COMPARISON OF CFAST PREDICTION TO REAL-SCALE-FIRE TESTS

by

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A Comparison of CFAST Prediction to Real-Scale-Fire Tests
Comparasion entre les prévisions CFAST et le résultat de tests proches de la réalité
Vergleich zwischen CFAST Modellierung und 1:1 Brandversuchen

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Summary

As computer modelling use increases as a means to insure the safety of constructed facilities, the models have progressed to the point of providing predictions of fire behaviour with an accuracy suitable for most engineering applications. They can be used to provide a metric for performance codes for constructed facilities. We examine the question of how precise the inputs need to be, and how accurate is the output using the CFAST model, and present a number of these alternatives for analyzing the sensitivity of complex room fire models and show how they can be used in practice.

Résumé

Avec l'utilisation de plus en plus répandue de la modélisation sur ordinateur pour assurer la sécurité des bâtiments, les modèles se sont perfectionnés au point de permettre de prédire le comportement au feu avec une précision convenable pour la plupart des applications d'ingénierie. Ces modèles peuvent servir à évaluer les normes de performances pour les bâtiments. Nous étudions la question de savoir quelle précision est nécessaire pour les entrées et quelle sera la précision des résultats en utilisant le modèle CFAST. Nous présentons également un certain nombre de ces variantes pour analyser la sensibilité des modèles d'incendie pour locaux complexes et pour montrer comment les utiliser dans la pratique.

Zusammenfassung

Da der Einsatz von Computer-Modellen als Mittel, die Sicherheit von Bauten zu gewährleisten, zunimmt, wurden die Modelle nunmehr soweit entwickelt, dass sie auch in der Lage sind, Vorhersagen über das Brandverhalten mit einer Genauigkeit zu machen, die für die meisten brandschutztechnischen Anwendungen ausreicht. Sie können als Massstab für die Einhaltung der zielorientierten Vorschriften für Gebäude eingesetzt werden. Wir gehen unter Einsatz des CFAST Modells der Frage nach, wie genau der Input sein muss und wie genau der Output ist und legen im Anschluss daran eine Reihe dieser Alternativen vor, um die Empfindlichkeit von Brandmodellen in Raumkomplexen zu analysieren und zu zeigen, wie solche Modelle in der Praxis eingesetzt werden können.

A Comparison of CFAST Predicitions to Real Scale Fire Tests

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Abstract: This paper describes a new algorithm of the Consolidated Fire Growth and Smoke Transport (CFAST) fire model and compares to data from real scale fire tests conducted onboard the ex-USS SHADWELL, the Navy's R&D Damage Control Platform. The new phenomenon modeled in this work is the conduction of heat in the vertical direction. The SHADWELL tests chosen for validation purposes were part of the Internal Ship Conflagration Control (ISCC) program. The work focusses on the four compartments of the ship which were vertically aligned. The temperatures of three of the compartments and the decks between them were compared with model predictions. Predictions compared very closely with experimental results for all compartments, although the temperature rise in the topmost compartment was barely above ambient.

Introduction

As computer models of fire spread gain wide spread acceptance, features are added to address new questions which arise. This report describes some features of the Consolidated Fire Growth and Smoke Transport (CFAST) fire model[1] and compares its predictions to data from real scale fire tests conducted onboard ex-USS SHADWELL, the Navy's R&D Damage Control platform[2]. The ability to account correctly for conductive heat transfer through metal decks and bulkheads is especially important in a shipboard environment. Fire can spread as a result of rising temperatures in adjacent compartments that reach ignition levels even when no breach occurs in the initial fire compartment.

The SHADWELL tests chosen for this comparison were conducted in the Internal Ship Conflagration Control (ISCC) program[3]. The ISCC program was initiated to provide guidance to the Fleet on the control of fire spread in both the vertical and horizontal directions. An additional objective was the development of new ship design criteria to address the devastation that occurred on the USS STARK as a result of missile-induced fires. There were numerous compartments involved in this test series, but this work will focus on four compartments which were vertically aligned, *i.e.* four compartments stacked on top of one another.

The basis of the fire model

Analytical models for predicting fire behavior have been evolving since the 1960's. Over the past two decades, the completeness of the models has grown. In the beginning, the focus of these efforts was to describe in mathematical language the various phenomena which were observed in fire growth and spread. These separate representations have typically described only a small part of a fire. When combined they create a comprehensive computer code which can be used to give an estimate of the expected course of a fire based upon given input parameters. These analytical models have progressed to the point of providing predictions of fire behavior with an accuracy suitable for most engineering applications.

Once a mathematical representation of the underlying science has been developed, the

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conservation equations can be re-cast into predictive equations for temperature, smoke and gas concentration, and other parameters of interest, and are coded into a computer for solution. The environment in a fire is constantly changing. Thus the equations are usually in the form of *differential equations*. A complete set of equations can compute the conditions produced by the fire at a given time in a specified volume of air. Referred to as a *control volume*, the model assumes that the predicted conditions within this volume are uniform at any time. Thus, the control volume has one temperature, smoke density, gas concentration, etc.

Different models divide the building into different numbers of control volumes depending on the desired level of detail. The most common fire model, known as a *zone model*, generally uses two control volumes to describe a compartment – an upper layer and a lower layer. In the compartment with the fire, additional control volumes for the fire plume or the ceiling jet may be included to improve the accuracy of the prediction (see Figure 1).

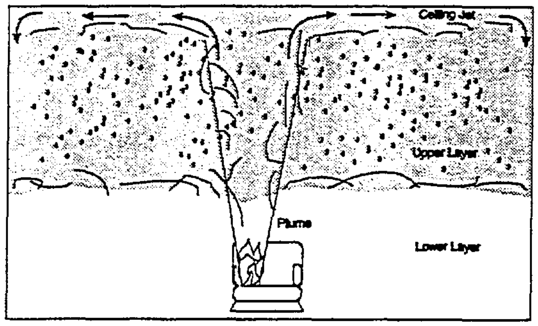


Figure 1. Zone Model Terms.

CFAST [4] is a zone model used to calculate the evolving distribution of smoke and fire gases and the temperature throughout a structure during a fire. This means that each compartment is divided into a small number of volumes (called layers), each of which is assumed to be internally uniform. That is, the temperature, smoke and gas concentrations within each layer are *assumed* to be exactly the same at every point. In CFAST, each compartment is divided into two layers. Since these layers represent the upper and lower parts of the room, conditions within a compartment can only vary from floor to ceiling, and not horizontally. This assumption is based on experimental observations that in a fire, conditions do stratify into two distinct layers. While we can measure variations in conditions within a layer, these are generally small compared to differences between the layers.

It is based on solving a set of equations that predict state variables (pressure, temperature and so on) based on the enthalpy and mass flux over small increments of time. These equations are derived from the conservation equations for energy, mass, and momentum, and the ideal gas law. Any errors which might be made by the model cannot come from these equations, but rather come from simplifying assumptions or from processes left out because we don't know how to include them. As enthalpy and mass are pumped into the upper layer by the fire plume, the upper layer expands in volume causing the lower layer to decrease in volume and the interface to move downward. If the door to an adjacent compartment has a soffit, there can be no flow through the vent from the upper layer until the interface reaches the bottom of that soffit. Thus in the early stages the expanding upper layer will push down on the lower layer air and force it into the next compartment through the vent by expansion.

Heat transfer is the mechanism by which the gas layers exchange energy with their surroundings. Convective transfer occurs from the gas layers to the compartment surfaces and to the exterior. The enthalpy thus transferred in the simulations conducts through the wall, overhead or deck in the direction perpendicular to the surface only. CFAST is more advanced than most models in this field since it allows different material properties to be used for the ceiling, floor, and walls of each room (although all the walls of a room must be the same). Additionally, CFAST uniquely allows each surface to be composed of up to three distinct layers for each surface, which are treated separately in the conduction calculation. This not only produces more accurate results, but allows one to deal naturally with actual construction. Material thermophysical properties are *assumed* to be constant, although they actually vary somewhat with temperature. This assumption is made because data over the required temperature range is scarce even for common materials, and because the variation is relatively small for most materials. The ability to utilize actual material properties in the context of their use is important to the current application.

Predictive Equations Used by the Model:

The way CFAST equation set is formulated, the physical input can be couched as source terms for a set of ordinary differential equations. The basic principles and the equation set which is currently used are described adequately elsewhere [1].

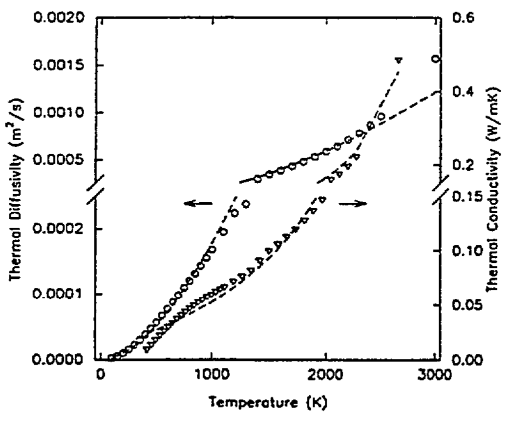
The Source Terms Which Have Changed:

In order to couple the heat transfer from one compartment to another, the convection algorithm has changed, and the means by which the boundary conditions for the conduction algorithm are implemented have been modified. The convection and radiation routines provide the heat flux that forms the source term for conduction (Von Neuman boundary condition). In the present application, the radiation routines have not changed.

Convection is one of the mechanisms by which the gas layers lose or gain energy to walls, objects or through openings. Conduction is a process which is intimately associated with convection; but as it does not show up directly as a term for heat gain or loss, it will be discussed separately. Convective heating describes the energy transfer between solids and gases. The enthalpy transfer associated with flow through openings will be discussed in the section on flow through vents.

Convective heat flow is enthalpy transfer across a thin boundary layer (film). The thickness of this layer is determined by the temperature difference between the gas zone and the wall or object being heated [5]. In general, convective heat transfer depends directly on the thermal diffusivity and conductivity of the boundary layer gas. The form of these parameters has changed based on the necessity of providing a much closer coupling between the convection, radiation and conduction routines..

The thermal conductivity, k, and thermal diffusivity, α, of air are defined as a function of the film temperature from data in reference [6]. The accompanying figure illustrates the fit of the data which we now use.



$$\alpha = 1.0\times10^{-9}\ T_f^{7/4}$$

$$100k = \left(\frac{0.0209+2.33\times10^{-5}T_f}{1-0.000267T_f}\right)$$

It is the coupling of radiation and convection as heat fluxes which determines the boundary condition for the conduction algorithm. This is true both in the compartment of origin as well as distant rooms and the outside. The requirement for self-consistency places a limit on the size of the time step which the solver can use.

Conduction of heat through solids is not a source term in the sense discussed earlier. That is, loss or gain of energy from solids occurs by convective heating, which in turn is influenced by subsequent gain or loss through the solids. However, as much of the net heat loss from a compartment occurs through loss to the walls and heating of interior objects and thus provides the boundary conditions for the other source terms discussed above.

The equation which governs the heat transfer in solids is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\nabla^2 T \tag{2}$$

and is a linear parabolic equation. As such it must be solved by a different technique than is used for the ordinary differential equations which describe mass and enthalpy flux. The equation is linear only if the coefficients k, ρ and c are independent of temperature throughout the material. To the accuracy that we know most of the thermal properties, it is a reasonable approximation. Procedures for solving 1-d heat conduction problems are well known. For finite difference methods such as backward difference (fully implicit), forward difference (fully explicit) or Crank-Nicolson, see [7]. For finite element methods see [8].

To advance the solution for the wall temperature profile, a finite difference approach [9] is used. A graded (non-uniform) mesh with n_x breakpoints was introduced for the spatial variable x (the coordinate into the solid). The second spatial derivative in the heat equation was replaced by a second divided (finite) difference approximation. This produces a system of n_{x-2} ODE's for the n_{x-2} unknown temperatures at the interior breakpoints. The conduction is tightly coupled to the compartment conditions from temperatures at the interior boundary supplied by the differential equation solver. The exterior boundary conditions (constant flux, insulated, or constant temperature) is specified in the configuration of CFAST. For this, the flux condition is used and is based on the far side (exterior) gas layer temperature. The solution at time $t + \delta t$ can be found by solving a tridiagonal system of linear equations. The temperature gradient at $x=0$ (the exposed wall) and time $t + \delta t$ was approximated by computing a derivative difference using the first two temperatures.

In all zone models to date, heat lost from a compartment by conduction has been assumed to be lost to the outside ambient. In reality, compartments adjacent to the room which contains the fire can be heated, possibly catastrophically, by conducted energy not accounted for in the model. This work implements the concept of connecting two compartments through the ceiling/floor. In principle, any two surfaces of any pair of compartments may be connected. the most straight forward connection is from the ceiling of one compartment to the floor of another. This insures that the boundary condition for the conduction equation is uniform.

In order to calculate the temperature on the far side of a bounding wall, we need to redo the boundary conditions used for the partitions. The original idea for incorporating room to room heat transfer into CFAST was to use the inside (exposed) wall temperature computed at a previous time step and to use it to compute an explicit boundary condition for the far (unexposed) wall in another compartment. The explicit nature of the boundary condition allowed for a simple representation of the temperature field at the exterior side of walls since the boundary condition did not involve any unknowns. Unfortunately, every scheme that was tried resulted in unstable algorithms which gave unphysical answers. The solution technique that worked then was to solve the heat conduction problem implicitly. This was done by using CFAST's present multi-slab capabilities (a wall material can have up to three distinct components) by treating two connected walls as simply one wall with extra slabs. The "two" walls are then solved together implicitly.

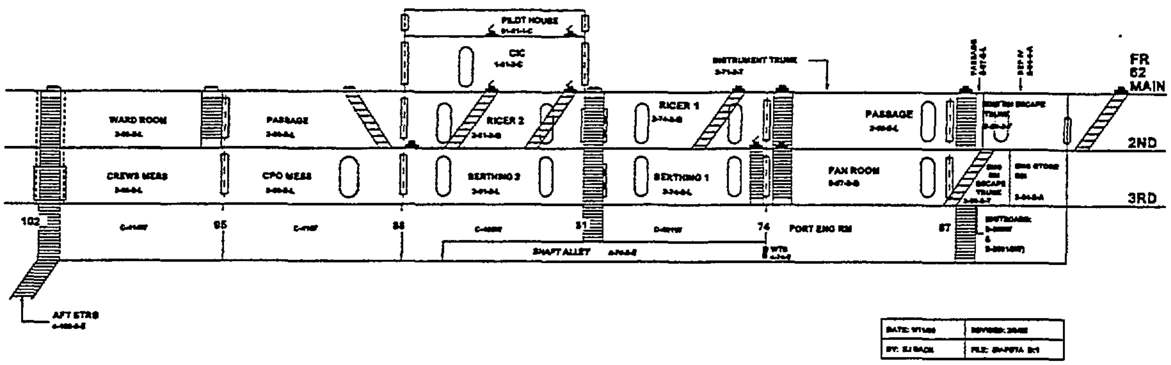


Figure 3. Crossection View of ex USS SHADWELL Showing the ISCC Test Configuration.

Single Zone Approximation:

A useful addendum to the general set of equations to be solved in this zone model is the possibility that there is only a single zone. Nominally this will improve the computation time by 25% since we eliminate one zone and the species associated with that zone. In practice, the improvement is less but still noticeable. For the cases where it is applicable, *e.g.* far from the fire origin, we combine the two zone into one using the following modification

$$
\begin{aligned}
\dot{m}_U^{new} &= \dot{m}_L + \dot{m}_U, \\
\dot{m}_L^{new} &= 0 \\
\dot{q}_U^{new} &= \dot{q}_L + \dot{q}_U, \\
\dot{q}_L^{new} &= 0.
\end{aligned}
\qquad (3)
$$

This is not a fundamental improvement, but rather is designed to fit in with the concept of single zone and network models that are being utilized currently. It is this modification to the basic set of equations used in CFAST that allows us to propagate heat through a compartment that has no fire.

Selection of Experiments

The ISCC test series on SHADWELL was conducted from 1989 to 1993 and included over a hundred tests. The experiments that were used in this comparison were chosen based on several criteria. Efforts were focused on the beginning of the series, before the cumulative effect of the fires on the integrity of the test compartments became too great. At this point, the initial conditions for modeling could no longer be known with certainty. The tests had to be very similar in terms of experimental procedure, mass loss rate, and fuel flow. Many of the early experiments which fit the above criteria had undergone statistical analysis by Desmatics, Inc. [10]. The analyses concluded that wind speed and direction had a significant effect on the temperatures produced by a fire. Since the analyses also identified anomalous experiments, these experiments were used excluded. To minimize the effect of wind, experiments which experienced low winds were chosen.

Test Configuration

The ISCC experiments were conducted on the port wing wall of ex-USS SHADWELL, fig. 3. The compartments which were of interest for this validation study were: Berthing 2 (the fire compartment), Ricer 2, the CIC, and the Pilot House. All four compartments were located between frame 81 and frame 88. Berthing 2 and Ricer 2 were bounded by the well deck and hull. A deckhouse, which contained the CIC and Pilot House, was set on top of the main deck above Ricer 2.

Berthing 2: The overhead and deck were both 0.95 cm thick steel. The forward (fwd), aft, and well deck bulkheads were 0.64 cm, 0.64 cm, and 1.27 cm thick steel, respectively. The hull was 1.59 cm thick steel. There were two standard Navy archways (1.7 m x 0.7 m) which were open to the well deck and were 0.61 m above the deck of Berthing 2.

Ricer 2: The overhead was 2.22 cm thick steel. The deck, fwd, aft, and well deck bulkheads were all 0.95 cm thick steel. The hull was 2.54 cm thick steel. In the fwd bulkhead there were two circular holes, both 2.86 cm in diameter, approximately 2.54 m above the deck. In the aft bulkhead, there was one circular hole, 2.86 cm in diameter, also 2.54 m above the deck. These three openings were partially blocked (50% to 75%) by instrumentation tubing and wiring. All the doors in this compartment were closed during the experiments. As the series progressed, cracks developed in the deck because of the intense fire in the compartment below.

CIC: The deck was 2.22 cm thick steel. The overhead and all bulkheads were 0.95 cm thick steel. There were four openings, 2.46 m above the deck, in the fwd bulkhead. Two of these openings were 1.91 cm in diameter. The other two were 2.86 cm in diameter. An additional opening in the aft bulkhead, 1.37 m above the deck, was 1.91 cm in diameter. The outboard bulkhead had an opening, 2.22 cm in diameter, located 1.23 m above the deck. The bottom edge of the CIC was not sealed where it contacted the main deck, so there were openings to weather all around the CIC perimeter. The total area of these openings was estimated and will be discussed later under "Modeling Procedure."

Pilot House: The deck, overhead, and bulkheads were all 0.95 cm thick steel. There was a 5.1 cm diameter hole in the deck.

Experimental Procedure

Most of the experiments in the ISCC series were similar in procedure; however, differences did occur depending on the purpose of the particular experiment. The following description of the experimental procedure is limited to the eight experiments of interest in this series.

A fully involved fire was created in Berthing 2 using three diesel spray fires. Initially, there was a pre-burn period of 170 to 190 s (183 s average) during which time heptane was burned in three fuel pans. These fuel pans, each 1.2 x 1.2 m, were placed 5.1 cm above the deck. The fwd, mid, and aft pans were centered 1.5 m from the well deck bulkhead and 1.8 m, 4.3 m, and 6.7 m from the fwd bulkhead, respectively. The initial fuel charge to the center fuel pan was 26.5 liters. The other two held 15 liters each. All three pans were ignited simultaneously and the pool fires were allowed to die down before the diesel fuel was sprayed across the hot pans. A flat fan spray nozzle (Bete Fog Nozzle, Inc. Model FF 073145) was positioned over each pan, approximately 17 cm above the deck. The total fuel flow, split evenly to the three nozzles, varied from 14.4 lpm to 18.2 lpm with an average of 16.4 lpm. The entire burn time was 20 minutes, including the preburn period.

Instrumentation

The instruments discussed in this section are limited to those used for comparison purposes.

Berthing 2: There were two vertical thermocouple strings, each containing five thermocouples. One string was located near the fwd bulkhead and the other was located near the compartment center at frame 86. The thermocouples were located 46 cm, 91 cm, 137 cm, 183 cm, and 229 cm above the deck.

Ricer 2: There were two vertical thermocouple strings. One string was located in the fwd portion of the compartment at frame 82 and the other was located in the aft portion at frame 86. Both the fwd and aft strings contained thermocouples located at 91 cm, 137 cm, 183 cm, and 229 cm above the deck. The aft string had an additional thermocouple located 46 cm above the deck. At least three thermocouples were used to measure the deck temperature.

CIC: There were two vertical thermocouple strings in this compartment. The fwd string was located at frame 83 and the aft string was located at frame 86. Each string contained six thermocouples, 20 cm, 46 cm, 91 cm, 137 cm, 183 cm, and 229 cm) above the deck. There was one thermocouple which measured the deck temperature in this compartment.

Pilot House: There were only two thermocouples on each of the two thermocouple strings in the Pilot House. They were 56 cm and 112 cm above the deck. The deck temperature was measured using a single thermocouple.

Modeling Procedure

The quality of a model depends upon the accuracy of the model input, i.e. the model input must reflect the experimental conditions as closely as possible. Further, when doing a comparison, it is important that the measured values represent the actual experiment as closely as possible. There are instances where estimates had to be made and they will be discussed in following sections.

Uncertain Experimental Set-up Information: The size of the vent openings, both between decks and to weather, must be included in the model input. These were not always known precisely. Cracks formed in the deck of Ricer 2 as a result of the intense fire in the compartment below. These cracks were periodically repaired, but there was not a precise record kept as to their size during any given experiment. The area of the opening represented by cracks between Berthing 2 and Ricer 2 was estimated to be 19 sq cm. It is important to realize that this is a small area compared to the size of the compartment. Its effect was investigated using model runs, and was determined to be well within the statistical error of either the model or the experiment in this situation. The effect is more pronounced in the situation where the precise flow pattern is the issue but will have little effect on either the compartment temperature or layer height. It is the latter which determine the boundary conditions for heat conduction and therefore the effect on heat vertical heat transfer.

There were also openings between the lower edge of the CIC and the main deck. The opening used for the model was 290 cm^2 Once again, the effect was investigated using the mode and was found to be irrelevant, that is, deviations were well within the error bars of either the predictions or the experiment. The model gave the same results regardless of which size opening was chosen.

The final estimate which had to be made was the mass loss rate of fuel during the *pre-burn* period. As previously mentioned, a total of 57 liters was charged to the fuel pans and ignited. The diesel spray was started as the pool fires started to die down. The actual mass loss rate of the heptane during this period could not measured. Consequently, the mass loss rate was estimated to be 0.097 kg/sec. This translates to a total of 26 liters burned during the pre-burn period. In order to ascertain whether this preheating period was important, the model was run with this pyrolysis rate, and with a value of twice the rate. The initial heating period was short compared to the time for the heat wave to penetrate the deck and the subsequent diesel fire was oxygen limited. Because of these two effects, the initial burn had little effect on the vertical heat transfer. In addition, the estimated rate produced an excellent (well within statistical error bars) agreement with the measured temperature. The physical effect that is being measured (and calculated) is the combustion efficiency.

Model Limitations:

The model assumes that each compartment is a rectangular parallelepiped. Since none of the compartments were rectangular their dimensions had to be adjusted for input to the model. For all compartments, the actual compartment length was used (the distance between frames 81 and 88). Effective widths were calculated so that the surface area of each overhead was the same as that in the actual compartment. The heights were then adjusted, if necessary, so that the compartment volumes were the same as the actual compartment volumes. This meant that the wall surface areas of the compartments were different than those in the actual compartments. The wall surface area is used by the model to calculate the total heat transfer to and from the walls. Since heat transfer through the ceiling/floor connection was the subject of this study, the deck surface area was the important parameter to control.

The model only accepts one thickness for all four walls in each compartment. Both Berthing 2 and Ricer 2 had walls of differing thicknesses. A weighted average based on actual surface area was used as input to the model for these compartments.

Results and Discussion

Before the results of the comparison are discussed in detail, it is important to review exactly what is being compared. CFAST is a zone model. It divides the compartments into two layers - an upper and a lower. Each layer is assumed to be of uniform temperature and composition. Experimentally, however, temperatures are measured at a limited number of discrete locations. This is of particular concern when the thermocouples show there is extreme non-uniformity in the temperatures between different parts of the compartment at the same height. For these situations, the model is still valid, since the basic conservation equations are being used, but the sensible variables being reported have associated with them a larger error.

In most cases, the experimental results given in the figures are an average of the eight experiments. The figures also show error bars which represent one standard deviation in the data obtained from the eight different experiments. This will illustrate the degree of repeatability obtained from these experiments. There was instrumentation for species concentration, temperature, and heat flux. Since heat transfer was the focus of this work, those measurements will be presented directly. Related measurements will be discussed when they have a bearing on the issue of heat propagation.

The model results given in the figures are an average of eight predictions. The eight predictions were obtained by using the actual fuel mass loss rate of each of the eight experiments. The error bars, representing one standard deviation in these results, show the scatter in temperature which would be expected from the variation in the fuel load among the experiments.

Berthing 2: Berthing 2 was the fire compartment. Both the model and the experimental data results show that almost the entire compartment was in the upper layer during the experiments, based on the interface height as calculated from the thermocouple trees. The experimental interface was derived from the vertical temperature readings [11]. With the exception of the transition time between the pre-burn and diesel spray fires, the small error bars show there was very good agreement among the experiments. The effect of variation in fuel mass loss rate on the predictions was very small. The error bars, although plotted, are covered by the symbols in the plot. There was excellent agreement between the model-predicted and experimentally-determined interface heights.

For each experiment, all of the thermocouples were averaged to obtain the upper layer temperature in Berthing 2. The average compartment temperatures for each experiment were then averaged to obtain the experimental results shown in fig. 4. The error bars reflect substantial deviation in the average compartment temperature among the experiments. The largest error bars were in the transition period between the pre-burn and diesel spray fires.

Ricer 2: There were three deck thermocouples which were common to all experiments. The temperatures of these three thermocouples were averaged to obtain a deck temperature for all the experiments. Although not shown, the three thermocouples in this compartment also revealed that the deck temperature was non-uniform during all of the experiments. Since there was no flow into the upper compartments, the model predicted that the entire compartment remained in the lower layer, as would be expected when the compartment was sealed. A small upper layer formed when these openings were assumed to exist. The model predicted that this layer consisted of the combustion products from Berthing 2. In both cases the interface height was above the highest thermocouple in both strings. It did not make sense to calculate the interface height from the experimental data because of the inconsistent stratification revealed by the two thermocouple strings. The hottest temperatures were near the bottom of the aft string and near the top of the fwd string. Therefore, for each experiment, all the thermocouples were averaged to determine the temperature of the lower layer in Ricer 2. The error bars on the experimental data show that there was much better agreement among the experiments than there was in the case of the Berthing 2 temperatures. The experimental error bars are even smaller than those on the model predictions which resulted from variations in the fuel mass loss rate.

The two thermocouple strings in Ricer 2 will be designated in the following discussions as fwd and aft, referring to their location within the compartment. The thermocouples on the fwd string were averaged together and the thermocouples on the aft string were averaged together for each experiment. These average temperatures from the individual experiments were then averaged and compared with the predictions. The error bars on the experimental data show the variation among the experiments, not the variation among the thermocouples on each of the strings. Even though the thermocouples on each of the strings read very close to each other (within 30 degrees Celsius), the difference between the average of the fwd and the average of the aft strings reached about 70 degrees Celsius toward the end of the experiments. The thermocouples on the aft string all read temperatures higher than any on the fwd string. On the aft thermocouple string, the hottest temperatures were observed near the bottom. On the fwd string, the cooler temperatures were near the bottom. This suggests there was some type of circulation pattern within the compartment and no consistent stratification. For this reason, the single zone approximation was used for Ricer 2, the CIC and the Pilot house.

The oxygen concentration in Ricer 2 decreased as a result of dilution with combustion products coming through the cracks from Berthing 2. This decrease, obtained by averaging the readings from these two sample points, varied from experiment to experiment depending most likely on the size of the cracks in the deck. By the end of the experiments, the total decrease in oxygen concentration ranged from about 1 vol% to 3 vol% and increased sequentially in the order that the experiments were done. This also suggests that the cracks in the deck got bigger as the series progressed. Even though both of the sampling points were located in the lower layer as defined by the model, the readings from neither one remained at 21 vol% as predicted by the model. These observations suggest that there was no consistent pattern of gas species concentration within Ricer 2 among these eight experiments. It is clear that regardless of how the combustion products were dispersed within the compartment, whether evenly or unevenly, they definitely did not rise to the top of the compartment completely unaffecting the lower layer as predicted. One well mixed layer, rather than two separate layers, is probably a more accurate depiction of this compartment.

CIC Deck: There was only one thermocouple measuring the temperature of the CIC deck. The readings from this one thermocouple were averaged over all eight experiments and compared to model predictions.

The predicted and measured CIC deck temperatures did not agree as well as those in the case of the Ricer 2 deck. It is interesting to note that the CIC deck was twice as thick as the deck between Berthing 2 and Ricer 2. Another difference between the Ricer 2 deck and CIC deck was the presence of raised scuttles on the CIC deck. No zone model will allow for this type of configuration. Consequently, the specification did not include the raised scuttles even though their presence may affect the results. The final difference between the Ricer 2 and CIC decks was the fact that the Ricer 2 deck and Berthing 2 overhead had the same area, whereas the CIC deck had a smaller area than the overhead in Ricer 2.

There was very good reproducibility in the experimental data, as evidenced by the small error bars as shown in the figure. They were smaller than those on the model predictions, generated by the variation in fuel mass loss rate. As always, had we not incorporated the algorithm which properly accounts for the conductive heat transfer through decks, the predictions would be that the deck would remained at ambient temperature throughout the experiment.

CIC: The model predicted the interface height would remain very close to the overhead throughout the experiment. Experimentally, all twelve thermocouples read very close to each other. Therefore, these twelve readings were averaged to obtain the compartment temperature for each experiment. These averages were then averaged and compared to the model predictions in fig. 4. Again, the model over predicted the temperature, 120 versus 50 degrees Celsius at the end of the experiment. This is not surprising since the CIC deck temperature was over predicted. Reproducibility in the experimental data was excellent. Predictions obtained from the model when the openings in Ricer 2 deck and around Ricer 2 doors were assumed to be absent were slightly higher than those obtained when they were assumed to be present. This is consistent with previous results.

As with Ricer 2, it appears that treating this compartment as one layer instead of two is more realistic. It is interesting to note that the model did not predict a cool upper layer temperature relative to the lower layer in Ricer 2. This is because the hot combustion gases from Berthing 2 were deposited into the upper layer. Without this mass transfer, the upper layer would have remained cool relative to the lower layer.

Pilot House Deck and *Pilot House:* The model predicted the entire Pilot House compartment was essentially in the lower layer. During the experiments all four thermocouples read very close to each other. Therefore, all four thermocouples were averaged from each of the eight experiments. These averages were then averaged to obtain the experimentally-determined temperature which was compared to the model predictions. Experimentally, the temperature increased only a few degrees above ambient and therefor are not shown.

Conclusion

The agreement between predicted and measured temperatures in this series of experiments was excellent. The one problem was that the during the early stages of the fire, the for side temperatures were under predicted This is indicative of a heat capacity which is too high and conductivity which is too low. This should be a subject of further investigation. Investigation into the differences between the Ricer 2 and CIC decks (thickness, presence of raised hatches, and unequal heat transfer surface areas) may also provide reasons for the discrepancies. Replacing the two layer assumption with one well mixed layer for this particular scenario should, however, provide a more accurate prediction for both species concentration in the compartment and convective heat transfer to the overhead.

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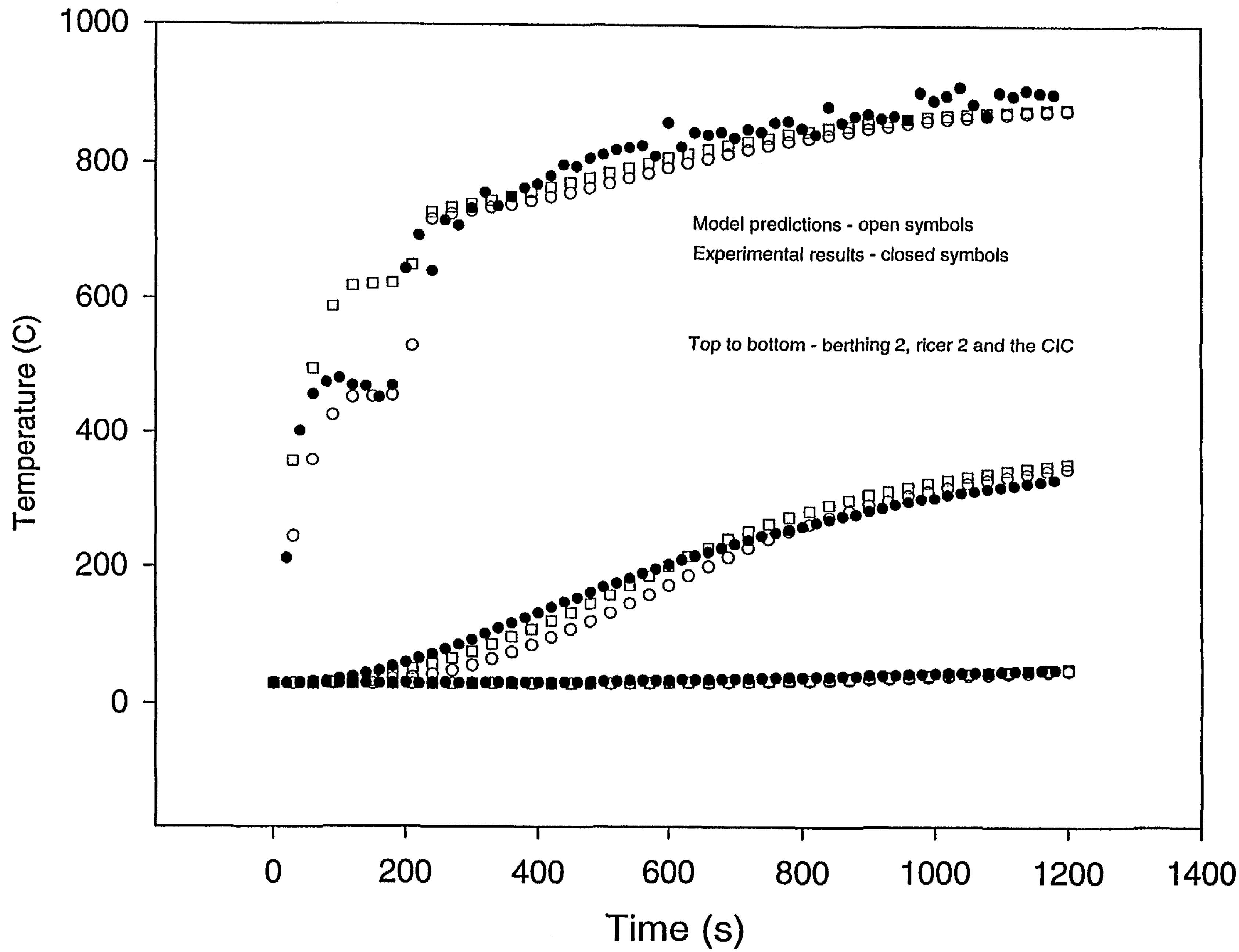

1000
800
600
400
200
0
Temperature (C)
0
200
400
600
800
1000
1200
1400
Time (s)
Model predictions - open symbols
Experimental results - closed symbols
Top to bottom - berthing 2, ricer 2 and the CIC