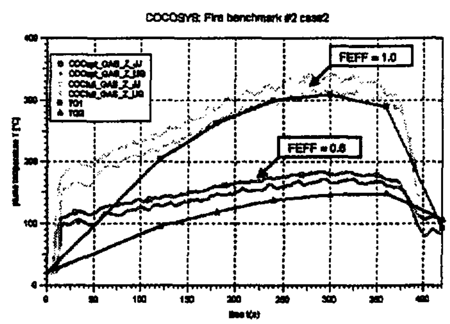
- lower part of tree 3
- upper part of tree 3

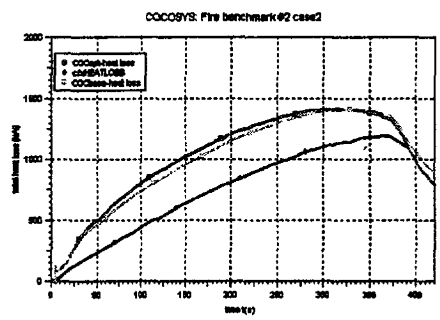




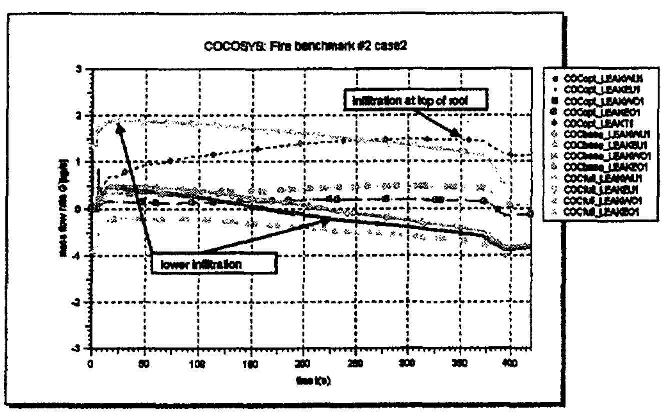
First results: Case 2 (cont.)

- Plume temperatures
- Heat loss to wall structures



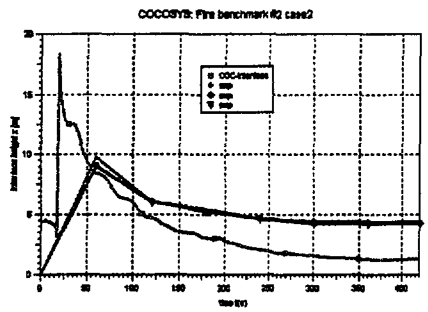


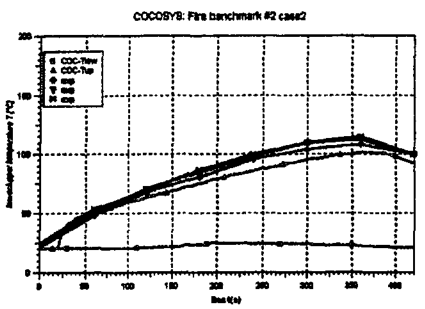
First results: Case 2 (cont.)



First results: Case 2 (cont.)

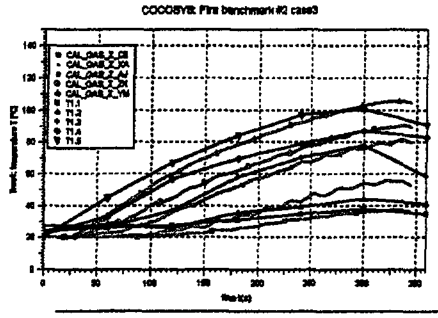
- Height of interface layer
- Upper layer temperature

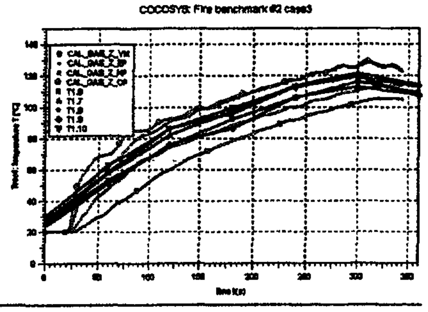




First results: Case 3

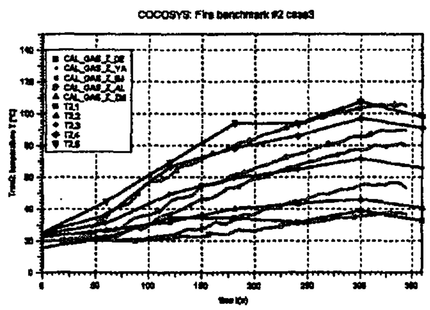
- lower part of tree 1
- upper part of tree 1

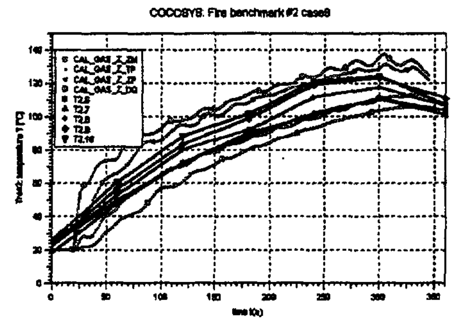




First results: Case 3 (cont.)

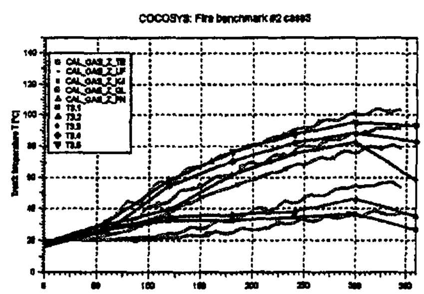
- lower part of tree 2
- upper part of tree 2

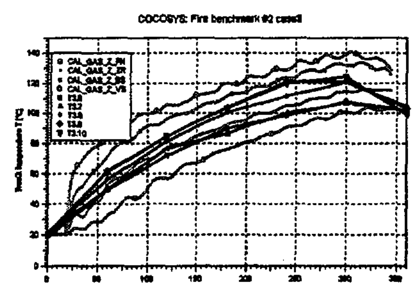




First results: Case 3 (cont.)

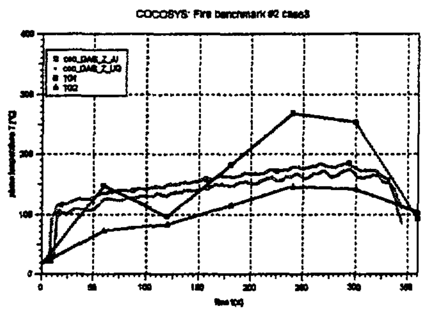
- lower part of tree 3
- upper part of tree 3



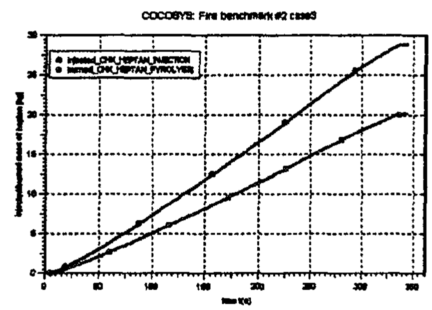


First results: Case 3 (cont.)

- Plume temperature

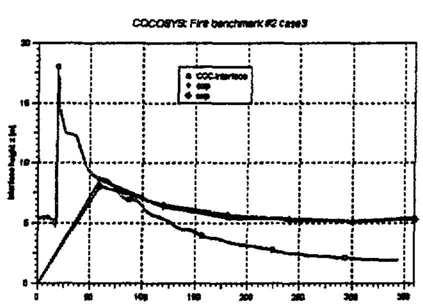


- Injected/burned heptan mass (about 70% is burned)

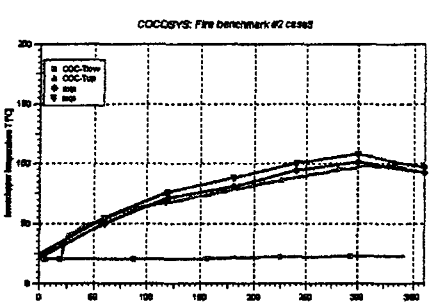


First results: Case 3 (cont.)

- Height of interface layer



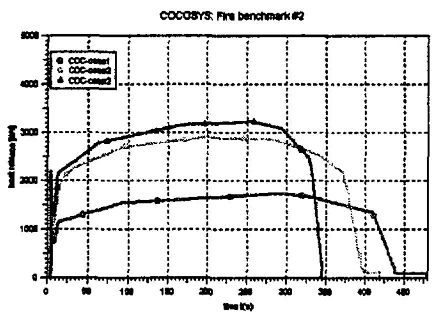
- Upper layer temperature

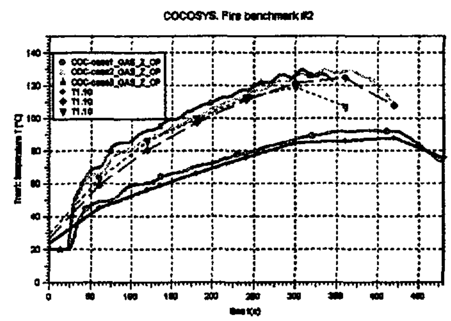


GRS

Comparison between the cases

- Heat release
- Temperature (Tree 1 top position)

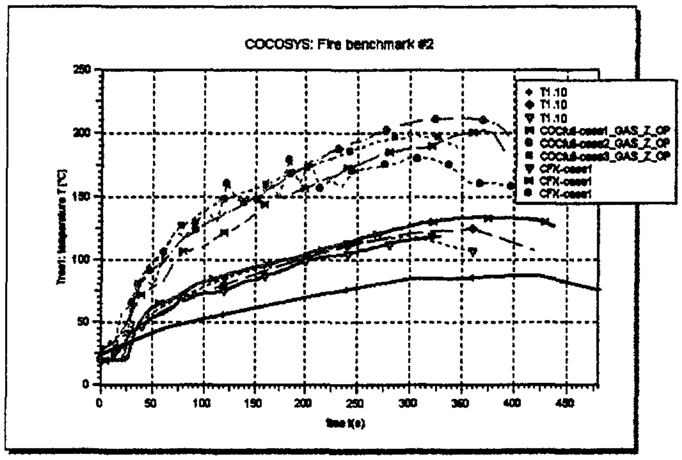




GRS

Comparison between the cases (cont.)

- Preliminary CFX results and COCOSYS results with complete reaction



Conclusions – next steps

- COCOSYS
  - Temperature results
    - good results after introducing reactions efficiency of 60% above the pool
    - to strong stratification in the hot gas layer
    - no plume model (→ temperature behavior TG1, TG2)
  - Additional experimental data available?
    - Temperature decrease (to check heat loss)
    - Concentration measurements

Conclusions – next steps (cont.)

- COCOSYS (cont.)
  - Infiltration position/heat loss to walls
    - only small effects on the results
    - care have to be taken for the definition of boundary conditions (environment pressure)
- CFX
  - too high temperatures (similar to COCOSYS results with full reaction) → variation of eddy-break-up rate constant
  - hot gas layer temperature homogeneous mixed (as measured)
  - still some problems with boundary conditions

Conclusions – next steps (cont.)

- Next steps
  - Continue with CFX calculations
  - Use of detailed oil burning model in COCOSYS
    - some more initial data is necessary (oil + water mass, geometry)
  - *Additional tests against other experiments*

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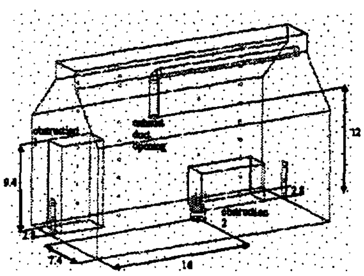
Misusing (Using) Fire Models



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- Tools:
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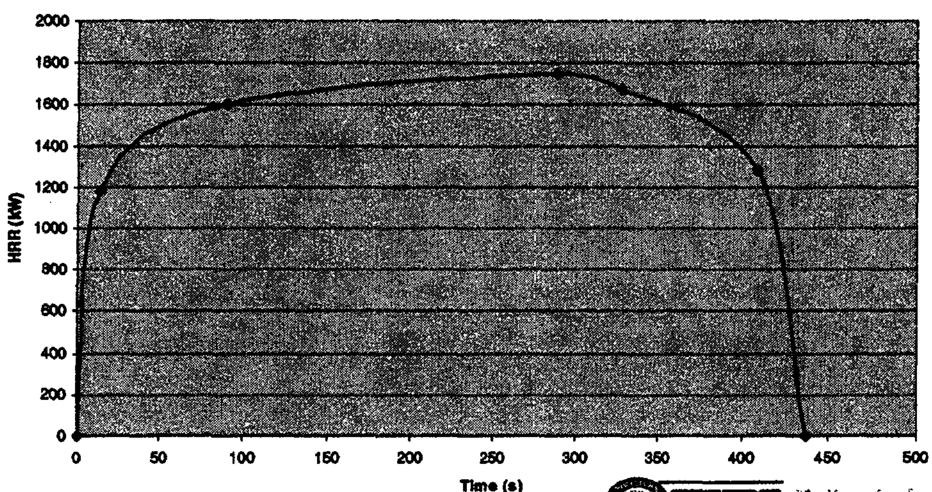

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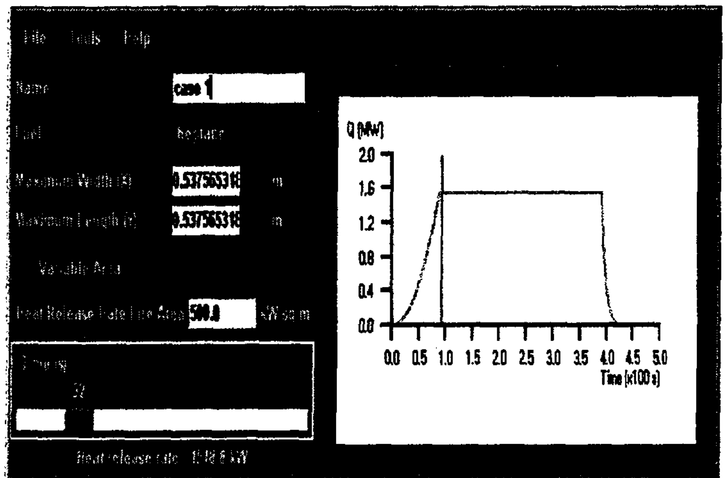

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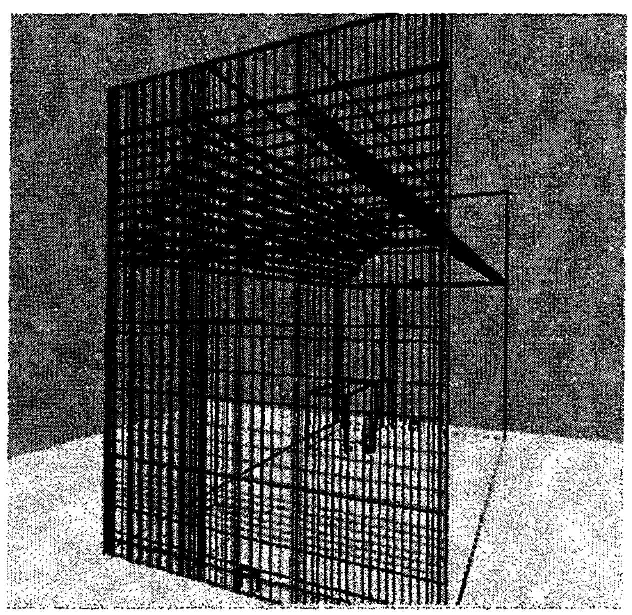

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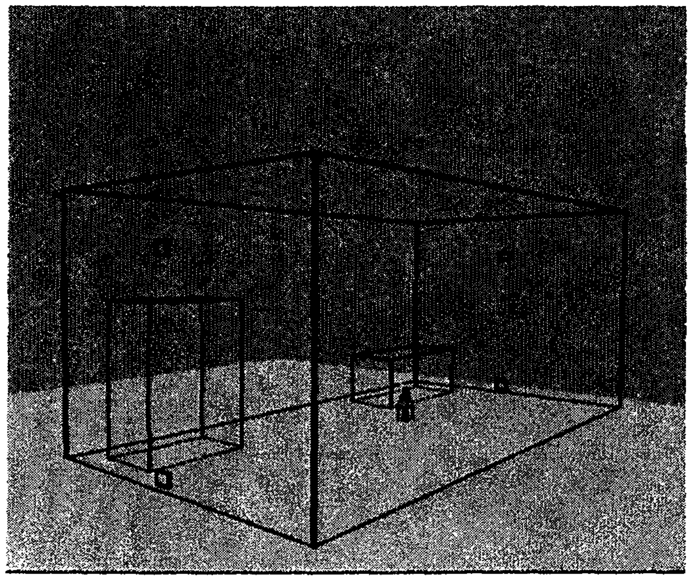

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- Material
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- Geometry
- Radiation
- Turbulence

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- o 400 secs/80 hours
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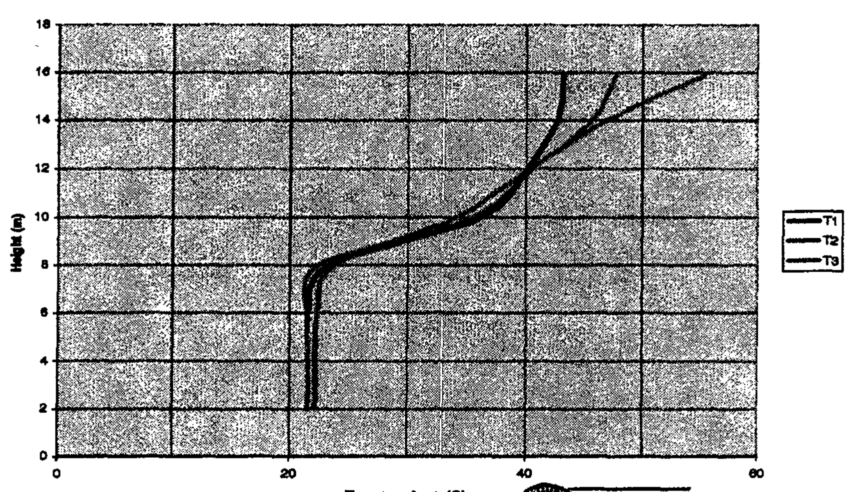
Height v. Temperature @ 120 s



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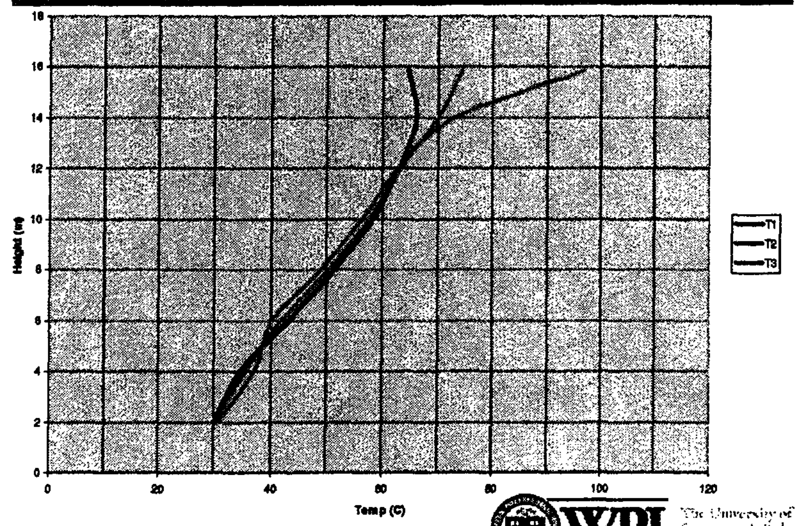
Height v. Temperature @ 240 s



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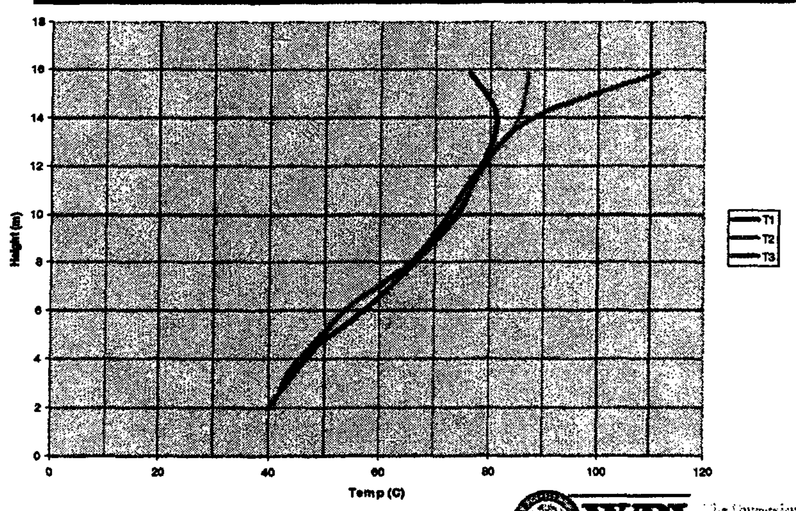

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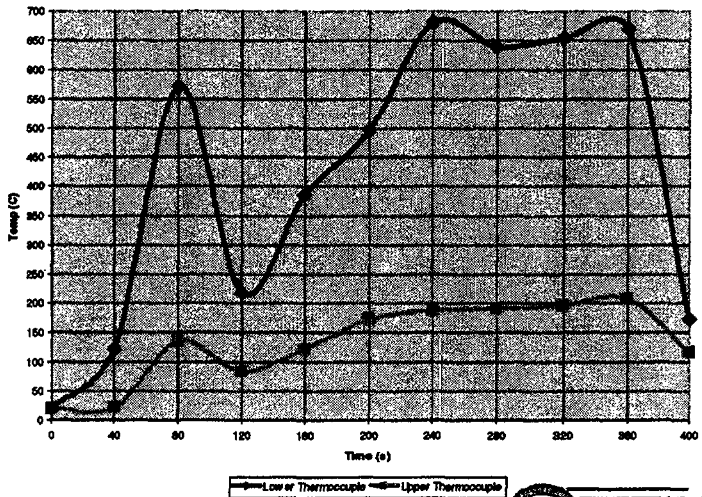

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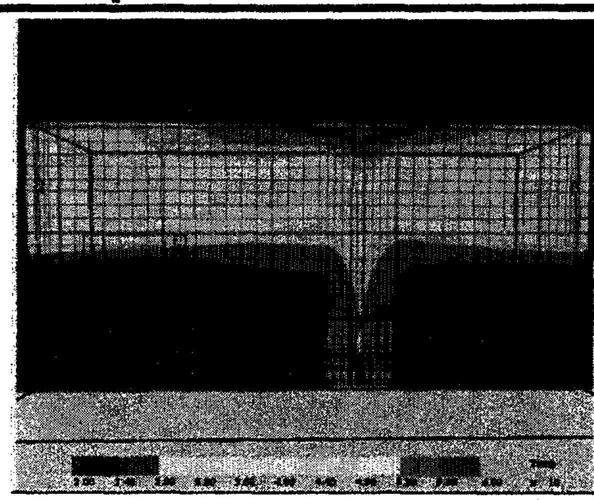
Sample Profile



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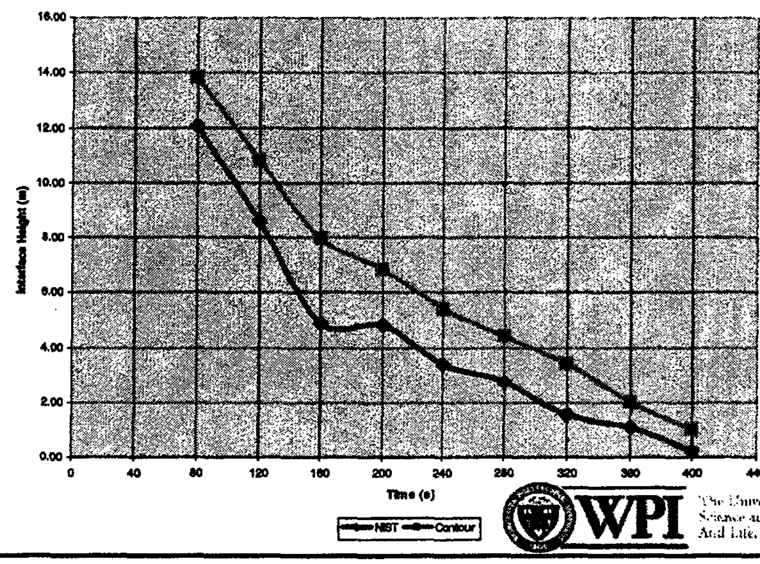

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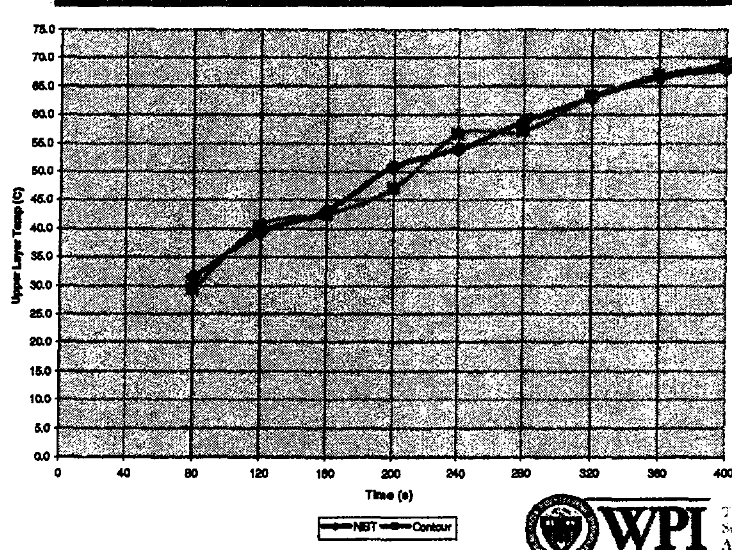
Upper Layer Temp v. Time



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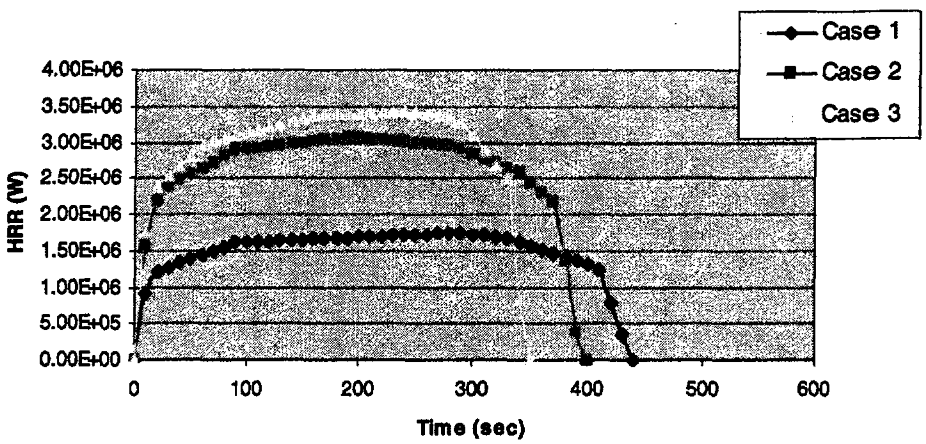

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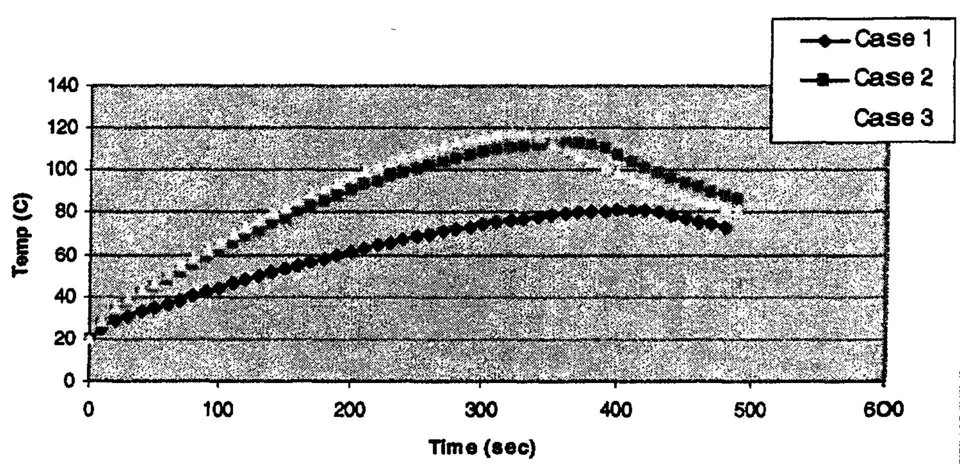

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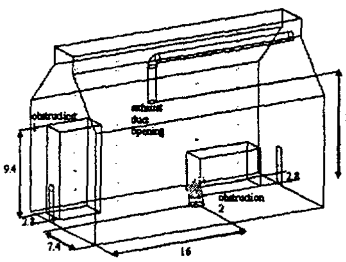

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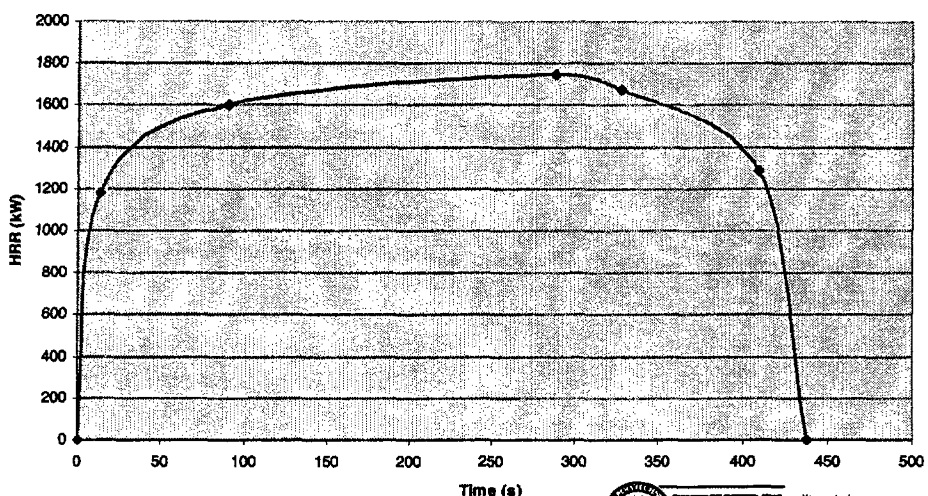

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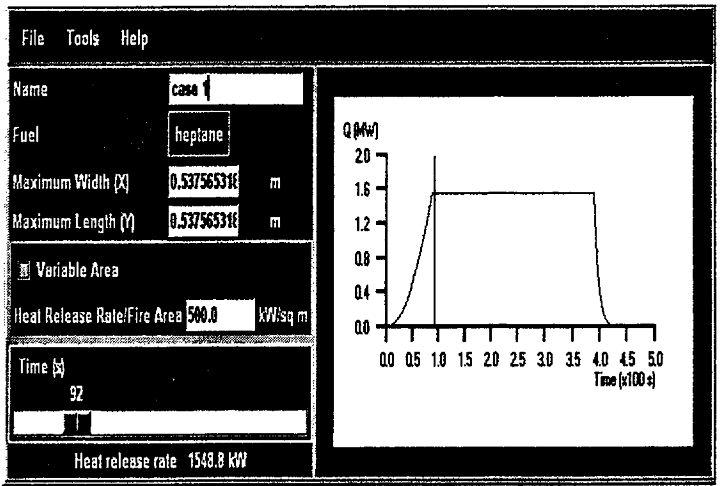

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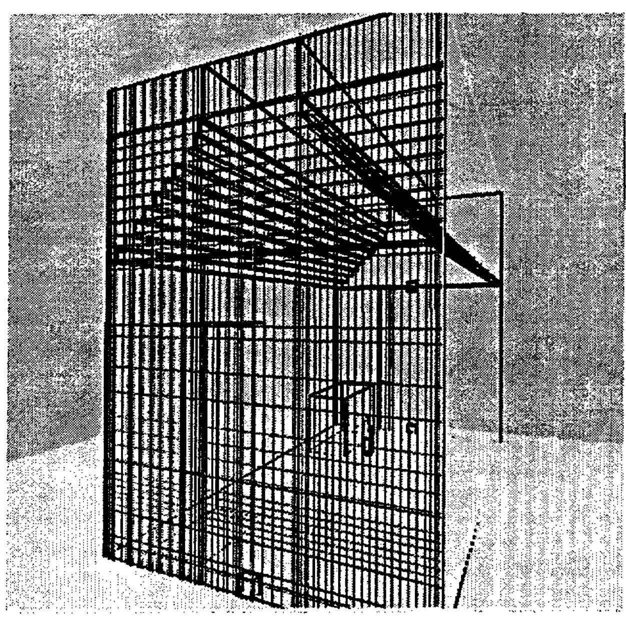

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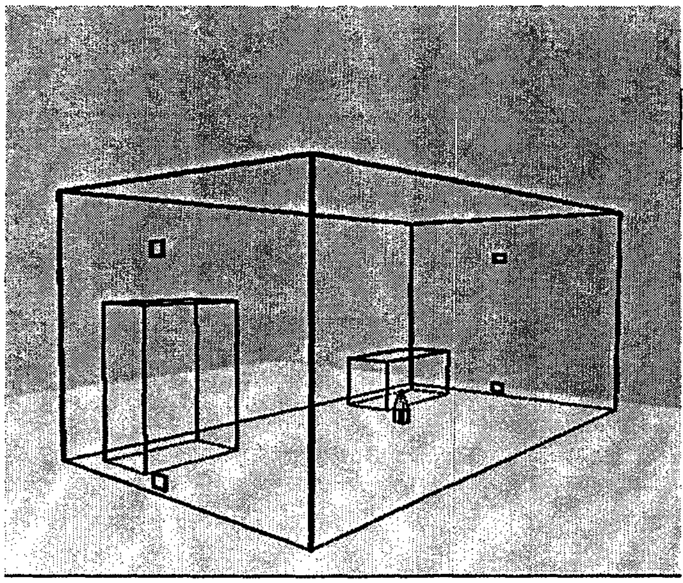

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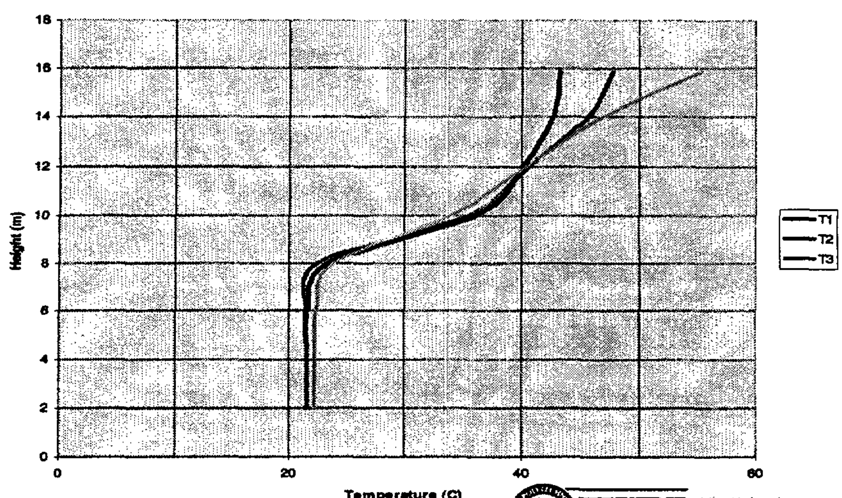
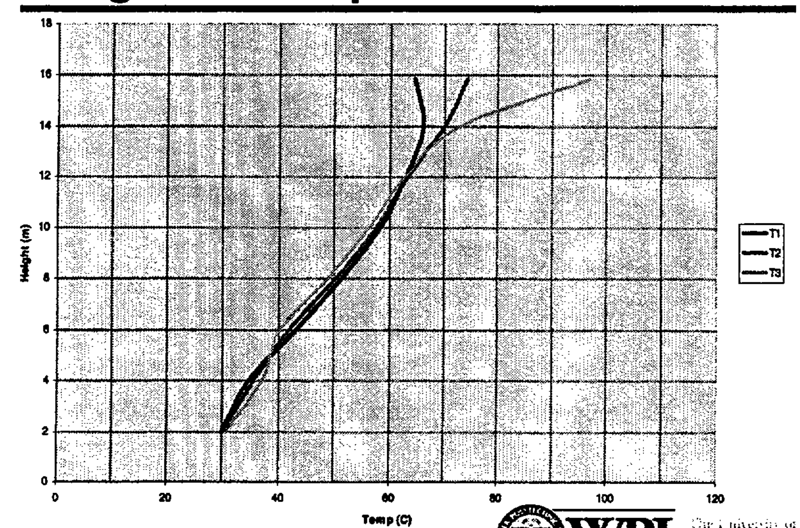


D-238

Height v. Temperature @ 240 s



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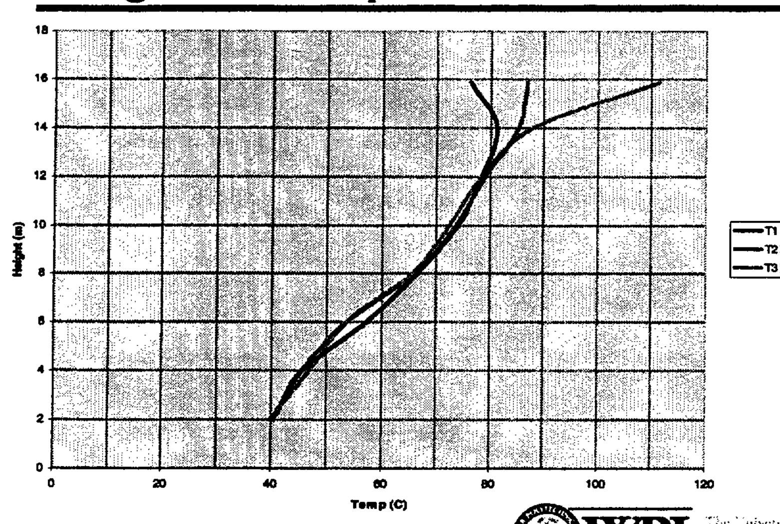

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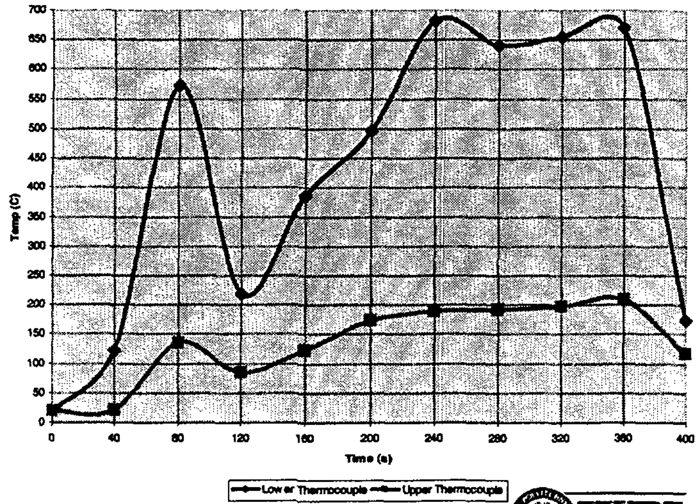

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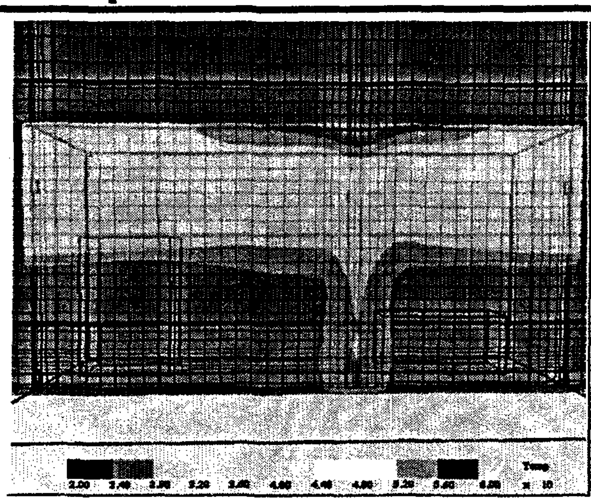
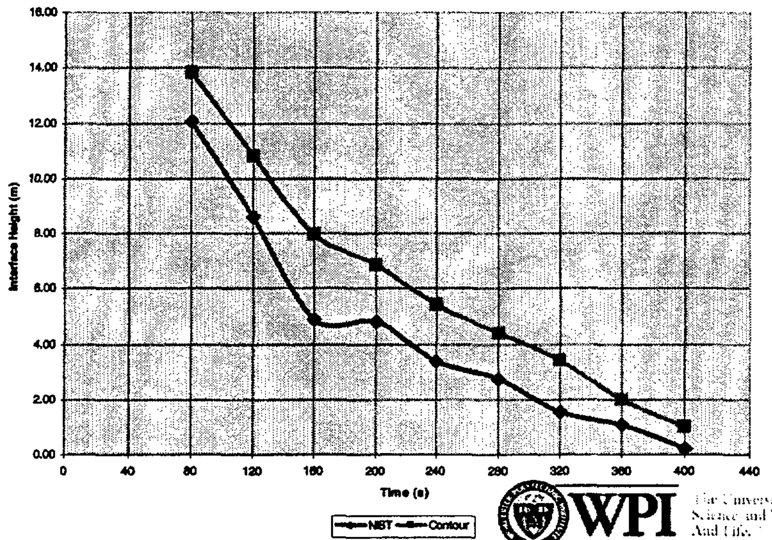


D-240

Interface Height v. Time



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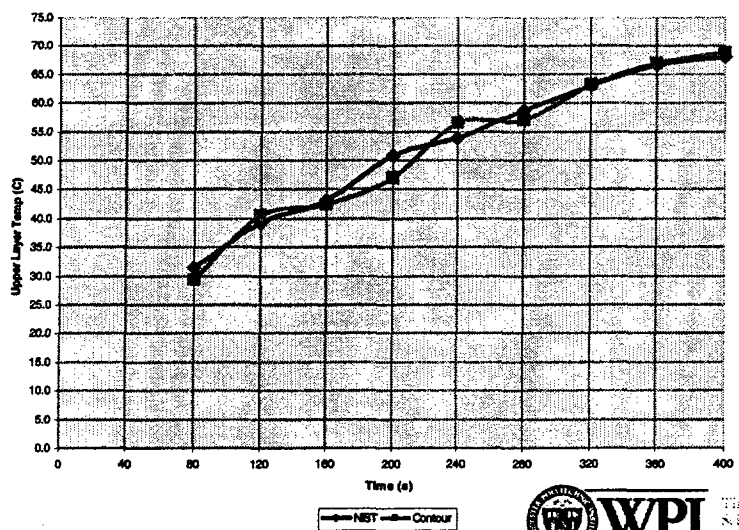

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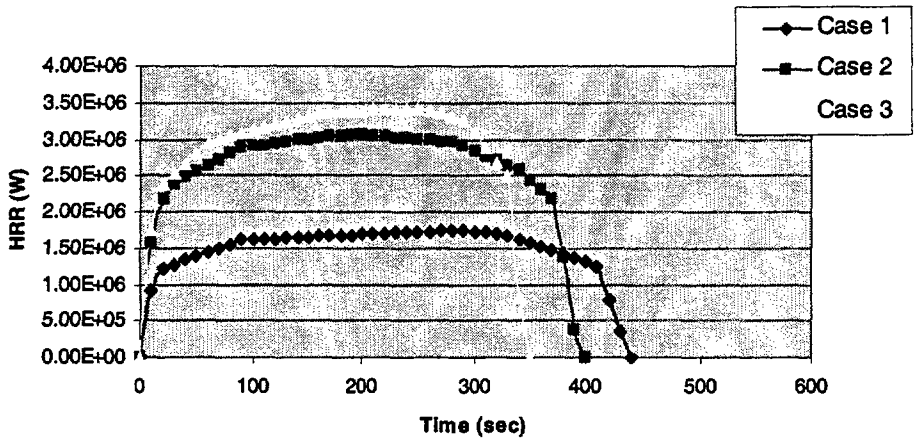

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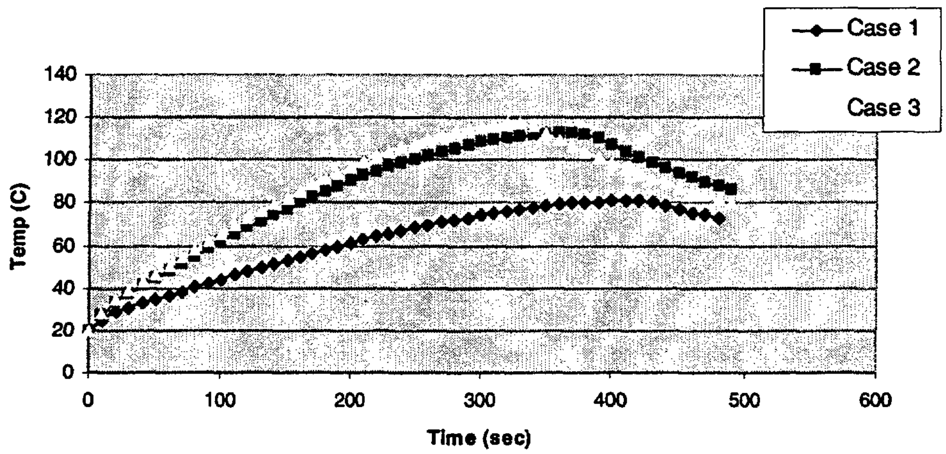

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Analysis of Benchmark Exercise Two: An Examination of Large Turbine Hall Fires with the CFAST Fire Modeling Code

A. R. Martin and D. A. Coutts

amber.martin@wxsms.com

Washington Energy & Environment

Westinghouse Safety Management Solutions

Washington Energy & Environment

SRS Perspective

- SRS has an obligation to fulfill DOE expectations
- DOE Fire Safety Program

  "... the use of such models is predicated on their being conservative and validated."
- Defense Nuclear Facilities Safety Board

  "Given the prominent role played by computer codes in ensuring the safe operation of DOE facilities, it is imperative that a thorough and effective approach to guaranteeing their quality be implemented." [TECH-25]

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SRS Focus

- ➢ Demonstrate code capabilities
- ➢ Understand code limitations
- ➢ Establish sample problems
- ➢ Ensure consistent analytical approach
- ➢ Document V & V efforts

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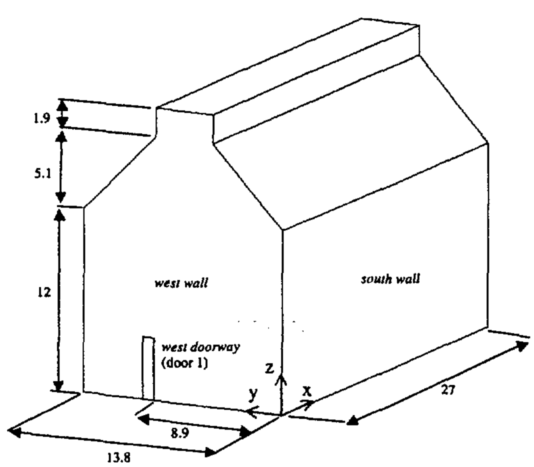
Turbine Hall Geometry



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Approach

- ➢ CFAST Version 3.1.6
- ➢ Adjusted ceiling height to maintain constant volume
- ➢ Lower Oxygen Limit - 12%
- ➢ Radiative Fraction - 20%
- ➢ Relative Humidity - 50%
- ➢ Wall Layers?

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Summary of Cases

Pyrolysis Rates for Part 1

Case 1		Case 2		Case 3	
t (min)	*dm/dt* (kg/s)	*t* (min)	*dm/dt* (kg/s)	*t* (min)	*dm/dt* (kg/s)
0.0	0.0	0.0	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	0.0	5.67	0.072	5.5	0.07
		6.2	0.06	5.75	0.0
		6.58	0.0		

Ventilation Conditions for Part 1

Case 1	Case 2	Case 3
doors closed no mech. exhaust natural leakage	doors closed no mech. exhaust natural leakage	doors open (0.8 m x 4m) mech. exhaust (11 m^3/s) ignore natural leakage

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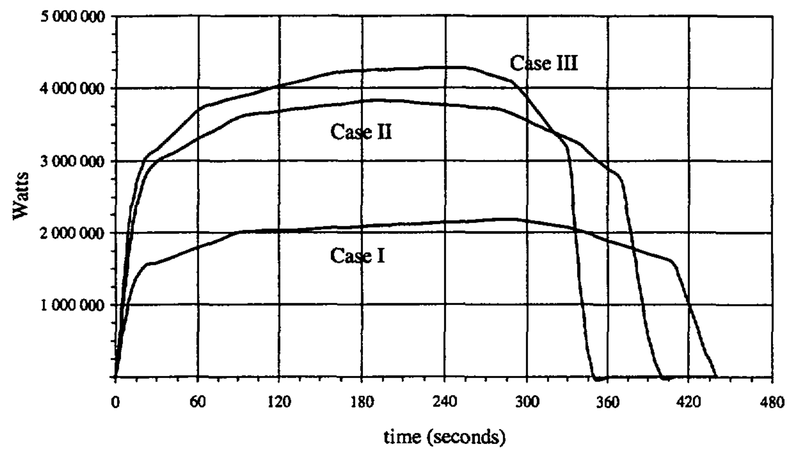
Heat Release Rate



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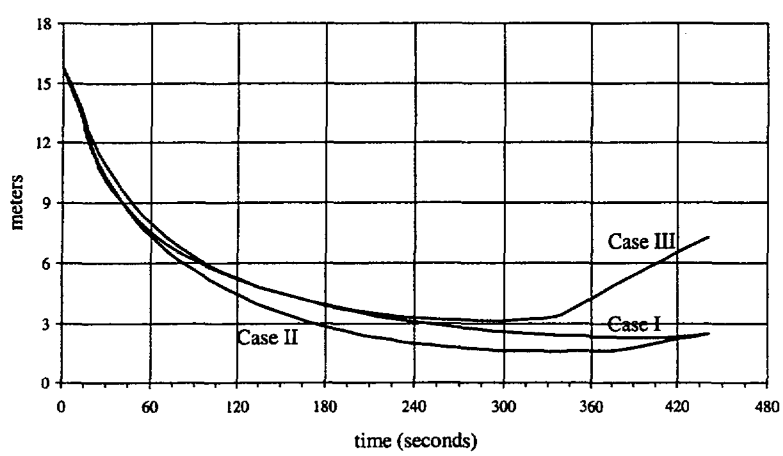
Interface Height



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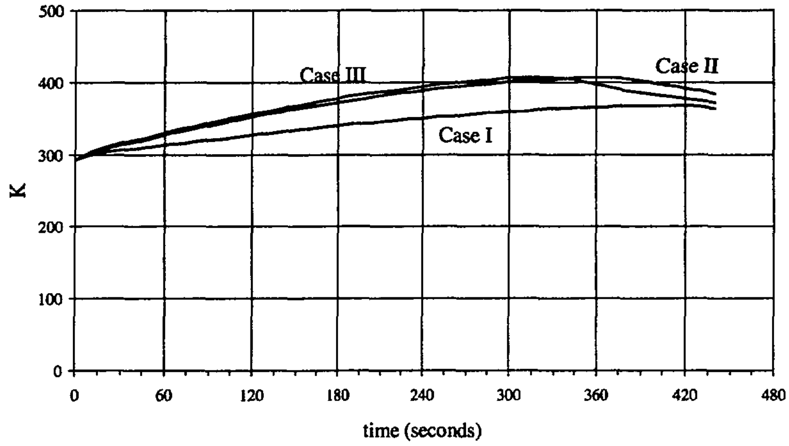
Upper Layer Temperature



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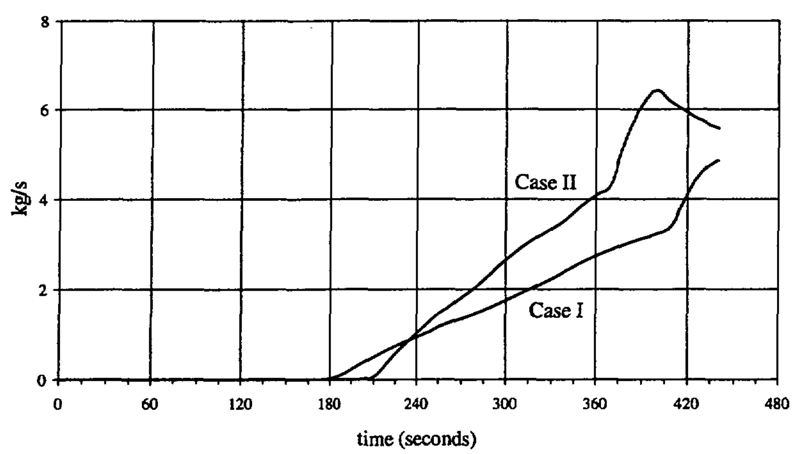
Infiltration Flow Rate (Cases I & II)



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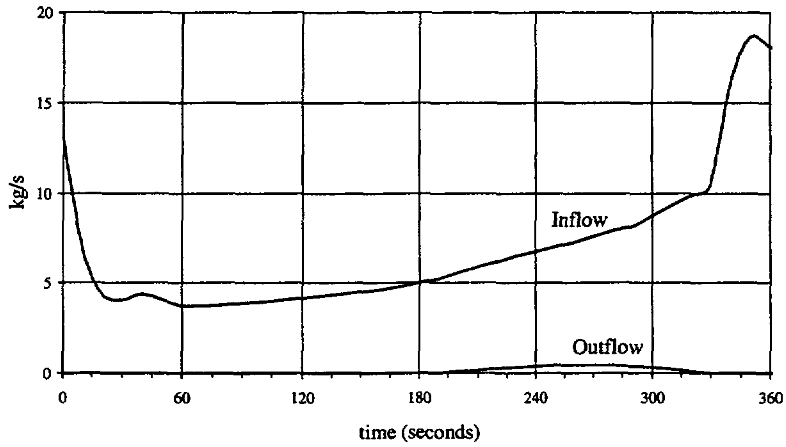
Door Flow Rate (Case III)



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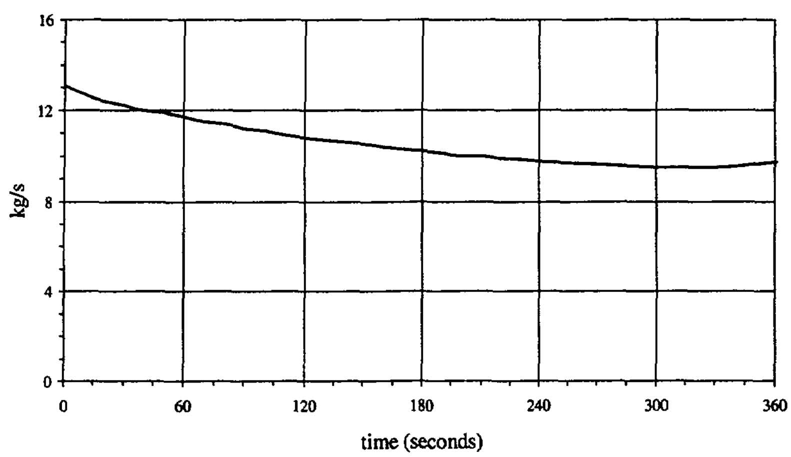
Mechanical Exhaust Flow Rate (Case III)



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Conclusions

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- ➢ Establish sample problems
- ➢ Ensure consistent analytical approach
- ➢ Document V & V efforts

HADCRT Results for Benchmark Exercise #2

May 3, 2002

Presented to the:

International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications

Presented by:

Boro Malinovic and Martin G. Plys

Fauske and Associates, Inc.

16W070 West 83rd Street

Burr Ridge, IL 60521

Background

- **Nuclear fuel cycle facility source term analysis code, HADCRT (Hanford Double Contained Receiver Tanks).**
- **Logical to extend HADCRT explosion & accident capability by adding fire models to the validated baseline code.**

Background

- **Generic features:**
  - Arbitrary topology
  - Arbitrary specification of chemical species & properties
  - Fog formation (vapor/aerosol equilibrium)
  - Density-driven counter-current gas flows between compartments
  - Aerosol agglomeration, settling, transport, & source models
  - Radiation networks
  - Multi-dimensional heat conduction

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Background

- **Fire features include:**
  - Stratified layer composition and thickness per compartment
  - Pilot fire definitions (burn rates, yields, etc.)
  - Plume model

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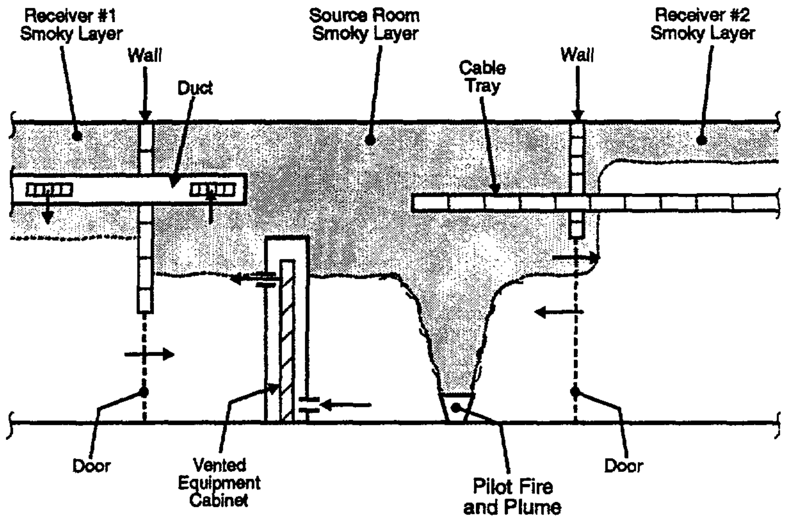
HADCRT Fire Model Features



MP99D450.CDR 3-19-2001

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HADCRT Model for Benchmark Exercise #2

- **Two regions: hall and the environment**
  - **Hall: 5891 m^3, 378 m^2 floor area, 1800 m^2 wall HX area, parallelepiped, 22 C, 101350 Pa**
  - **Environment: 20 C, 101350 Pa**
- **Seven Heat Sinks**
  - **Floor 1 ft. thick concrete; adiabatic on the outside**
  - **Sheet metal is neglected**
  - **Walls and ceiling are 5 cm mineral wool**
  - **One HS for floor, six for walls**
  - **Wall HS model the wall as six panels**
  - **Material properties from Table 1 of the problem specification**

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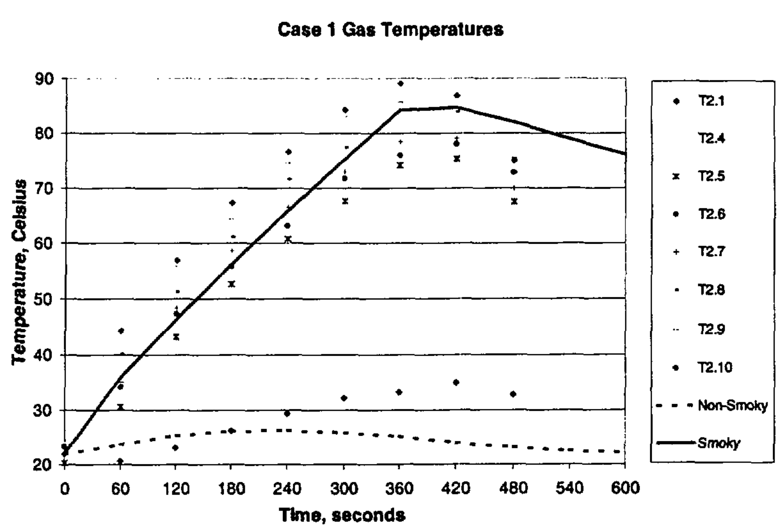
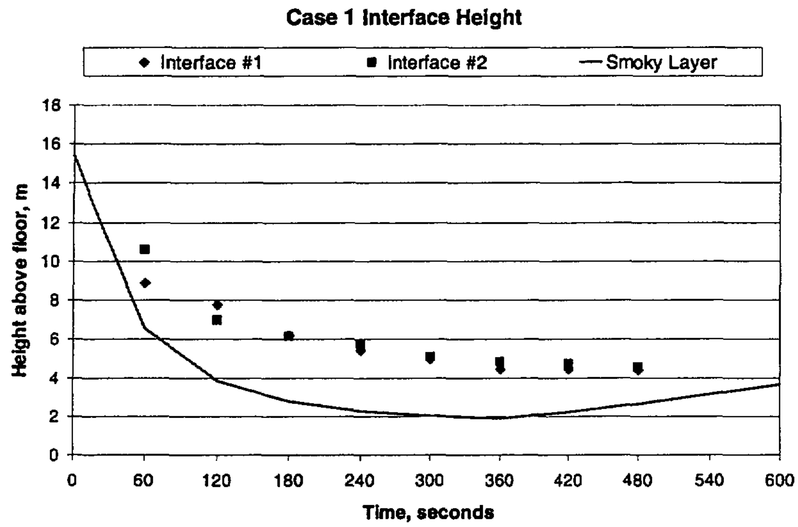
HADCRT Model for Benchmark Exercise #2

- **Junctions: depends on the case**
  - **Case 1: Four junctions, as shown in Table 2 of the problem specification, but only "z" coordinate matters**
  - **Case 2: Same as Case 1**
  - **Case 3: Two doors, one top junction has 11 m^3/s forced flow**
- **Code inputs for fires: region, area, burn flux, fuel properties, start time, fuel mass, yields for CO, CO2, CH, soot, H2O; limit of five fires**
- **Use handbook values for heptane; e.g., 44.6 MJ/kg**
- **As a first cut, skip radiation; fire is 100% convective**





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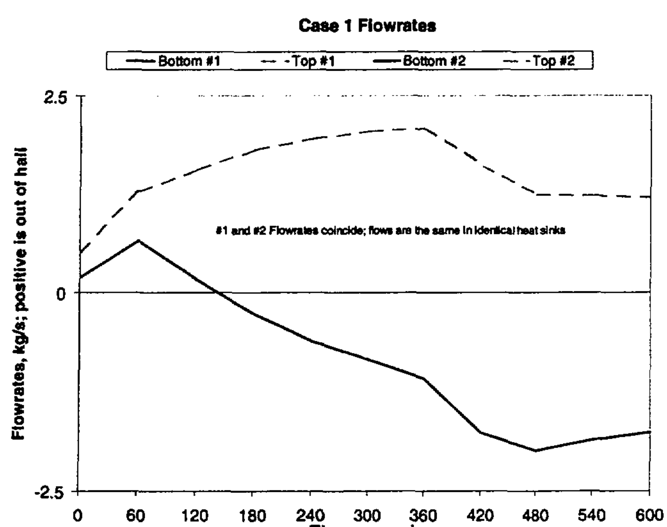

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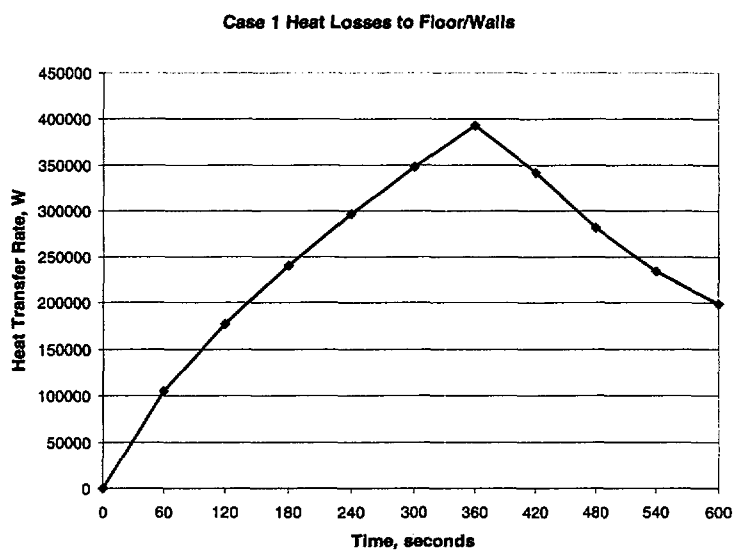

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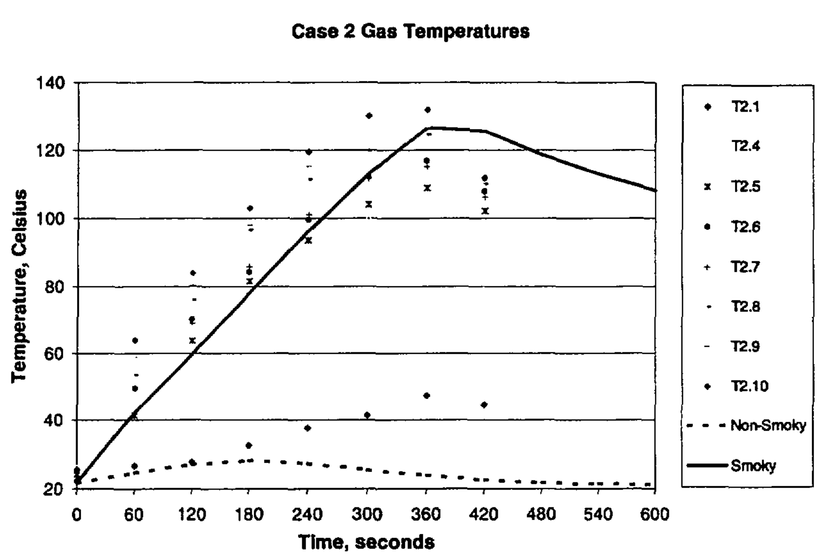

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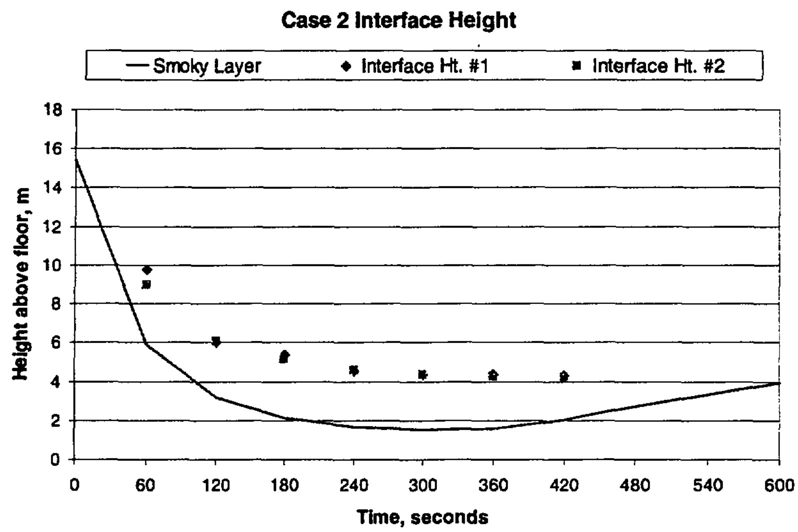

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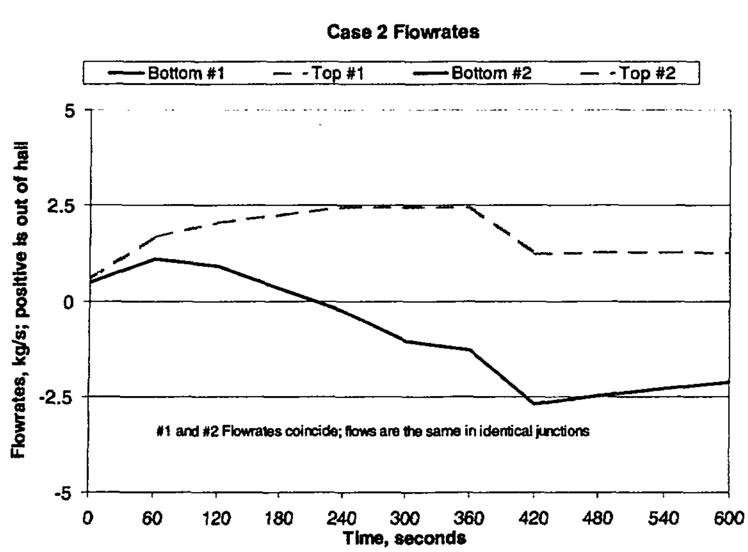

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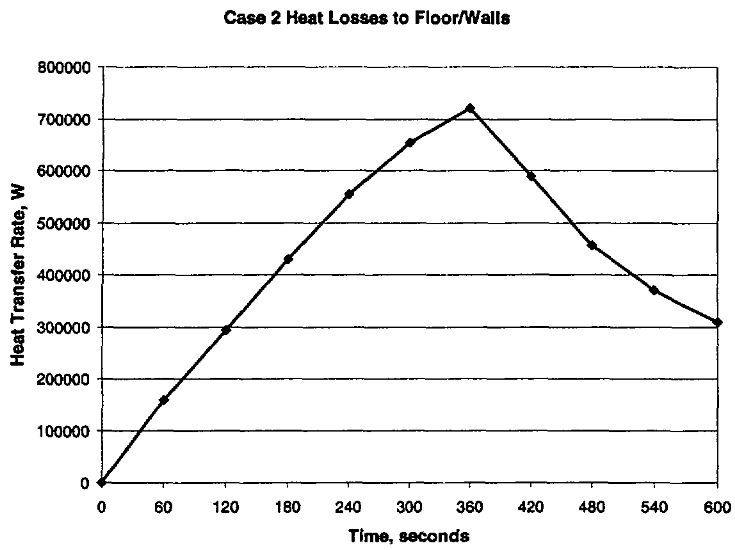

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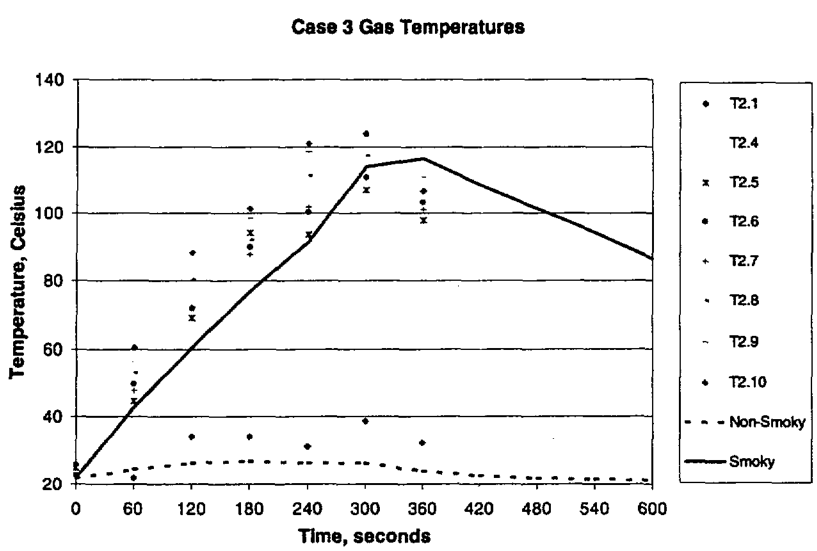

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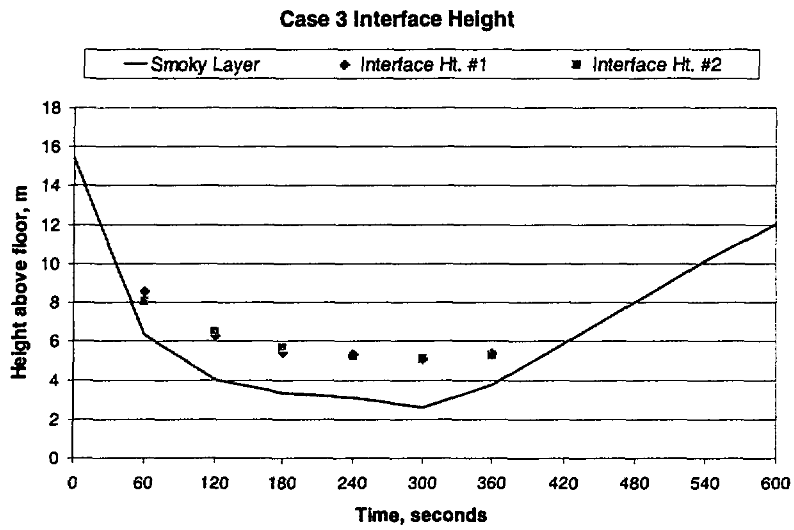

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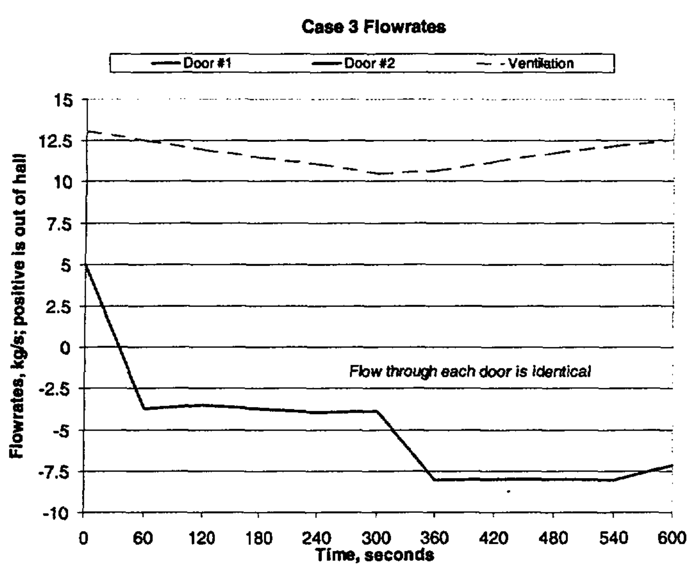

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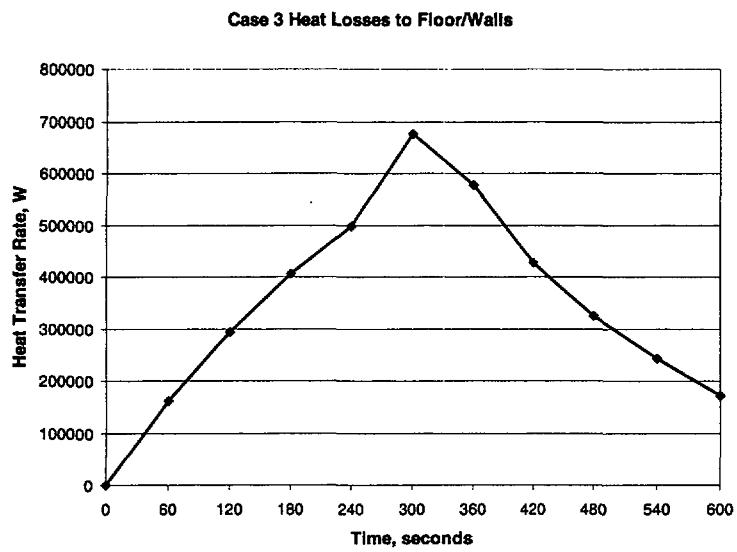

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Results Summary

- Non-smoky layer temperatures are low
  - Radiation neglected
  - Problem specification for junctions creates a chimney effect that brings cold air into the non-smoky layer
- Junction specification creates no pressure differential between the hall and the environment
- Parametric studies for leakage areas and infiltration are desirable
- Smoky layer temperatures are in good agreement
  - need to include the 80/20 split between convection and radiation and consider absorptivity

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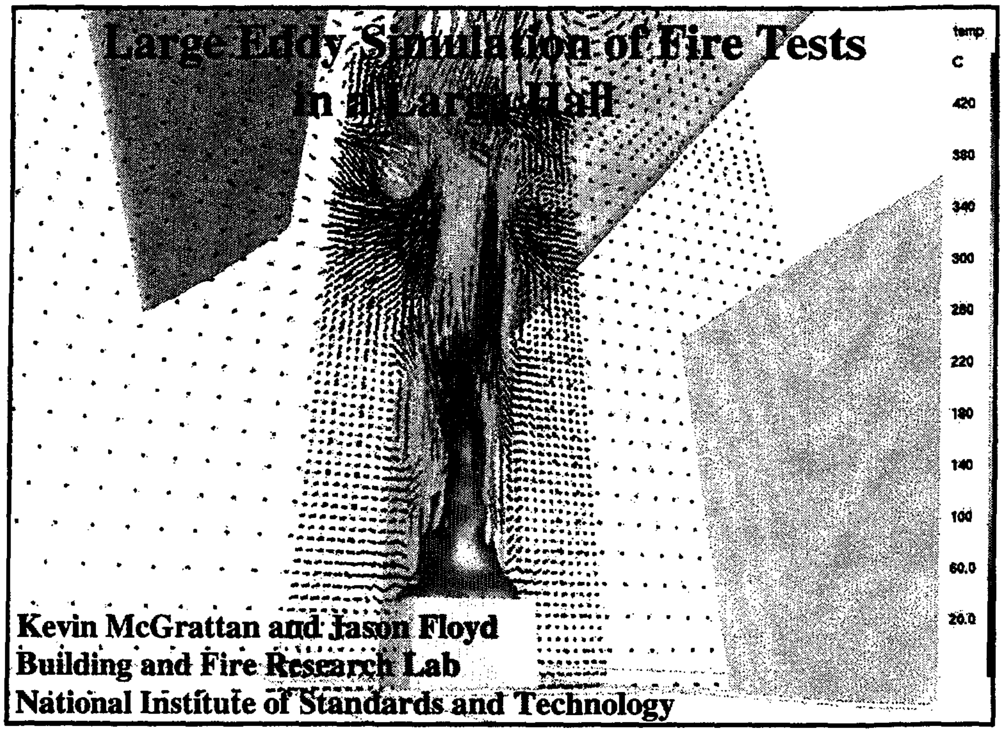
Future Work

- Parametric studies of leakage and infiltration
- Radiative aspects of the problem; set up radiation networks to better model gas and heat sink temperatures in the non-smoky layer, and target temperatures
- Smoky layer absorptivity
- Report plume temperatures
- Volume vs. height relationships for regions



Acknowledgements

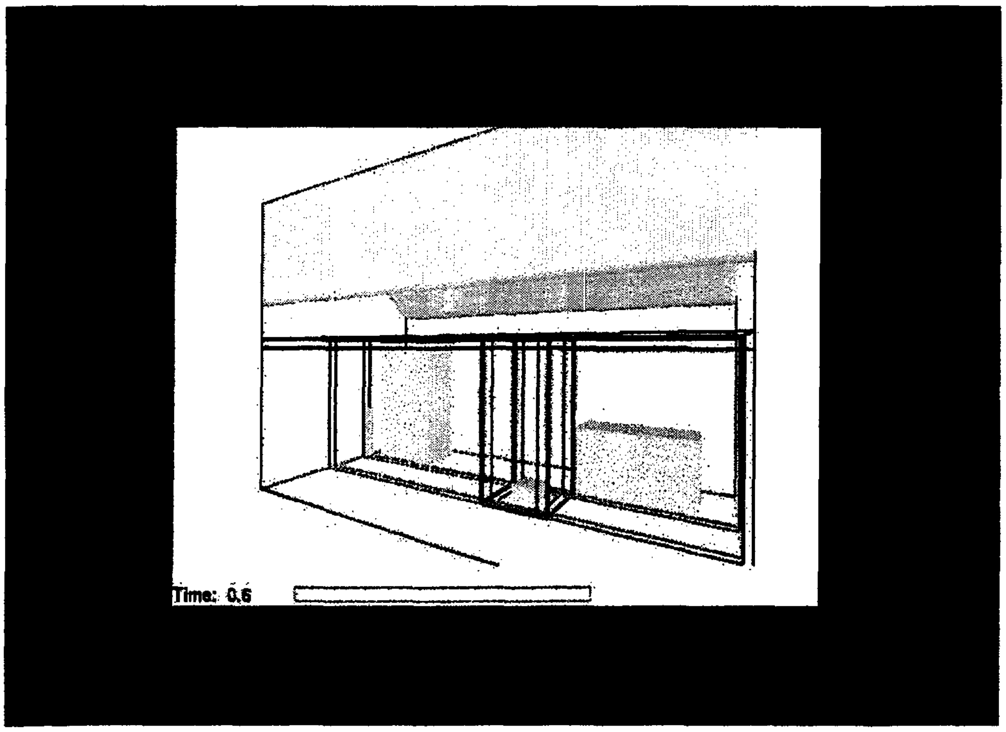
Glenn Forney – Smokeview Visualization

Howard Baum -- Radiation and combustion

Ron Rehm – Large Outdoor Fires, Wind

Simo Hostikka (VTT Finland) - Radiation

D-269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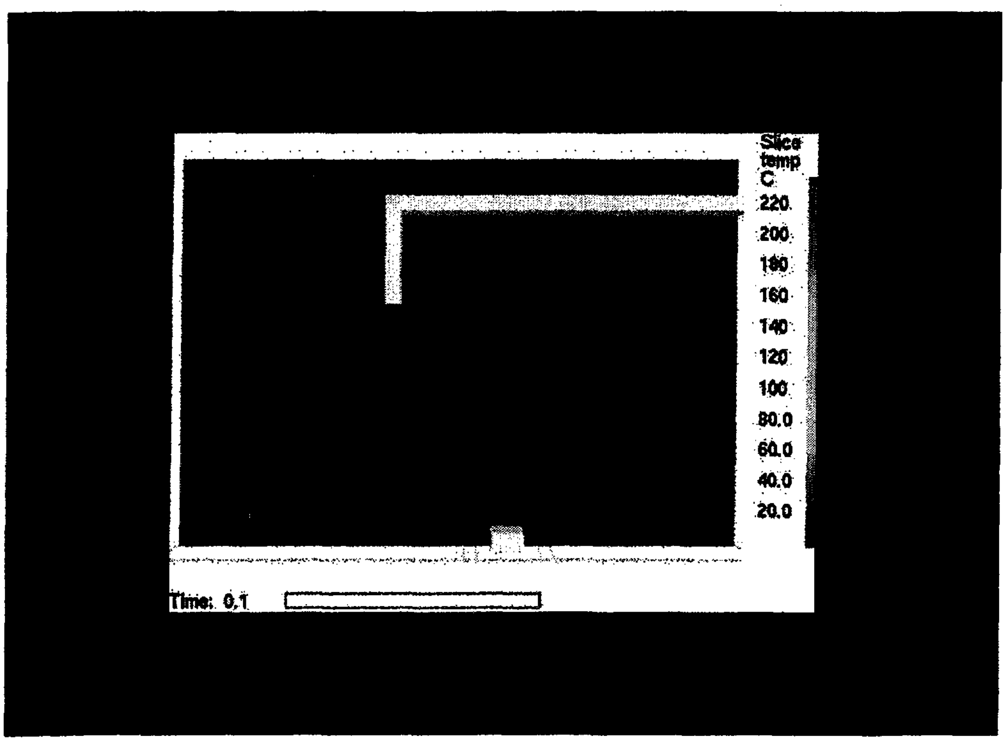
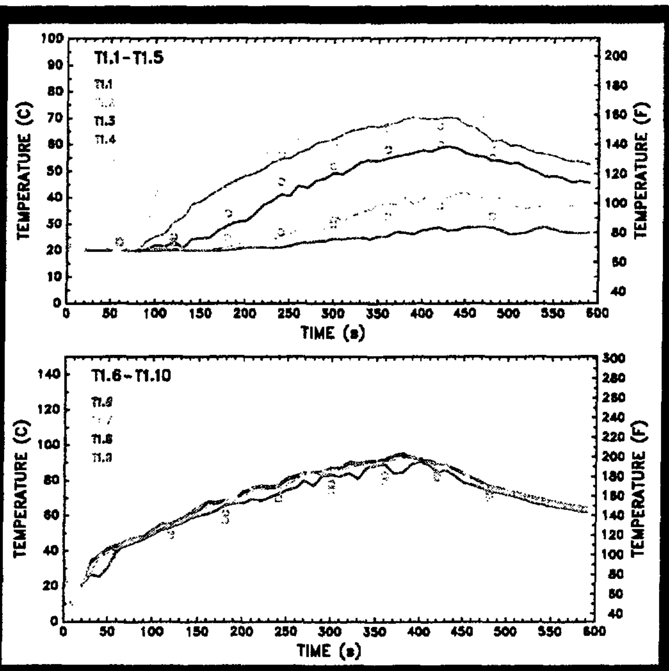
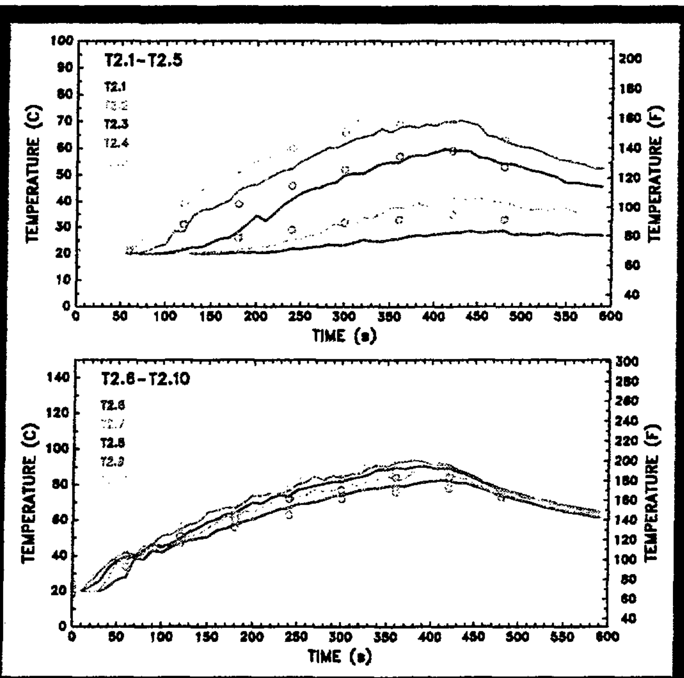
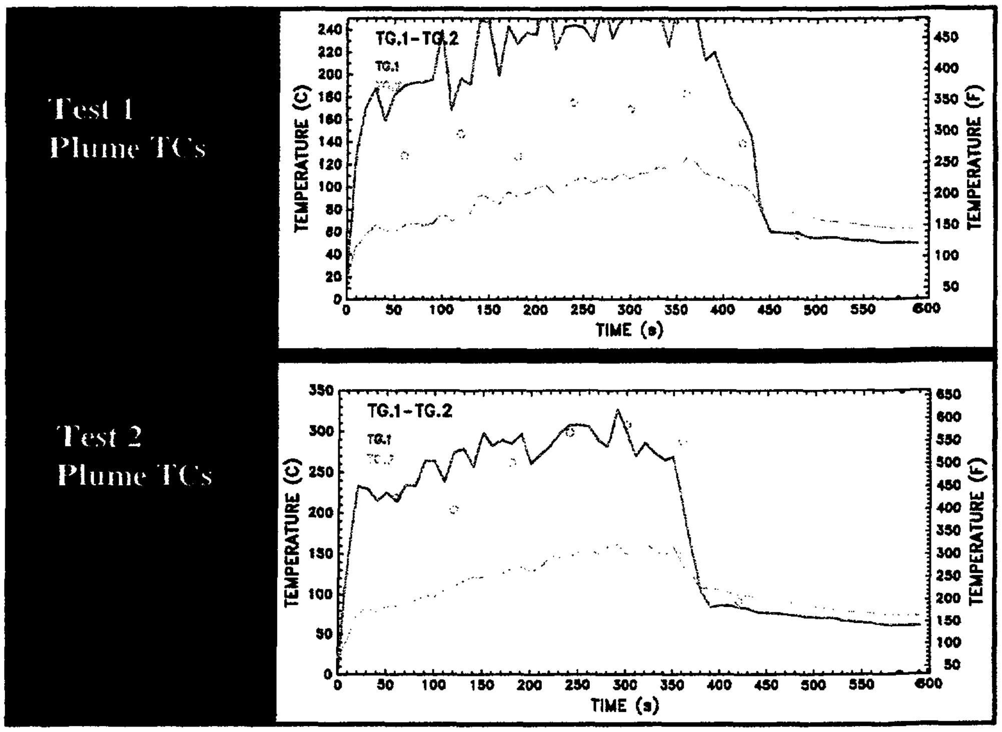

Slice
temp
C
220.
200.
180.
160.
140.
120.
100.
80.0
60.0
40.0
20.0
Time: 0.1

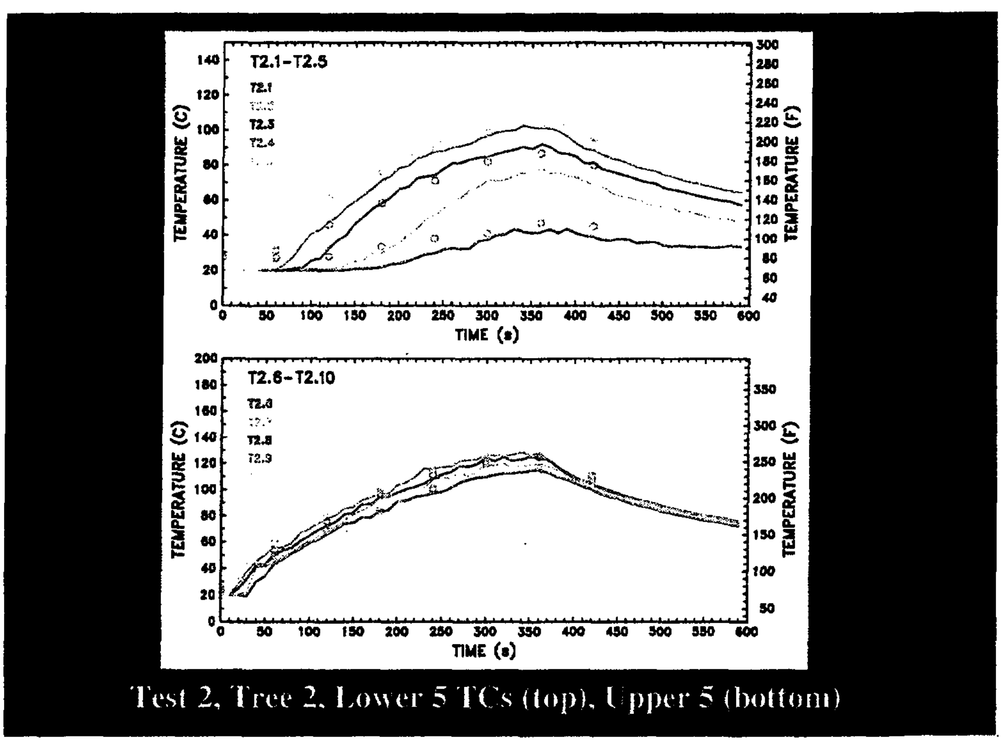


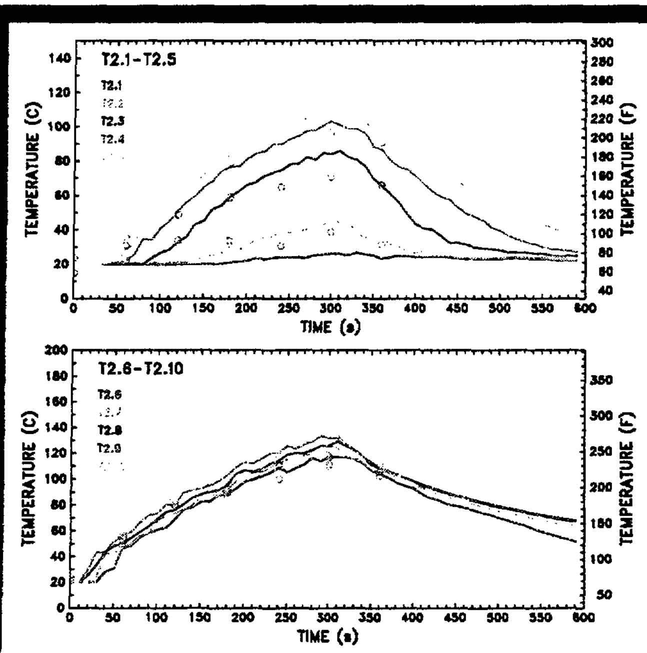
Test 1, Tree 1, Lower 5 TCs (top), Upper 5 (bottom)



Test 1, Tree 2, Lower 5 TCs (top), Upper 5 (lower)


Test 1
Plume TCs
TG.1-TG.2
TG.1
TEMPERATURE (C)
TEMPERATURE (F)
TIME (s)
Test 2
Plume TCs
TG.1-TG.2
TG.1
TEMPERATURE (C)
TEMPERATURE (F)
TIME (s)


T2.1-T2.5
T2.1
T2.3
T2.4
TEMPERATURE (C)
TEMPERATURE (F)
TIME (s)
T2.6-T2.10
T2.8
T2.9
TEMPERATURE (C)
TEMPERATURE (F)
TIME (s)
Test 2, Tree 2, Lower 5 TCs (top), Upper 5 (bottom)



Test 3, Tree 2, Lower 5 TCs (top), Upper 5 (bottom)

#1

Benchmark Analysis # 2

Fire in a Large Hall

Preliminary CFAST and JASMINE Simulations for Part I

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E-mail: miless@bre.co.uk

#2

Summary of Simulations

- Cases 1, 2 and 3 investigated
- CFAST/FAST version 3.1.6
  - predictions of upper layer temperature and layer height
  - investigation into implementation of geometry (complex roof)
  - investigation into boundary (conduction) heat losses
  - investigation into restricted ventilation openings (cases 1 & 2)
- JASMINE (CFD) version 3.2.1
  - comparison with temperature profiles at thermocouple trees 1,2 & 3
  - investigation into boundary (conduction) heat losses
  - investigation into restricted ventilation openings (cases 1 & 2)
  - grid refinement study

BRE

#3

CFAST Simulations - Cases 1&2

- Baseline simulations (following problem specification)
  - 2 horizontal flow vents (1.414 x 0.707 m) at floor level and 12 m
  - 'equivalent flat ceiling' height = 15.84 m
  - heptane fire source
    - $\Delta H_c = 44.6 \times 10^6$ J kg^{-1}
    - pyrolysis rate as specified
    - radiative fraction = 0.2
    - hydrogen to carbon ratio = 0.19
  - two-layer solid material at walls and ceiling (steel and mineral wool)
- Variant simulations
  - steel only and mineral wool only solid material at walls and ceiling
  - adiabatic boundaries
  - single horizontal flow vent (8 x 4 m) at floor level (e.g. two 4 x 4 m doors)
  - 2 horizontal flow vents (0.2 x 0.1 m) at floor level and 12 m
  - 'equivalent flat ceiling' height = 13 m and 18 m
  - upper vent at 6 m and 14 m

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BRE

#4

CFAST Simulations - Case 3

- Baseline simulations (following problem specification)
  - 1 horizontal flow vent (1.6 x 4 m) at floor level (two 0.8 x 4 m openings)
  - 'equivalent flat ceiling' height = 15.84 m
  - heptane fire source
    - $\Delta H_c = 44.6 \times 10^6$ J kg^{-1}
    - pyrolysis rate as specified
    - radiative fraction = 0.2
    - hydrogen to carbon ratio = 0.19
  - two-layer solid material at walls and ceiling (steel and mineral wool)
  - 11 $m^3 s^{-1}$ extraction flow rate through HVAC vent at 10 m height
- Variant simulations
  - 'equivalent flat ceiling' height = 13 m and 18 m
  - HVAC vent at 8 m height

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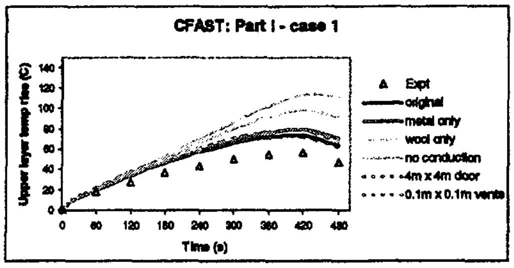
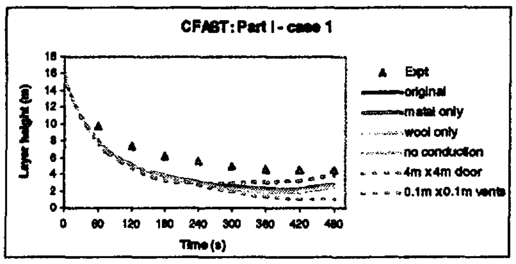
BRE

#5

CFAST Analysis - Case 1





Findings:

upper layer temperature sensitive to conduction heat loss mechanism (but only after 2 minutes)

upper layer temperature not sensitive to size of 'restricted ventilation openings'

layer height not sensitive to conduction heat loss mechanism

layer height sensitive to size of 'restricted ventilation openings' (but only after 4 minutes)

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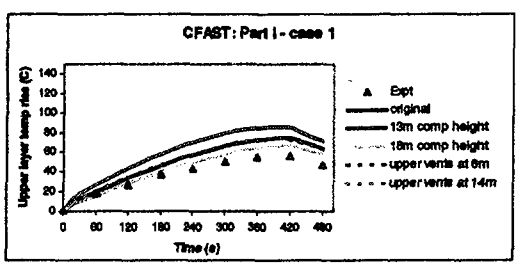
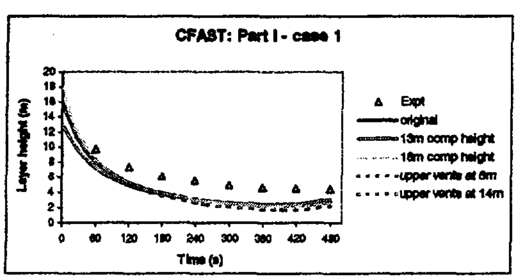
BRE

#6

CFAST Analysis - Case 1





Findings:

location (height) of upper 'restricted ventilation openings' not significant

upper layer temperature sensitive to height of 'equivalent flat ceiling'

layer height sensitive to height of 'equivalent flat ceiling' only for first 60 seconds

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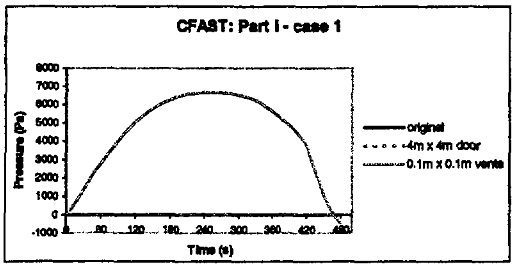
CFAST Analysis - Case 1

#7

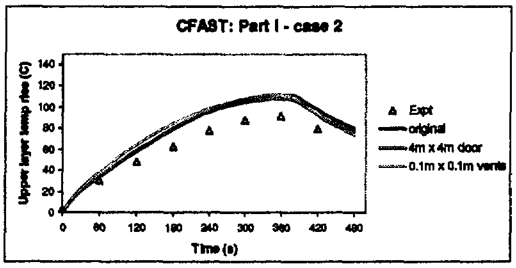


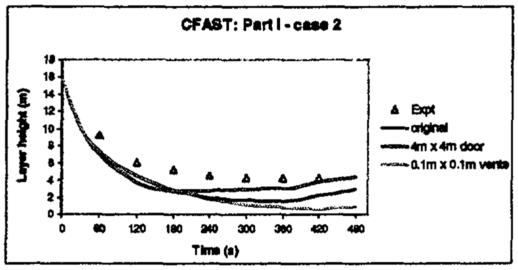
significant over-pressure with the very small openings

pressure ~ ambient for other opening sizes

CFAST Analysis - Case 2

#8





Findings:

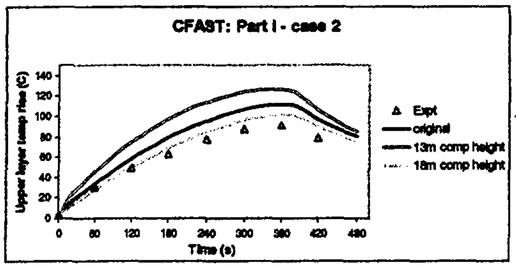
upper layer temperature not sensitive to size of 'restricted ventilation openings'

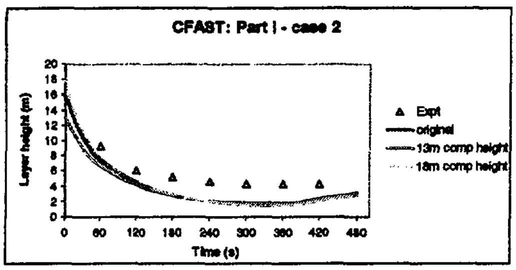
layer height sensitive to size of 'restricted ventilation openings' (but only after 3 minutes)

BRE

#9

CFAST Analysis - Case 2





Findings:

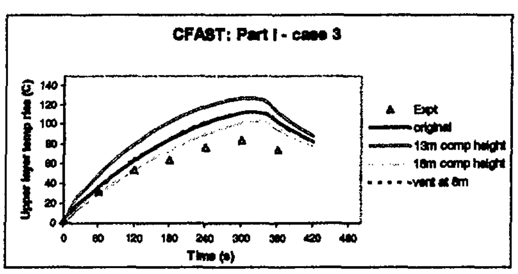
upper layer temperature sensitive to height of 'equivalent flat ceiling'

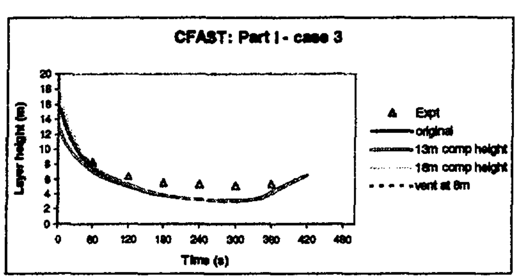
layer height sensitive to height of 'equivalent flat ceiling' only for first 60 seconds

BRE

#10

CFAST Analysis - Case 3





Findings:

location (height) of HVAC vent not significant (within range investigated)

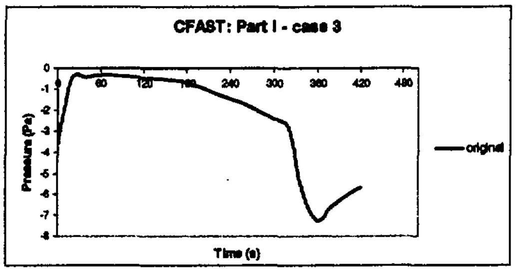
upper layer temperature sensitive to height of 'equivalent flat ceiling'

layer height sensitive to height of 'equivalent flat ceiling' only for first 60 seconds

BRE

#11

CFAST Analysis - Case 3



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BRE

#12

JASMINE Simulations - Cases 1&2

RANS with standard κ-ε turbulence model

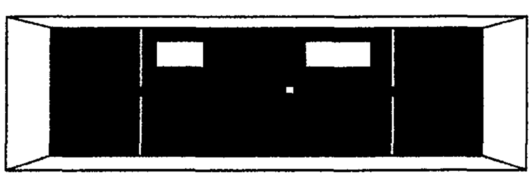
Numerical time-step = 1s

Eddy break-up combustion model with heptane (ΔH_c=0.8 x 44.6x10^6 J kg^{-1})

Six-flux radiation model (& Truelove's emissive power model)

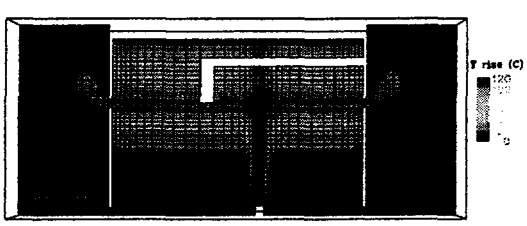
Convection (h_c=10 J s^{-1} m^{-2} K^{-1}) and radiation heat losses to solid boundaries

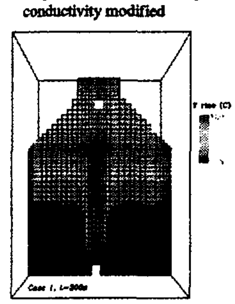
Semi-infinite approximation for conduction at boundaries (time-dependent conduction depth) - steel ignored



Ventilation options investigated:
- 0.5 m^2 squares
- 0.072 x 6.9 m slots
- slightly porous east & west walls

Boundary heat losses investigated:
- conductivity modified





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BRE

13

JASMINE Simulations - Case 3

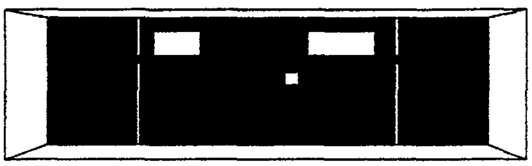
RANS with standard κ-ε turbulence model — Numerical time-step = 1s

Eddy break-up combustion model with heptane (ΔH_c=0.8 x 44.6x10^6 J kg^{-1})

Six-flux radiation model (& Truelove's emissive power model)

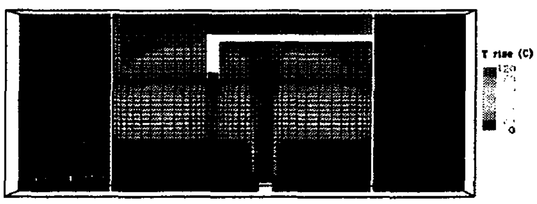
Convection (h_c=10 J s^{-1} m^{-2} K^{-1}) and radiation heat losses to solid boundaries

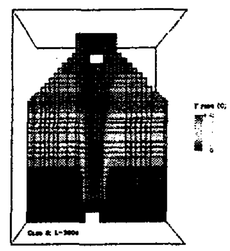
Semi-infinite approximation for conduction at boundaries (time-dependent conduction depth) - steel ignored



Boundary heat losses investigated:
conductivity modified

Mesh refinement investigated





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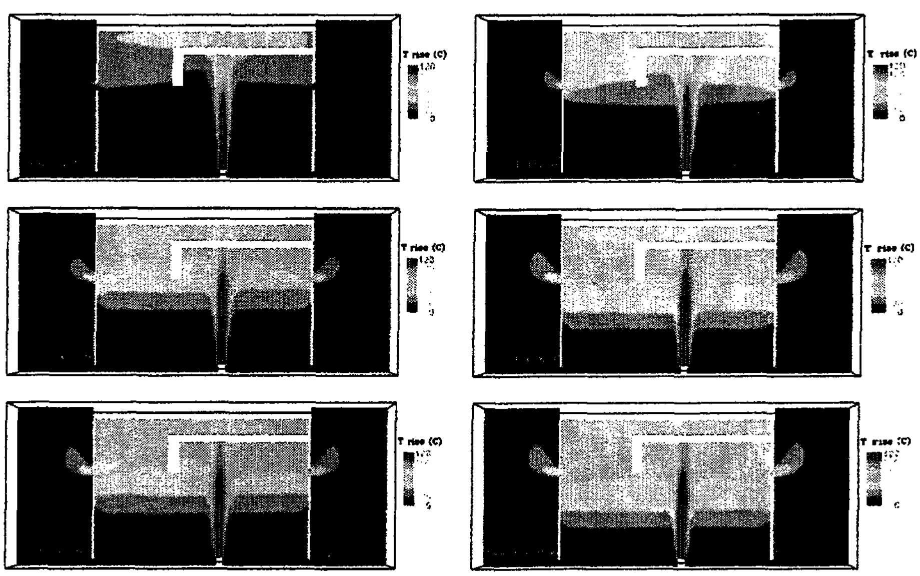
BRE

14

JASMINE Temperatures for Case 1



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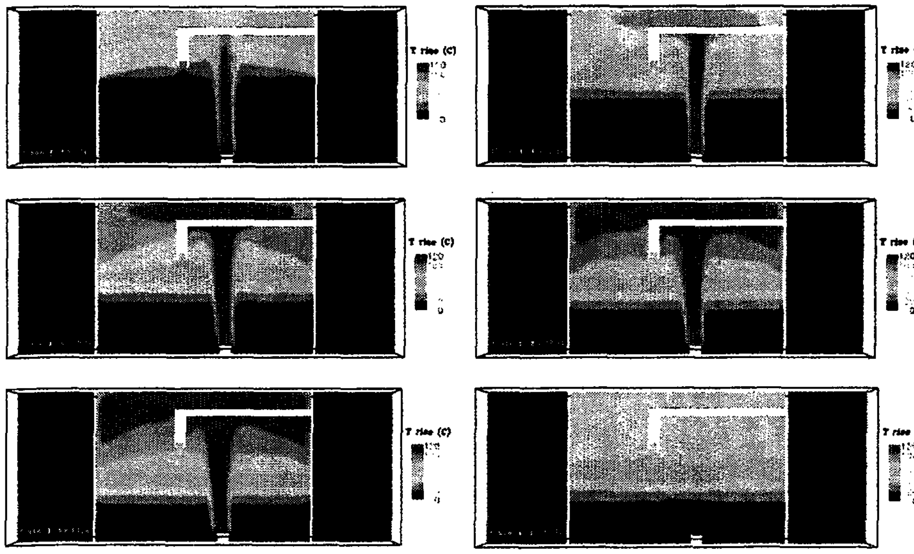
#15

JASMINE Temperatures for Case 3

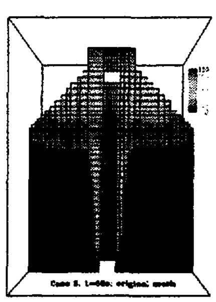


BRE

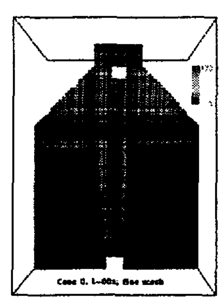
#16

CFD Mesh Refinement

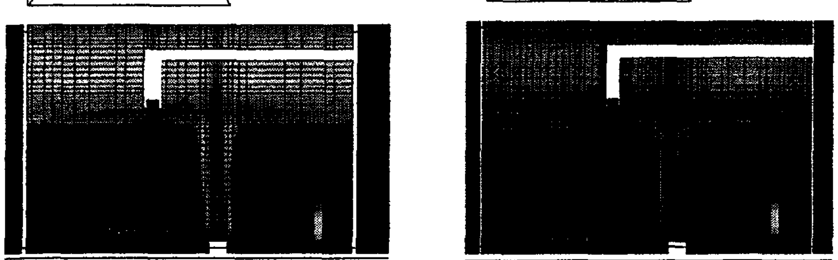
Predictions of temperature for case 3 at 60s



~ 136 500 elements



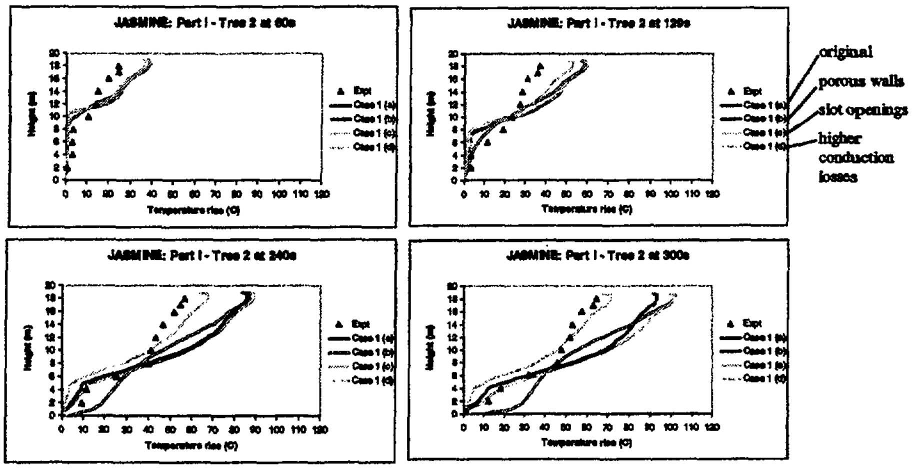
~ 1 100 000 elements
(x2 in each direction)



BRE

#17

JASMINE Analysis - Case 1



Smoke layer temperature sensitive to conduction heat loss mechanism (but layer height is less so)

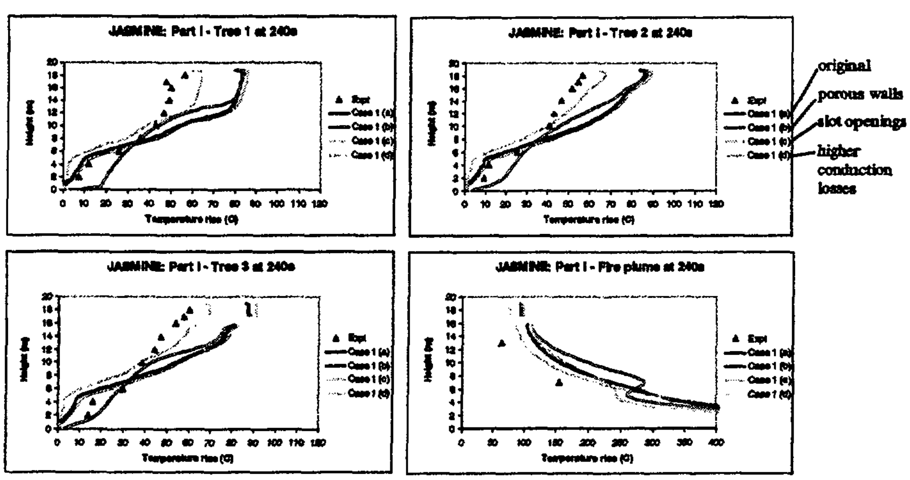
Narrow slot openings give same results as square openings

Porous walls 'restricted ventilation' reduces stratification

BRE

#18

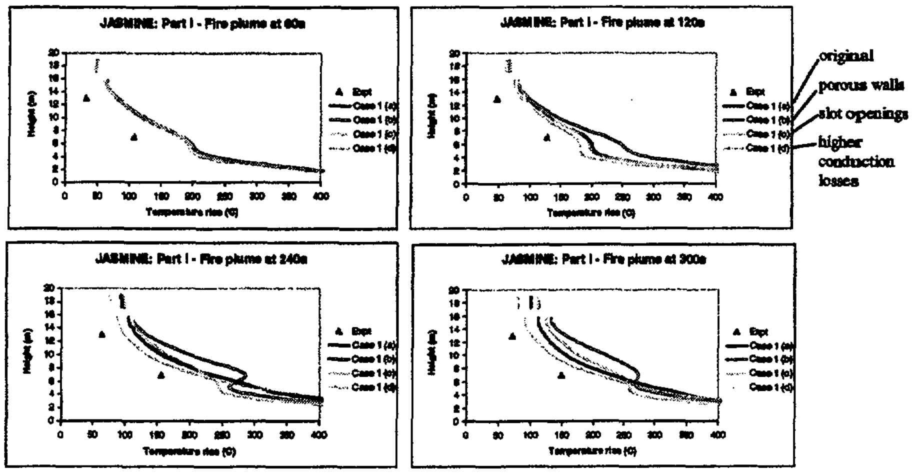
JASMINE Analysis - Case 1



BRE

#19

JASMINE Analysis - Case 1



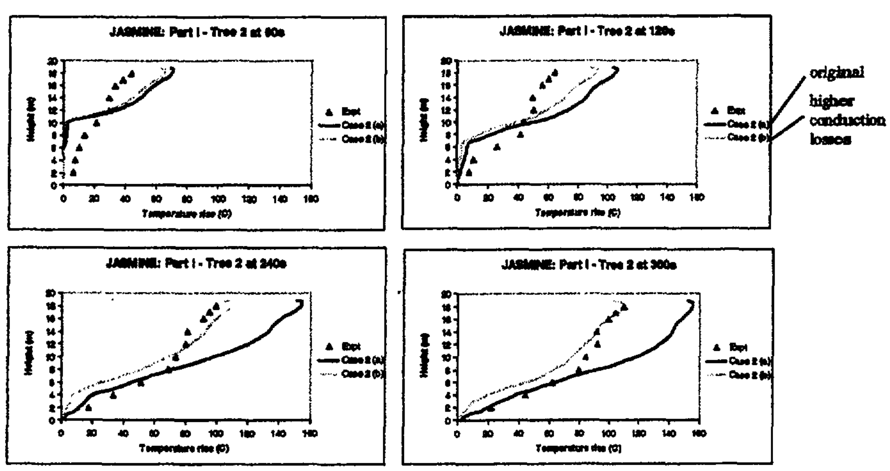
Conduction heat loss mechanism has less pronounced influence on plume temperature

NIST, Gaithersburg *Benchmark Analysis # 2 - Preliminary Simulations for Part I* *2-3 May 2002*

BRE

#20

JASMINE Analysis - Case 2



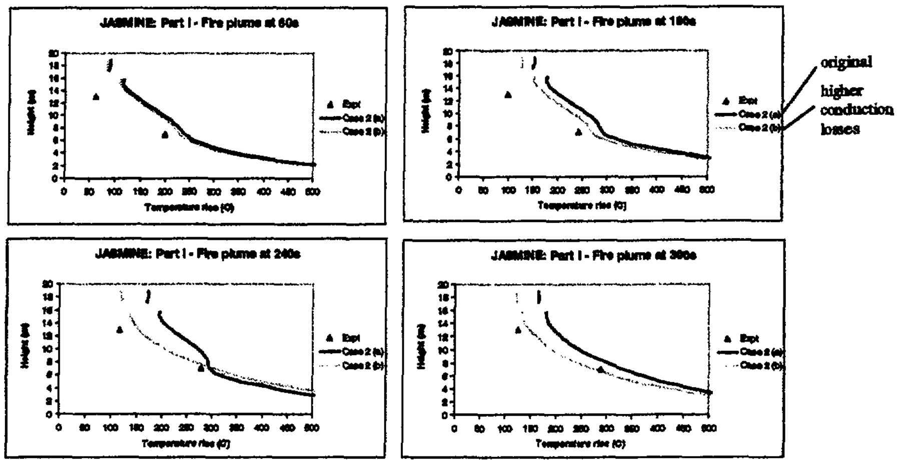
Smoke layer temperature sensitive to conduction heat loss mechanism (but layer height less so)

NIST, Gaithersburg *Benchmark Analysis # 2 - Preliminary Simulations for Part I* *2-3 May 2002*

BRE

#21

JASMINE Analysis - Case 2

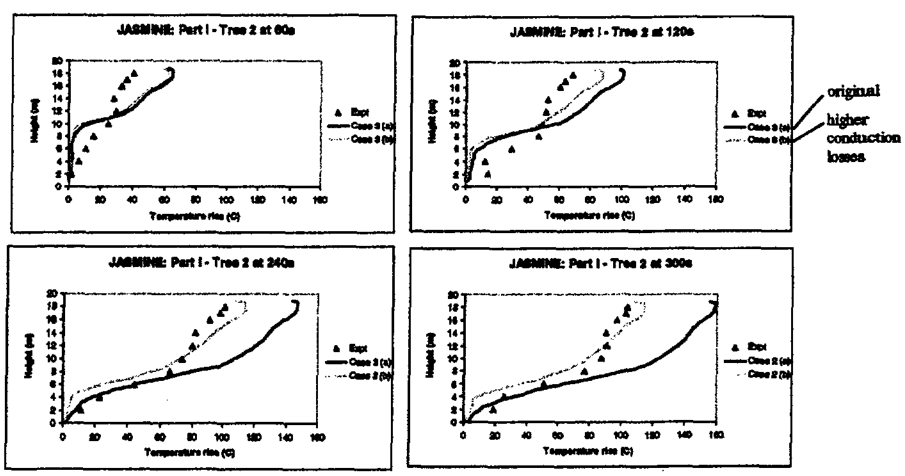


NIST, Gaithersburg *Benchmark Analysis # 2 - Preliminary Simulations for Part I* *2-3 May 2002*

BRE

#22

JASMINE Analysis - Case 3



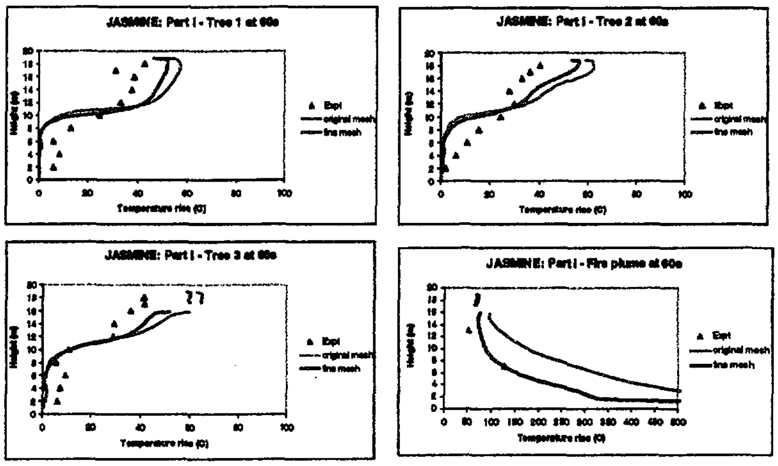
Smoke layer temperature sensitive to conduction heat loss mechanism (but layer height less so)

NIST, Gaithersburg *Benchmark Analysis # 2 - Preliminary Simulations for Part I* *2-3 May 2002*

BRE

JASMINE Analysis - Case 3

#23



Mesh resolution also an important consideration

NIST, Gaithersburg *Benchmark Analysis # 2 - Preliminary Simulations for Part I* *2-3 May 2002*

BRE

Closing Remarks

#24

- Important general findings:
  - conduction losses into walls/ceiling needs care
    - sheet metal influences layer temp
  - specification of restricted ventilation openings:
    - has only small influence on layer temperature
    - has a more important influence on layer height (mainly during later stages)
- Important findings for CFAST:
  - choice of 'equivalent' ceiling height:
    - influences upper layer temperature
    - but influences layer height only at early stages
- Important findings for JASMINE:
  - mesh resolution needs consideration
  - sloping ceiling approximation ?

NIST, Gaithersburg *Benchmark Analysis # 2 - Preliminary Simulations for Part I* *2-3 May 2002*

#1

Benchmark Analysis # 2

Fire in a Large Hall

Proposal for Part II

Stewart Miles
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Fax: +44 (0)1923 664910
E-mail: miless@bre.co.uk

NIST, Gaithersburg — *Benchmark Analysis # 2 - Proposal for Part II* — *2-3 May 2002*

#2

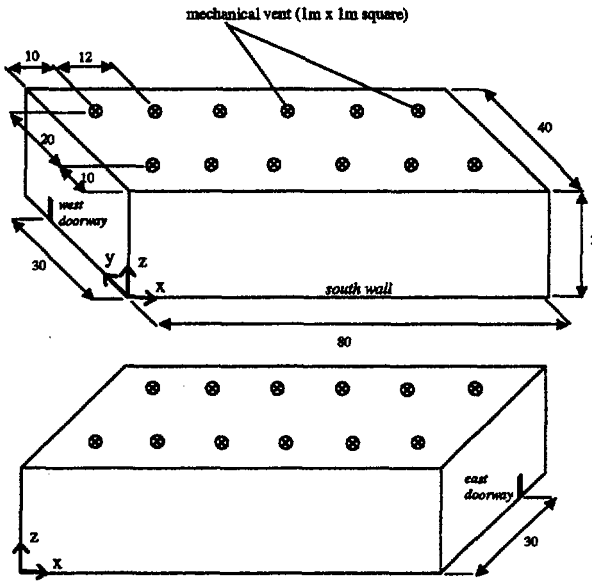
Objectives of Part II

- To extend scope of Part I to include:
  - a realistic large volume nuclear power plant building
    - turbine hall
  - larger fires
    - producing temperatures capable of greater damage
  - 'target objects'
    - cables
    - structural elements
  - additional complexities:
    - oxygen limitation effects
    - multi-compartment (internal ceiling with openings)

NIST, Gaithersburg — *Benchmark Analysis # 2 - Proposal for Part II* — *2-3 May 2002*

#3

External Geometry and Vents



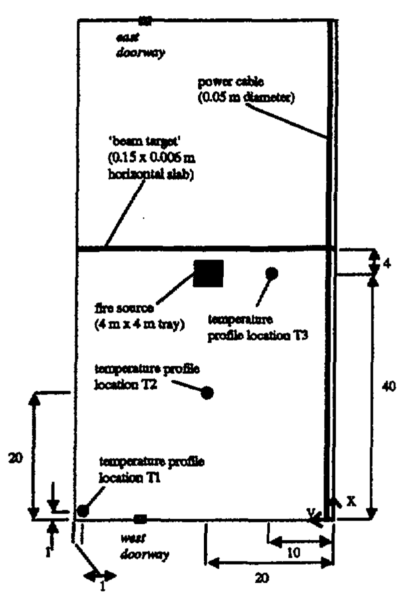
To simplify task assume floor, walls and ceiling constructed from concrete

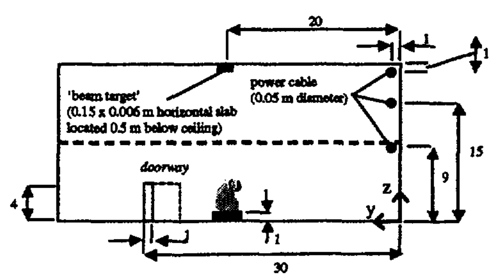
Doorways either 1 x 4 m or 4 x 4 m

NIST, Gaithersburg *Benchmark Analysis # 2 - Proposal for Part II* *2-3 May 2002*

#4

Internal Geometry and Targets





cable target

conductivity $(J s^{-1} m^{-1} K^{-1})$	density $(kg m^{-3})$	specific heat $(J kg^{-1} K^{-1})$	emissivity	convective htc $(J s^{-1} m^{-2} K^{-1})$
0.092	1710	1040	0.8	10

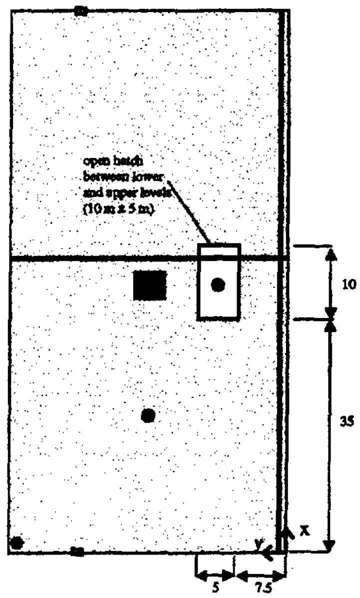
beam target

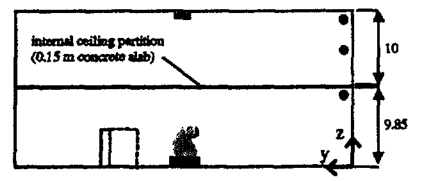
conductivity $(J s^{-1} m^{-1} K^{-1})$	density $(kg m^{-3})$	specific heat $(J kg^{-1} K^{-1})$	emissivity	convective htc $(J s^{-1} m^{-2} K^{-1})$
54	7833	465	0.8	10

NIST, Gaithersburg *Benchmark Analysis # 2 - Proposal for Part II* *2-3 May 2002*

#5

Internal Ceiling





Model as two vertical compartments with one opening (vent) connecting them ?

#6

Exercises

Case 1a	*Case 2a*
1m x 4m doorway openings no mechanical exhaust ventilation	*1m x 4m* doorway openings *16 m^3 s^{-1}* mechanical exhaust ventilation (divided evenly between the 8 vents)
Case 3a	*Cases 1b, 2b and 3b*
4m x 4m doorway openings *80 m^3 s^{-1}* mechanical exhaust ventilation (divided evenly between the 8 vents)	As for *cases 1a, 2a* and *3a*, but with addition of the internal ceiling partition, dividing the volume into two levels

Heptane fuel (as in Part I)

5.325×10^{-6} kg s^{-3} (= α)

$\dot{m}_f = \alpha t^2$ $\quad 0 \le t < 9$ minutes

$\dot{m}_f = 1.55$ $\quad 9 \le t < 20$ minutes

Reporting procedure as for Part I, plus:

- oxygen level
- target maximum incident flux, surface temp & centre-line temp (and estimate of likelihood of damage)

Detector Response Modeling

Doug Beller
NFPA International

Purpose

- Background
- Proposal

Background

- SFPE Computer Model Evaluation Task Group
  - First model DETACT
    - 3+ year effort
    - Report issued soon
  - Next model ASET
    - (shouldn't take 3 years...)

DETACT evaluation

- ASTM E-1355: many tasks
  - Verification of algorithm
  - Sensitivity analysis
  - "Blind" runs
- Attempted to compare algorithm to original data
- New tests conducted
  - Problems eventually worked out

DETACT

- Predicts activation time of fixed-temperature detectors
  - Not for rate-of-rise
  - Smoke detectors…
- Correlations for
  - Ceiling jet temperature
  - Ceiling jet velocity

DETACT Limitations

- Large, flat, smooth ceiling
- Unconfined, minimal layer formation
- Detector assumed to be exposed to max CJ velocity and temperature
- Implicit accounting of radiation and conduction

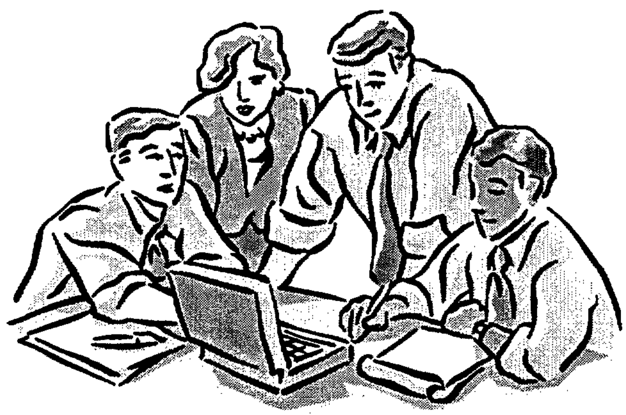
Proposal

- Nuclear installations not
  - Smooth
  - Flat
  - Open
- Does DETACT still apply?
  - What happens when DETACT is used?

Proposal

- Is an evaluation of DETACT for nuclear power plant applications a good thing to do?
  - Focus too narrow?
- Is it possible to develop a "post-prediction" correction factor to account for nuclear configurations?
  - "Implicit" accounting of non-ideal configurations

Discussion



International Collaborative Project to Evaluate Fire Models
for Nuclear Power Plant Applications
Gaithersburg, MD, May 2-3, 2002

A new model for time lag of smoke detectors

O. Keski-Rahkonen
VTT Building and Transport

VTT

Contents

VTT

VTT BUILDING AND TRANSPORT

Introduction

- Smoke detection links from the source to the detector only partially modelled
- Smoke measurements difficult
- Large detection delays observed
- Smoke penetration into the detector still a problem

30.4.2002 3

VTT

VTT BUILDING AND TRANSPORT

Time lag theories and data

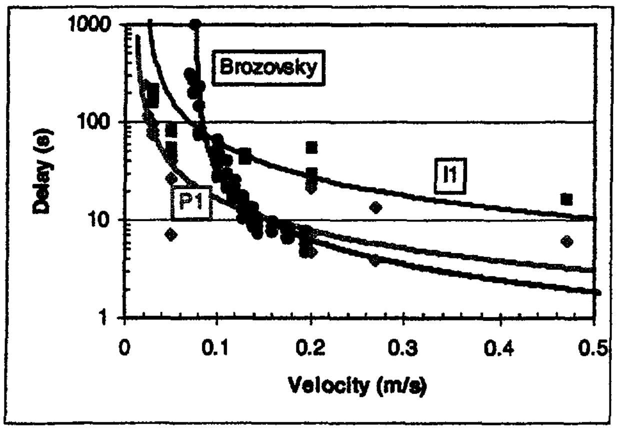
- Heskestad 1977

$$\Delta t = \gamma l / \bar{v}$$

30.4.2002 4

VTT

Experimental observations



Data:

Brozovsky 1991

Cleary at al. 2000

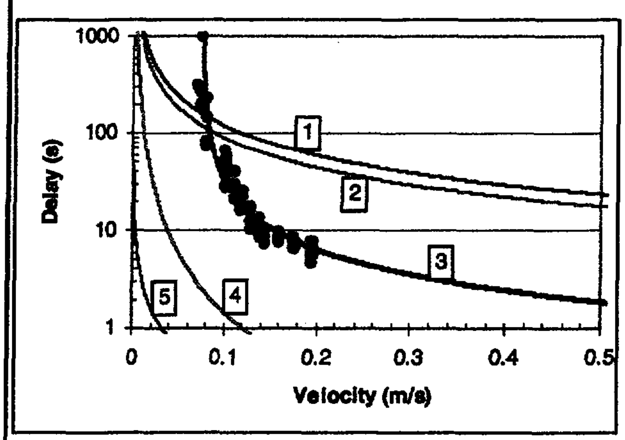
Fits:

Keski-Rahkonen 2001

$$\Delta t = \gamma l / (\bar{v} - \bar{v}_0)$$

Confirming finite ceiling jet velocity

Modelling of time lag



Calculations:

Heskestad 1977 (1,2)

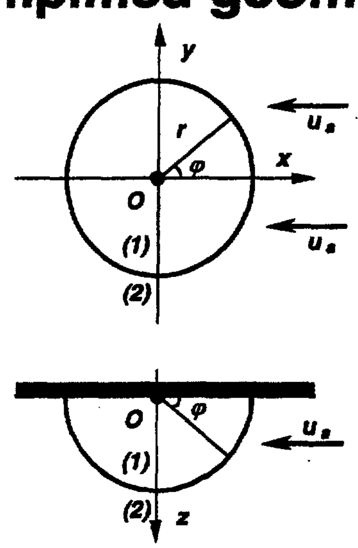
Keski-Rahkonen 2001 (4,5)

No newtonian fluid dynamic theory able to explain finite critical velocity

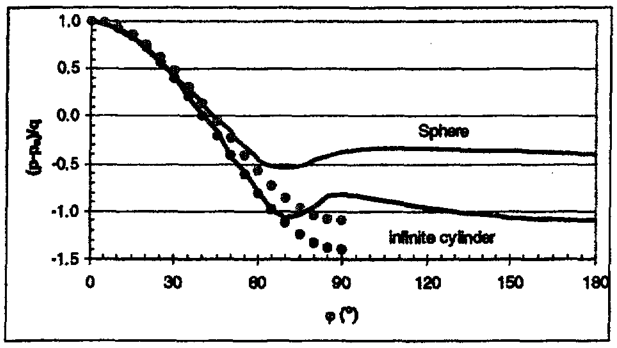
New modelling ideas

- Simplified hemispherical detector body
- Insect screen separates inner from outer field
- Outer field from potential flow
- Screen penetration from diffusion battery models
- Air flow in the detector from the continuity equation
- Selective separation of smoke particles on the screen

Simplified geometry



Outer pressure field



Curve fitting on experimental and potential flow models around the stagnation point

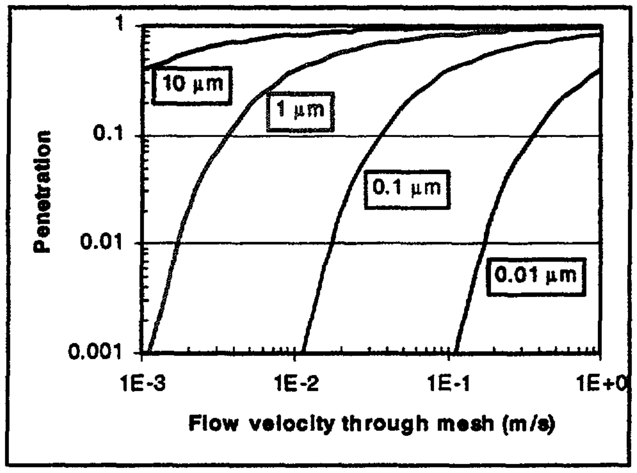
Diffusion batteries

- Cheng and Yeh 1980, Yeh et al. 1982

$$m = A_0\ Pe^{-2/3} + A_1 R^2 + A_2\ Pe^{-1/2}\ R^{2/3}$$

- Closed form solution available for smoke particle penetration

Smoke particle penetration



Conclusions

- Heskestad: $\Delta t = \gamma l / \bar{v}$
- Experimental data show large time lag for slow ceiling jet velocity
- Brozovsky: a finite critical ceiling jet velocity in variance with Heskestad's theory
- Keski-Rahkonen: No newtonian fluid flow model able to explain finite critical velocity
- This work:
  - A new model proposed based on selective filtering of smoke particles
  - A closed calculation form derived for smoke penetration

D-303

iBMB

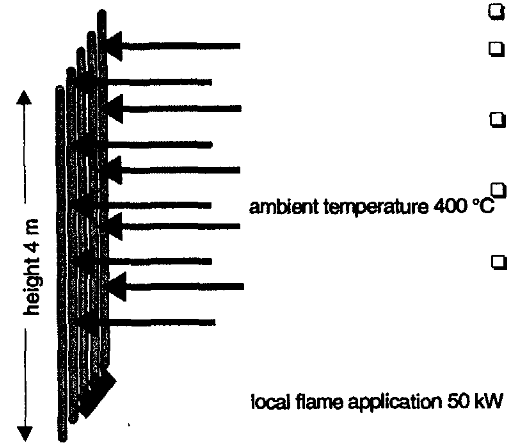
Foreseen German Real Scale Cable Fire And Functional Failure Tests

M. Roewekamp (GRS)

O. Riese, D. Hosser (iBMB)

Room Fire Test

iBMB



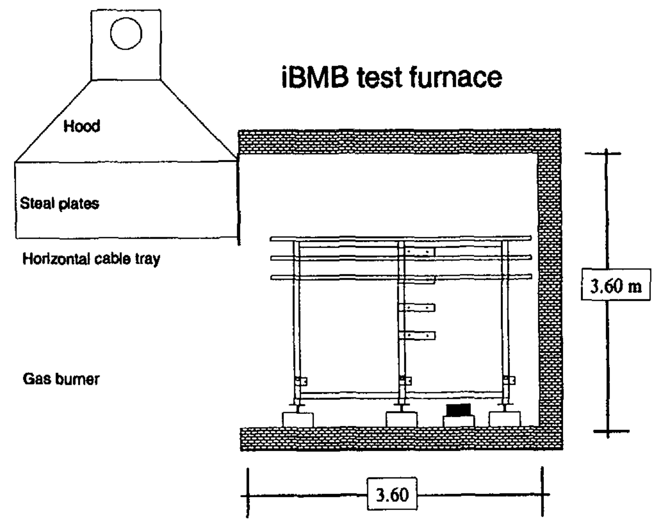
- Large scale test
- Horizontal or vertical cable tray
- Pre-heating up to 400 °C
- Local ignition source (50 kW)
- Typical results
  - Time to ignition
  - Flame spread
  - Local temperatures
  - Rate of heat release
  - CO/CO_2 production
  - Smoke production

D-304

Cable Tests Equipment — iBMB

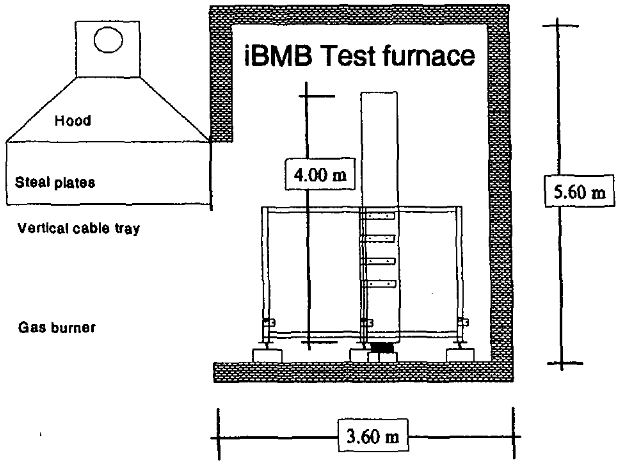
- iBMB test furnace
  - Vertical
  - Horizontal
- Smoke density measurement
- Function loss test equipment according to DIN 4102-12
- Gas analysis equipment O_2 , CO, CO_2
- ➡ Oxygen consumption method for the determination of the heat release

Cable Fire Tests (horizontal) — iBMB



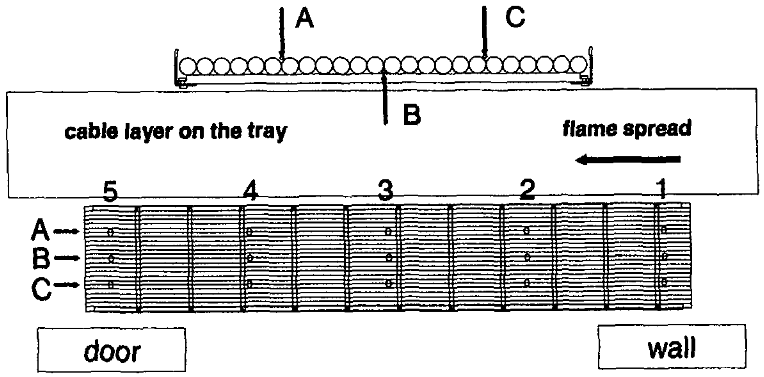
D-305

Cable Fire Tests (vertical) iBMB



Horizontal / Vertical Cable Tray iBMB

- Example of a horizontal cable tray
- Position of thermo-couples



D-306

Cable Fire And Functional Failure Tests iBMB

iBMB Proced.	Test 1 - 2	Test 3 - 4	Test 5 - 6	Test 7 - 8
Heater and ventilation	Gas burner: max. 50 kW / 1 opening 2.6 m²			
Material	PVC	PVC	PVC	PVC
Direction	Horizontal	Horizontal	Vertical	Vertical
Type of cables	Power cables	Signal cables	Power cables	Signal cables
Pre-heating	200 °C / 400 °C	200 °C / 400 °C	0 °C / 400 °C	0 °C / 400 °C
Functional test	yes	yes	yes	yes

*) based on DIN 4102-12

Test furnace according to iBMB procedure

iBMB
TU BRAUNSCHWEIG

Kerosene Fire Experiments

Dr. M. Roewekamp, GRS
Prof. Dr.-Ing. D. Hosser and Dr.-Ing. R. Dobbernack,
iBMB of TU Braunschweig

5th International Collaborative Project meeting to Evaluate Fire Models for NPP Applications,
Gaithersburg, MD, May, 2-3, 2002

Contents — iBMB

- Goals and work program
- Available results from German research
- First results from literature
- First actual experimental results
- Summary and conclusions

Goals and Work Program — iBMB

- Goals
  - Estimation of basic data for simulating kerosene fires under different boundary conditions
  - Exemplary calculation of fire effects for selected kerosene fire scenarios
  - Rough estimate of the risk of explosion in case of sprayed kerosene and the consequences
- Work program
  - Kerosene pool fire experiments
  - Comparison of the experimental results with data from literature
  - Definition of fire scenarios outside as well as inside of buildings
  - Fire simulations
  - Rough estimate of the consequences of explosions

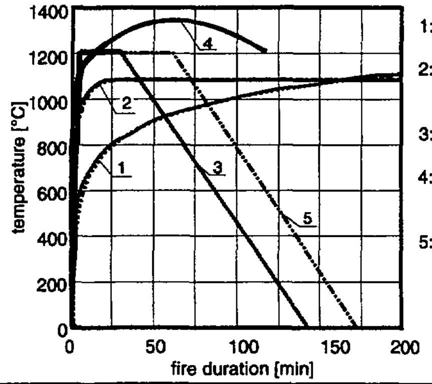
Results of German Research — iBMB

- SR 144/1 experiments (1982-1985)
  - Experiments with oil fire loads in pans of 2 m^2 with and without continuous feeding of oil and different ventilation conditions
  - Fire compartment temperatures 1080 – 1370 °C
  - Burning rate 1,35 – 3,15 kg / m^2•min
  - Energy release rate up to 2,2 MW / m^2
- HDR fire experiments (1986-1992)
  - Experiments with oil fire loads in pans of 1 - 3 m^2 with feeding of oil for different room geometries
  - Fire compartment temperatures up to 1500 °C
  - Burning rate up to 3,6 kg / m^2•min
  - Energy release rate up to 2,6 MW / m^2

Results from Literature (1) iBMB

- Hydrocarbon fires
  - Scaled offshore fire experiments (SINTEF, Norway)
  - Fast fire spreading on the pool surface
  - Energy release rate 1,7 – 4,9 MW / m²
- Fluid fires in general
  - In case of pool fires with sufficient oxygen, medium "burning velocity"of approx. 3 mm/min
  - Energy release rate of kerosene depending on the heat release approx. 11,7 kWh / kg, i.e. 1,4 MW / m²

Time-temperature Curves iBMB



1: ISO curve
2: Hydrocarbon curve HC
3: RABT curve
4: Rijkswaterstaat curve RWS
5: EBA-curve

Results from Literature (2) iBMB

- Kerosene pool fire experiments
  - Open kerosene pool fires (SANDIA, USA) 280 m² pan, 15 cm water + 25 cm kerosene
  - Fire spreading on the pool surface within 20 s
  - Burning rate 4,1 – 4,9 kg / m²•min (effects of wind)
  - Maximum temperatures 1300 – 1500 °C
  - Heat flux density at a wall up to 4,5 m height 100 – 130 kW / m²
- Kerosene explosion experiments
  - Laboratory scale (Aeronautical Laboratories, USA)
  - Flame point and explosion points uncertain (composition of kerosene not well known)

Recent German Approach iBMB

- Kerosene pool fire experiments
  - Kerosene experiments (February 2002) in steel pans of 0,5 m², 1,0 m² und 2,0 m² and kerosene level of 10 cm and 3 cm
  - Measuring burning rate, temperature and radiation heat in the fire compartment
- *Definition of relevant fire scenarios*
  - Pool fires outside buildings
  - Fires with combinations of kerosene and other fire loads inside buildings; comparison with former experiments
- Fire simulations
  - Comparison of calculations with different types of codes

Aviation Fuel Fire Experiments Foreseen in Germany for 2002/03

iBMB

- Kerosene pool fire experiments
  - Inside confinements
  - Outside buildings
- Combustible mixtures from fuel gas and air inside confinements with the potential for deflagration / detonation
- Fuel spray formation and fireball outside buildings

Kerosene Pool Fires - Goals of the Experiments

iBMB

- Basic data for fire simulations
  - Burning rate
  - Energy release
  - Flame temperature
  - Heat flux density
- Consideration of dependencies
  - Pool size
  - Pool height
  - Underground material (steel/concrete)

Kerosene Pool Fires Inside Confinements

iBMB

- Room size (L x W x H = 3,6 m x 3,6 m x 5,8 m)
- Pool size: 0,5 m²; 1,0 m²; 2,0 m²; 4,0 m²
- Pool height: 3 cm; 10 cm
- Ventilation
  - Ventilation controlled
  - Fire load controlled
- Effects of structures and equipment
  - Concrete, steel, etc.
  - Heat sinks (water tank)
  - Cable trays in case of low fire loads

Measuring Equipment for Kerosene Pool Fires

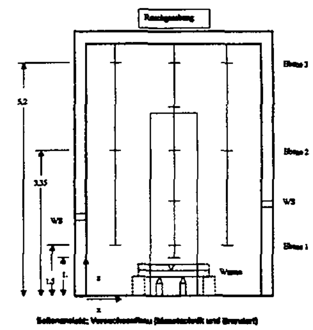
iBMB

- Burning rate by mass loss rate
- Temperatures
  - Plume
  - 3 levels above the fire
  - Inside and on structures and heat sinks
  - On cable surface (fire inside compartment)
- Velocity
  - Via Plume height and wind velocity
  - In the off-gas line (fire inside compartment)
- Heat flux at different locations
- Gas analysis (O_2, CO_2 and CO)
- Heat camera

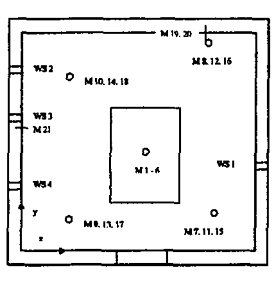
Experimental Layout, Measurements — iBMB

- Fire compartment
  - Length 3,6 m
  - Width 3,6 m
  - Height 5,7 m
- Measurements
  - Plume temperature (6 locations)
  - Three measurement levels (4 locations)
  - Surface temperature (3 locations)
  - Heat flux (4 locations)
  - Mass loss

Fire Compartment Layout (1) — iBMB



Fire Compartment Layout (2) — iBMB



Kerosene Pool Fires Outside Buildings — iBMB

- Pool size: 0,5 m²; 1,0 m²; 2,0 m²; 4,0 m²; 16 m²
- Filling level: 10 cm
- Ventilation
  - No wind
  - *Effects of wind*
- Reference equipment at a wall
  - Concrete, steel, etc.
  - Heat sinks (e.g. water storage tank)

Combustible Gas Air Mixtures Inside Confinements

iBMB

- Formation of combustible mixtures from kerosene and air inside nearly closed confinements
  - Formation of gas clouds
  - Spreading of gas and formation of mixtures
  - Combustion/explosion process (deflagration, detonation, DDT)

Combustible Gas Air Mixtures Inside Confinements

iBMB

- Steps of the investigations:
  - Comparison of data for kerosene and hydrogen
  - Comparison of combustion process of kerosene and hydrogen
  - Specification of additional experiments (PTB)
  - Status of the hydrogen modeling
  - Applicability of available models for fuel gas combustion/explosion (flame acceleration, possibility of DDT)
  - Exemplary analysis for model validation and applicability

Aviation Fuel Spraying And Fireball Outside Buildings

iBMB

Questions:

- How far will the fuel been distributed after the impact?
- What is the droplet size of the fuel droplets?
- Which amount of fuel is directly burnt in the fireball, which amount is available for a pool fire?
- What are the effects and consequences of a fireball?

Fuel Spraying And Fireball Outside Buildings

iBMB

Investigation methods

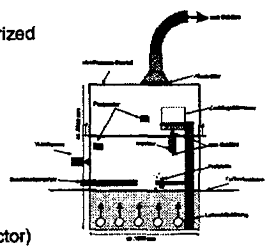
- Fuel spraying ⇒ impact experiments
  - Depending on velocity, potential targets, amount, etc.
  - Droplet spectra, distribution
- Combustion ⇒ ignition experiments and modeling
  - Amount of directly burnt droplets
  - Fireball characteristics, potential for scale up
- Comparison with literature including reports on aircraft crashes

⇒ Model for fireball effects and amount of fuel left

Fuel Spraying And Fireball Outside Buildings iBMB

Impact experiments with fluids (ITA Hannover)

- Experimental facility
  - Acceleration of pressurized air up to ~ 100 m/s
  - Video observation
  - Variation of velocity, fuel amount, target
- Droplet diagnosis
  - Total mass / surface (gravitational/optical)
  - Size distribution (Impactor)
  - Velocity (PDA)
- First experiments foreseen for July 2002



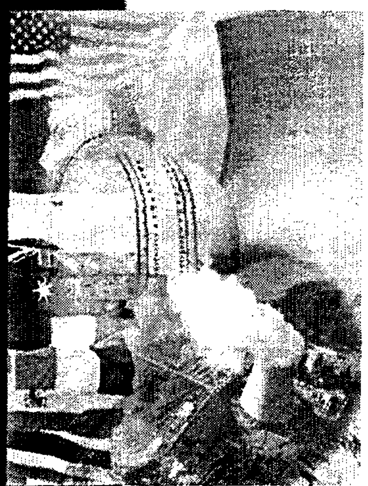
Fuel Spraying and Fireball Outside Buildings iBMB

Ignition Experiments (BAM/PTB) and Fireball Modeling

- Ignition experiments
  - Fuel spray ignition (droplet spectra analogous to ITA-experiments)
  - Fireball characteristics
  - Amount of fuel for pool fire
- Numerical simulations
  - Model validation with experiments
  - Scaling up from small scale to real scale experiments

Summary and Conclusions iBMB

- Goals of the activities
  - Gaining important basic data with respect to kerosene as used in Germany
  - First rough estimates of the potential consequences of kerosene fires outside and inside of buildings
- Recent status
  - Analysis of experimental data from German as well as other institutions
  - Kerosene pool fire experiments inside buildings)
- Continuation of work
  - Definition and simulation of fire scenarios
  - Identification of the significant parameters
- Expected results
  - Statements with respect to the significance of kerosene fires
  - Assumptions for further investigations



Challenges in use of State-of-the-Art Fire Modeling Tools in Nuclear Power Plant Applications

B. Najafi, F. Joglar,
Science Applications International Corp.

R. Kassawara
EPRI Project Manager

SAIC

EPRI

Outline

- Introduction
- Fire modeling issues in nuclear power plants
  - Areas where fire modeling can be applied
  - Areas for future research

SAIC

Slide: 2

EPRI

Objectives

- Prioritize fire modeling issues in nuclear power plants
- Identify areas where future research can reduce the uncertainty associated with these fire modeling issues

SAIC Slide: 3 EPRI

Scope

- Technical issues discussed in this presentation are based on the capabilities of models evaluated in EPRI's fire modeling project.
  - MAGIC
  - CFAST
  - CompBrnIIIe
  - FIVE

SAIC Slide: 4 EPRI

EPRI Fire Modeling Project

- EPRI's Fire Modeling project provides guidance in using fire models including hand calculations and selected zone models
  - FIVE
  - COMPBRN-IIIe
  - CFAST
  - MAGIC
- Our conclusions are limited to lessons learned while using the models.
- Some conclusions may apply to other models, including computational fluid dynamics (CFD)

SAIC Slide: 5 EPRI

Areas Where Fire Modeling can be Applied (Based on examined models)

- *Either there is confidence in the modeling tools OR estimates are adequate to support anticipated applications*

1. Thermal effects of plumes, ceiling jets and radiation
2. General room heat up, and hot gas layer
3. Elevated fires and oxygen depletion
4. Multiple fires
5. Multi-compartments: corridors and multi-levels
6. Smoke migration, generation and density
7. Partial barriers and shields
8. Fire detection

SAIC Slide: 6 EPRI

Plumes, Ceiling Jets and Radiation

- This is typical of many scenarios in NPPs where critical targets are located in close proximity of fire source
- Fire conditions, including temperature and heat flux in these areas can be estimated using hand calculations
- Hand calculations and zone models can be use to evaluate target response

SAIC Slide: 7 EPRI

Room Heat Up and Hot Gas Layer

- Larger, less congested plant areas
- These temperatures can be estimated with hand calculations and zone models
- Zone models are recommended in cases where natural and mechanical ventilation are part of the scenario

SAIC Slide: 8 EPRI

Elevated Fires and Oxygen Depletion

- Typical of cable tray fires
- Zone models can simulate oxygen depletion and elevated fires
- The amount of oxygen available for combustion is an indication of the capacity of the fire to burn
- Combustion in low oxygen environments is subject of research

SAIC Slide: 9 EPRI

Multiple Fires

- Scenarios involving intervening combustibles, such as transients and cables
- CFAST and MAGIC can simulate multiple fires
- Fires other that the pilot can be ignited based on time, temperature and heat flux
- The effects of multiple plumes is captured

SAIC Slide: 10 EPRI

Corridors and Multi-Levels

- Common fire scenarios in auxiliary or turbine building
- Sometimes approximated with larger combined or smaller separated enclosures
- Zone models can simulate fire conditions in multiple rooms
- CFAST and MAGIC have the capability of connecting rooms with vertical and horizontal openings
- MAGIC provides an image of the geometry that is useful when developing input files in multi-compartment scenarios

SAIC Slide: 11 EPRI

Smoke Generation and Migration

- Fires in the main control room specially those resulting in evacuation
- Smoke generation for the most part is plume entrainment
- Migration refers to the smoke movement between compartments
- CFAST estimates products of combustion based on yields

SAIC Slide: 12 EPRI

Partial Barriers and Shields

- Used mostly as radiation shield to protect against large fire source such as reactor coolant pump
- Magic can simulate radiation barriers (targets in lower layer)
- Barriers have no thermal behavior
- Once targets are immersed in the smoke, they are heated mostly by convection heat transfer.

SAIC Slide: 13 EPRI

Fire Detection

- Only a model for heat detection is available: DETACT
- Models for heat detection assumes well defined ceiling jets
- DETACT can be used for smoke detection - ?? - Smoke detectors are designed to operate before well established ceiling jets.
- Some hand calculations for smoke detection are also available

SAIC Slide: 14 EPRI

Current Tools DO NOT Provide Adequate Response to the NPP Fire Modeling Need

- *Some of these issues are not amenable to analytical solutions*
  1. Cable fires
  2. Fire growth inside the main control board
  3. Fire propagation between control panels
  4. High energy fires
  5. Fire suppression
  6. Hydrogen or liquid spray fires
- *Current EPRI methods rely on empirical models based on a combination of operating experience and fire tests*

SAIC Slide: 15 EPRI

Cable Fires

- Important in NPP applications since cables are major contributor to potential fire growth
- Fire propagation or flame spread throughout cable trays can not be modeled.
- Currently EPRI methods use empirical models based on cable fire tests

SAIC Slide: 16 EPRI

Fire Growth inside the Main Control Board

- Such fires can be critical to safety
- The combustion process in low oxygen environments is still subject of research
- Little empirical data to support the extent and timing of fire spread

SAIC Slide: 17 EPRI

Fire Propagation Between Control Panels

- This is critical where source and target are both electrical panels such as control room and electrical equipment rooms
- These scenarios could be critical to safety
- Although zone models can simulate multiple fires based on heat flux or ignition temperature, specification of required parameters is usually uncertain.
- The problem of ignition of internal components in electrical cabinets can not be addressed with current models
- Current EPRI methods use empirical models based on electrical cabinet fire tests.

SAIC Slide: 18 EPRI

High Energy Fires

- Such events are result of electrical faults in high voltage switchgears and transformers (more of a concern when indoors)
- The intensity and effects of explosions can not be predicted with fire models
- Currently we use empirical evidence suggesting that explosions can occur in high energy cabinets. Sustained fires after the explosion have been observed. Thermal effects of these fires can be assessed with existing fire models

SAIC Slide: 19 EPRI

Fire Suppression

- Automatic and manual suppression are one of the primary feature (in addition to barriers) to mitigate consequences of fire in NPPs
- Only CFAST can simulate water based fire suppression with some restrictive assumptions
- Effects of gaseous suppression systems can not be simulated with current models
- Effectiveness of suppression systems in deep-seeded fires
- EPRI methods relies on codes/standards to demonstrate effectiveness

SAIC Slide: 20 EPRI

Hydrogen or liquid spray fires

- Not very critical based of operating experience
- Fire models assume fires as a point source of heat release. Effects of jet fires can not be predicted
- Little empirical data to support a model

SAIC Slide: 21 EPRI

Conclusions

- Issues that may not be amenable to analytical solutions
  - Fire growth inside control room main control board
    - CFD codes may have the capability, the scenario description is questionable
  - High energy fires
    - *Prediction of consequences of initial blast require different type of models*
  - Hydrogen or liquid spray fires
    - ?? ?? ?? ??
- Areas for improvement in current codes
  - Cable fires
  - Fire suppression
  - Panel to panel fire growth

SAIC Slide: 22 EPRI

Summary

- Areas of application
  - Thermal effects of plumes, ceiling jets and flame radiation
  - Room heat up, and hot gas layer
  - Elevated fires and oxygen depletion
  - Multiple fires
  - Multi-compartments: corridors and multi-levels
  - Smoke generation and migration
  - Partial barriers and shields
  - Fire detection

- Areas for future research
  - Cable fires
  - Fire growth inside the main control board
  - Fire propagation between control panels
  - High energy fires
  - Fire suppression
  - Hydrogen or liquid spray fires

SAIC Slide: 23 EPRI

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SAIC Slide: 24 EPRI

Proposal for Full-Scale Tests and Blind Validation Exercises

Moni Dey, U.S. NRC

Outline

- Background and need for validation
- Proposed 3-year plan
- Solicitation of participation
- Proposed schedule for 1st full-scale test and blind validation exercise

Conclusions of Benchmark Exercise # 1

- Trends predicted by models are reasonable, and provide useful information
- Similar results from most codes, including zone and CFD
- International blind validation exercise, with emphasis on quantifying uncertainties, will add confidence to findings
- Flux incident on and thermal response of target were key issues in exercise

Review of Validation Database

- UK IMC validation database report
- Specific validation of fire models in benchmark exercise
- Improvement in quantification of uncertainty needed
- Thermal response of target may benefit from additional validation

Plan for NRC Fire Model Research Program

Near Term Needs

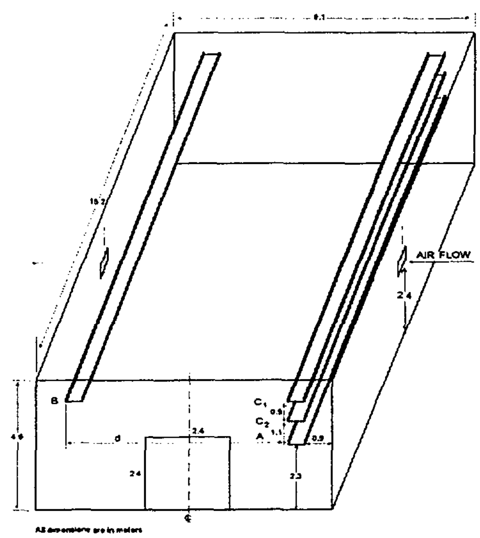
- Conduct tests for international blind validation exercises to extend confidence in current models

Long Term Needs

- Conduct research to improve fire modeling capability, and validate improved methods

Proposed Test Program

	FY 02	FY 03	FY 04
Test Series	Cable tray fires	Multi compartment fires	Control room fires (tentative)
Objective	Confirm present findings	Examine flow issues	Examine smoke issues



Cable Tray Fire Test Series

- Objective:
  - Investigate issues identified in benchmark exercise
  - Establish measurement uncertainties
  - Quantify uncertainties in prediction of cable temperatures for range of scenarios

Specific Investigation of Effects of Key Variables

- Fire intensity
- Distance between fire source and cable
- Cable diameter and composition
- Elevation of cable
- Bundling of cables in a tray
- Smoke concentration

Solicitation of Participation

- NRC invites participation in international blind validation exercises with respective fire models
- Mutual benefit gained through exercise of different models
- Invite engagement in experimental program and data analyses

Schedule for 1st Full-Scale Test and Exercise

- Develop detailed test specification – August 30, 2002
- Discuss proposed test specification – October, 02 (6th meeting at BRE)
- Finalize test specification – December, 2002
- Submit fire model predictions for defined problem – March, 2003
- Conduct tests – March 2003

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). SUPPLEMENTARY NOTES

See NUREG/CP-0170 and NUREG/CP-0173 for summaries of 1st and 2nd meetings.

I. ABSTRACT *(200 words or less)*

The 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was hosted by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce and held at NIST headquarters at Gaithersburg, Maryland on May 2 and 3, 2002. Thirty three participants from five countries attended the international meeting. The purpose of the 5th meeting was mainly to discuss the results of Benchmark Exercise # 2, "Pool Fires in Large Halls," conducted in the project. Validation and regulatory applications of fire models were also presented and discussed in the meeting. The results presented for Part I of Benchmark Exercise # 2 were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters. The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. The validation and application of several, diverse fire models, ranging from empirical equations organized in worksheets to zone, lumped-parameter, and computational fluid dynamic (CFD) models, were presented and discussed at the meeting. The discussions emphasized the need to validate and determine the accuracy of such models, especially to understand the differences in the predictive capabilities and margins of uncertainty for the different types of models over a range of fire scenarios. This information is needed to establish safety factors and implement effective applications of these models in a regulatory framework. The need to define credible fire scenarios and generate data for fire sources, especially cable tray fires, was emphasized.

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