DEVELOPMENT OF AN ALGORITHM TO PREDICT VERTICAL HEAT TRANSFER THROUGH CEILING/FLOOR CONDUCTION

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Reprinted from FIRE TECHNOLOGY, Vol. 34, No. 2, 139-155, Second Quarter, May/June 1998.

Fire Technology, Vol. 34, No. 2, 1998

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Abstract

This paper describes a new algorithm of the Consolidated Fire Growth and Smoke Transport (CFAST) fire model and compares the results with data from real-scale fire tests conducted aboard the ex-USS *Shadwell,* the U.S. Navy's Research and Development 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 focuses on four compartments of the ship that were vertically aligned. The temperatures of the compartments and the decks between them were compared with model predictions. The predictions were very close to the 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 widespread acceptance, features are added to address questions that arise. This report describes some features of the Consolidated Fire Growth and Smoke Transport (CFAST) fire model, Version 3.1,[1] and compares its predictions to data obtained from real-scale fire tests conducted aboard the ex-USS *Shadwell,* the U.S. Navy's Research and Development Damage Control platform.[2] The new phenomenon modeled in this work is the vertical conduction of heat. The ability to account correctly for conductive heat transfer through metal decks and bulkheads is especially important aboard ship. Fire can spread as a result of rising temperatures in adjacent compartments that reach ignition levels even when there is no breach in the compartment of fire origin.

None of the experiments described in this paper were conducted specifically to generate data for comparison with CFAST predictions. Rather, data were obtained from experiments conducted in the Internal Ship Conflagration Control (ISCC) program,[3] which was developed to provide guidance to the fleet on the control of vertical and horizontal fire spread. An additional objective was to develop ship design criteria that would address devastation of the type that occurred on the USS *Stark* as the result of fires caused by a missile.

Key Words: Fire model, zone model, heat transfer, model validation.

Numerous compartments were involved in this test series, but this work will focus on four that were vertically aligned, or stacked on top of one another.

The Basis of the Fire Model

Analytical models for predicting fire behavior have evolved since the 1960s. Over the past two decades, the models have become more complete. In the beginning, these efforts focused on describing in mathematical language the various phenomena observed in fire growth and spread. These separate representations typically describe only a small part of a fire. When combined, however, they create a comprehensive computer code that can be used to estimate the expected course of a fire based on the given input parameters. These analytical models can now predict fire behavior accurately enough for most engineering applications.

Once a mathematical representation of the underlying science is developed, the conservation equations can be re-cast into predictive equations for temperature, smoke and gas concentration, and other parameters of interest, then coded into a computer for solution. Different models divide a 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 in which the fire is located, additional control volumes for the fire plume or the ceiling jet may be included to improve the accuracy of the prediction (see Figure 1). CFAST[4] is such a zone model and is being used to calculate the evolving distribution of smoke and fire gases and the temperature throughout a structure during a fire.

CFAST is based on solving a set of equations that predict state variables, such as pressure and temperature, 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, as well as the ideal gas law. Any errors the model might make cannot come from these equations, but rather from simplifying assumptions or from processes we leave out because we don't know how to include them. As the fire plume pumps enthalpy and mass into the upper layer, that layer expands in volume, causing the lower layer to decrease in volume and the interface to move downward.

Heat transfer is the mechanism by which the gas layers exchange energy with their surroundings. Both convective and radiative heat transfer occur from the gas layers to the compartment surfaces. The enthalpy thus transferred in the simulations conducts through the walls, overhead, or deck in the direction perpendicular to the surface only. Many different material properties can be used for the ceiling, floor, and walls of each room, although all the walls of a room must be the same. The properties are given in a database of materials, and the model references that database when a wall, ceiling, or floor material, such as gypsum, is referred to in the data file. Each surface can be composed of as many as three distinct layers, which are treated separately in the conduction calculation. This not only produces more accurate results but allows one to deal naturally with actual construction. The ability to use actual material properties in context is important to the current application.

Material thermophysical properties are assumed to be constant, although they actually vary somewhat with temperature. There are several reasons for this assumption. One can linearize the parabolic differential equation if the conductivity is presumed to be constant. In addition, data over the required temperature range are scarce, even for common materials, and the variation is relatively small for most materials, although some do exhibit a wide variability under certain circumstances. For example, gypsum and concrete both release free and chemically bound water as they are heated. Good data are not available for these conditions, and the theory of implementing this additional complexity is not sound. Finally, it can be shown by numerical experiment that making fairly drastic changes in the material properties, such as might occur in a room that proceeds from ignition to full involvement has only a small effect on the resulting atmosphere. It can be important in cases in which the material deforms beyond its elastic limit, as in the case of steel, or in which the barrier breaks, as might occur with gypsum or concrete, but these situations are not of interest here.

Predictive Equations Used by the Model

In the equation set, the physical input can be couched as source terms for a set of ordinary differential equations. The basic principles and the equation set that is

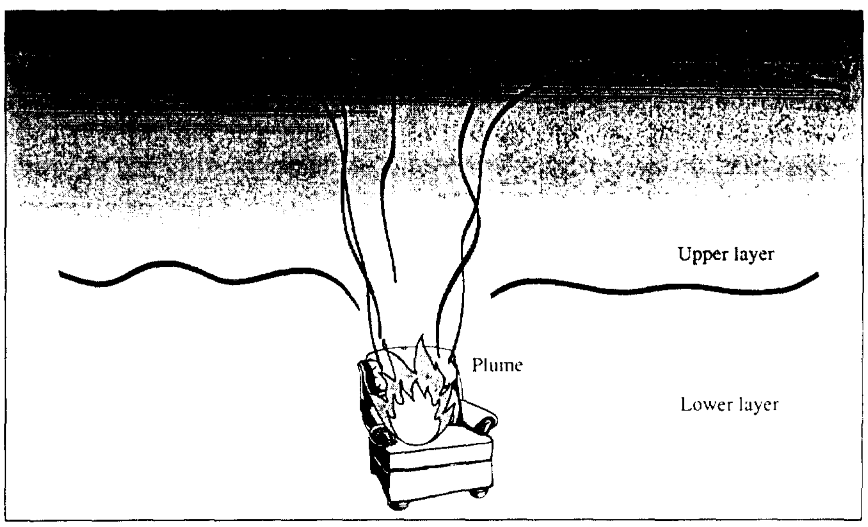

Figure 1. Definition of terms used in zone modeling.

currently used are described adequately elsewhere.[1] To couple the heat transfer from one compartment to another, the boundary conditions for the conduction algorithm have been modified. The convection and radiation routines provide the heat flux that forms the source term for conduction (Von Neuman boundary condition), so conduction of heat through solids is not a source term in this sense. That is, energy from solids is lost or gained by convective and radiative heating, which, in turn, is influenced by the subsequent gain or loss through the solids. Much of the net heat loss from a compartment is to the walls and as a result of heating objects in the room, and thus provides the boundary conditions for the other source terms discussed above.

All zone models to date have assumed that heat lost from a compartment by conduction is lost to the outside ambient.[5] In reality, compartments adjacent to the room that contains the fire can be heated, possibly catastrophically, by conducted energy for which the model does not account. This work connects two compartments through the ceiling/floor, although, in principle, any two surfaces of any pair of compartments may be connected. The most straightforward connection is from the ceiling of one compartment to the floor of another. This ensures that the boundary condition for the conduction equation is uniform. This is the essence of the new approach, namely, to connect the far side of a bounding surface of one compartment to the inside boundary of another. It is relatively straightforward for the ceiling/floor (overhead/deck) connection because of the uniformity of the boundary condition that arises from the use of the zone model concept. A uniform temperature profile with constant flux or temperature boundary conditions is applicable. It will not be as easy to implement for walls because three thermoclines arise—the two compartments and the partition itself.

The equation governing the heat transfer in solids is a linear parabolic equation which must be solved by a different technique than that used to solve the ordinary differential equations that describe mass and enthalpy flux. The equation is linear only if the coefficients k (thermal conductivity), ρ (density), and c (specific heat) are independent of temperature throughout the material. Given the accuracy of what we know of the thermal properties, it is a reasonable approximation.

Procedures for solving one-dimensional heat conduction problems are well-known.[6,7] To advance the solution for the wall temperature profile, a finite difference approach[8] is used. A graded (non-uniform) mesh was introduced into the solid for the spatial variable, and the second spatial derivative in the heat equation was replaced by a second divided (finite) difference approximation, producing a system of ODEs for the unknown temperatures at the interior breakpoints. The conduction is tightly coupled with 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—are specified in the model's configuration. For this simulation, the flux condition is used, based on the far-side (exterior) gas layer temperature. Normally, zone models assume that the outside boundaries of walls, ceilings, floors, and so on face ambient conditions. The solution at time $t + \delta t$ can then be found by solving a tridiagonal system of linear equations.

To calculate the temperature on the far side of a bounding wall, we reformulated the boundary conditions used for the partitions. The explicit nature of the boundary condition allowed for a simple representation of the temperature field on the exterior of the walls, since the boundary condition did not involve any unknowns. The heat conduction problem was solved implicitly using CFAST's multi-slab capabilities. In CFAST, a wall material can have up to three distinct components. Two connected walls are simply treated as one with extra slabs, and the "two" walls are solved together.

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 one zone in each room. In theory, eliminating a zone and the species associated with it will improve the computation time by 25%. In practice, however, the improvement is less but still noticeable. In cases in which it is applicable—such as those in which the walls are far from the point of fire origin—we combine the two zones into one using the following modifications:

$$\begin{aligned} \dot{m}_U^{new} &= \dot{m}_L + \dot{m}_U, \\ \dot{m}_U^{new} &= 0 \\ \dot{q}_U^{new} &= \dot{q}_L + \dot{q}_U, \\ \dot{q}_U^{new} &= 0. \end{aligned} \tag{1}$$

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

Selecting the Experiments

The ISCC test series on the *Shadwell* was conducted from 1989 to 1993 and included over 100 tests. The choice of experiments used in this comparison was 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. The tests had to be similar in terms of experimental procedure, mass loss rate, and fuel flow. Many of the early experiments that fit the criteria had been statistically analyzed by Desmatics, Inc.[9] The analysis concluded that wind speed and direction had a significant effect on the temperatures produced by a fire. To minimize the experimental variability, experiments that experienced low winds were chosen. The experiments the analysis identified as anomalous were excluded.

Test Configuration

The ISCC experiments were conducted on the port wing wall of the *Shadwell* (see Figure 2). The compartments modeled in this validation study were Berthing 2, the compartment of fire origin; Ricer 2; the CIC; and the Pilot House. All four compartments were located between Frame 81 and Frame 88, and Berthing 2 and Ricer 2 were bounded by the well deck and the hull. A deckhouse containing the CIC and Pilot House was set on the main deck above Ricer 2.

The overhead and deck of Berthing 2 were both constructed of steel 0.95 cm thick. The forward, aft, and well deck bulkheads were also of steel, 0.64 cm, 0.64 cm, and 1.27 cm thick, respectively. The hull was of steel 1.59 cm thick. Two standard Navy archways measuring 1.7 m by 0.7 m were open to the well deck and were located 0.61 m above the deck of Berthing 2 (see Figure 3). The lower portion of the hull, 1.8 m below the overhead, had seven openings. These openings, aligned horizontally, were all 1.13 m wide and varied in height from 0.80 m to 0.98 m.

The overhead of Ricer 2 was constructed of steel 2.22 cm thick. The deck, forward, aft, and well deck bulkheads were also of steel, all 0.95 cm thick. The steel hull was 2.54 cm thick. In the forward bulkhead there were two circular holes, both 2.86 cm in diameter, approximately 2.54 m above the deck (see Figure 4). In the aft bulkhead there was a circular hole 2.86 cm in diameter, 2.54 m above the deck. These three openings were blocked 50% to 75% by instrumentation tubing and wiring. All the doors in this compartment were closed during the experiments, although some were warped so they did not seal completely. As the

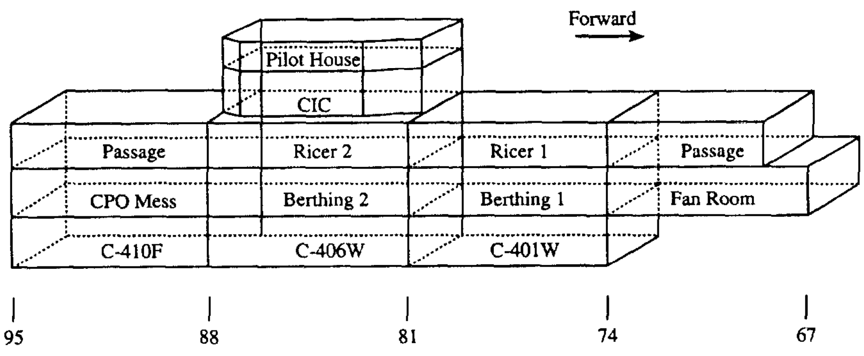

Figure 2. Ex-USS SHADWELL, section view, ISCC test area.

series progressed, the intense fire in the compartment below caused cracks to develop in the deck. The sizes of the openings around the doors and in the deck will be discussed later in the section titled "Modeling Procedure."

The CIC deck was constructed of steel 2.22 cm thick. The overhead and all bulkheads were also of steel, 0.95 cm thick. There were four openings, 2.46 m above the deck, in the forward bulkhead (see Figure 5). Two of these openings were 1.91 cm in diameter, and 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 came in contact with the main deck, so there were openings to weather around the entire perimeter of the CIC. The total area of these openings will be discussed later under "Modeling Procedure."

The Pilot House deck, overhead, and bulkheads were all constructed of steel 0.95 cm thick. There was a 5.1 cm diameter hole in the deck (see Figure 6).

Experimental Procedure

Most of the experiments in the ISCC series were similar in procedure, although experiments did differ depending on their purpose. The following description of the experimental procedure is limited to the eight experiments of interest here.

A fully involved fire was created in Berthing 2 using three diesel spray fires. During an initial pre-burn period of 170 to 190 seconds—183 seconds on average—heptane was burned in three fuel pans. These fuel pans, each measuring 1.2 x 1.2 m, were placed 5.1 cm above the deck. The forward, 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 forward bulkhead, respectively. The initial fuel charge to the center fuel pan was 26.5 liters. The other two pans held 15.1 liters each. All three 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 among the three nozzles, varied from 14.4 lpm to 18.2 lpm, with an average of 16.4 lpm. The entire burn time, including the pre-burn, was 20 minutes.

Instrumentation

The instruments discussed here are limited to those used for comparison purposes.

In Berthing 2, there were two vertical thermocouple strings, each containing five thermocouples (see Figure 3). One string was located near the forward bulkhead, and the other was located at Frame 86. The thermocouples were located 46 cm, 91 cm, 137 cm, 183 cm, and 229 cm above the deck.

In Ricer 2, there were two vertical thermocouple strings (see Figure 4). One was located in the forward portion of the compartment at Frame 82, and the other was located in the aft portion at Frame 86. Both forward and aft strings contained thermocouples located 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. Although the number of deck thermocouples varied among experiments, at least three were common to seven of the eight experiments. These were used to represent the deck temperatures.

There were two vertical thermocouple strings in the CIC (see Figure 5). The forward string was located at Frame 83, and the aft string was located at Frame 86. Each contained six thermocouples 20 cm, 46 cm, 91 cm, 137 cm, 183 cm, and 229 cm above the deck. One thermocouple measured the deck temperature in this compartment.

There were two thermocouples on each of the two thermocouple strings in the Pilot House 56 cm and 112 cm above the deck (see Figure 6). The deck temperature was measured with just one thermocouple.

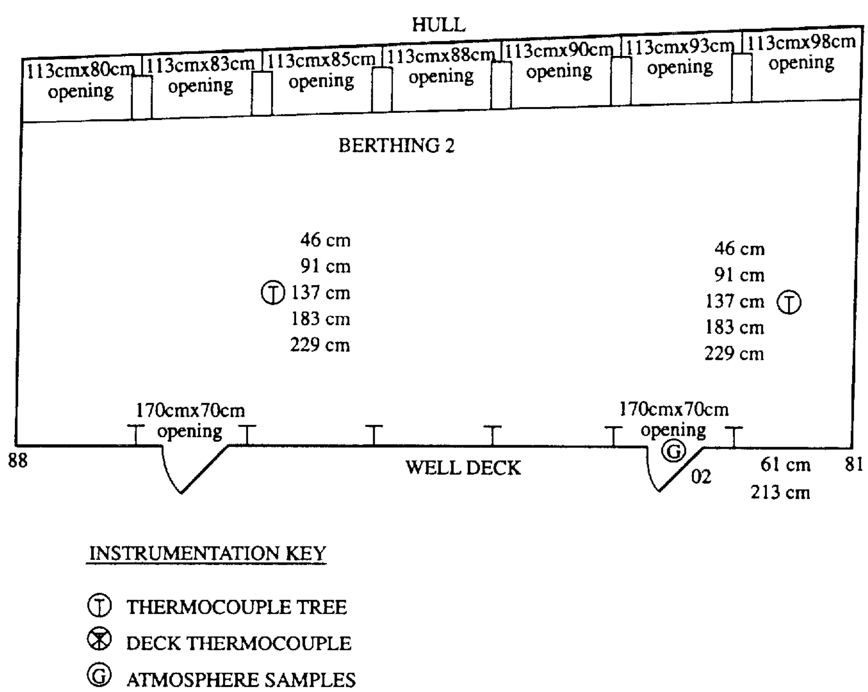

Figure 3. Plan view, Berthing 2.

Modeling Procedure

The quality of the output from a model depends on the accuracy of the model input, so the model input must reflect the experimental conditions as closely as possible. However, input had to be estimated in certain instances, either because the information about the experimental set-up was unknown or because the model could not handle certain configurations. The estimates will be discussed in following sections.

Uncertain Experimental Set-Up Information

The size of the vent openings between decks and to the weather must be included in the model input, but these were not always known precisely. Cracks that formed in the deck of Ricer 2 as a result of the intense fire in the compartment below were repaired periodically, but a precise record was not kept of their size during any given experiment. Personnel on-site during the experiments estimated the area of these cracks between Berthing 2 and Ricer 2 to be less than 19 cm^2. The total size of the openings to weather around the warped doors in Ricer 2 was also unrecorded and estimated to be no larger than 0.24 m^2. It is important to realize that these are very small areas compared to the size of the compartment. The area of the walls in Ricer 2 was over 64 m^2, and the deck area was over 34 m^2. The effects of the openings were investigated by running the model with the smallest—that is, zero—and largest estimates for the openings. The results for all cases were well within the statistical error of the model. The exact size of the

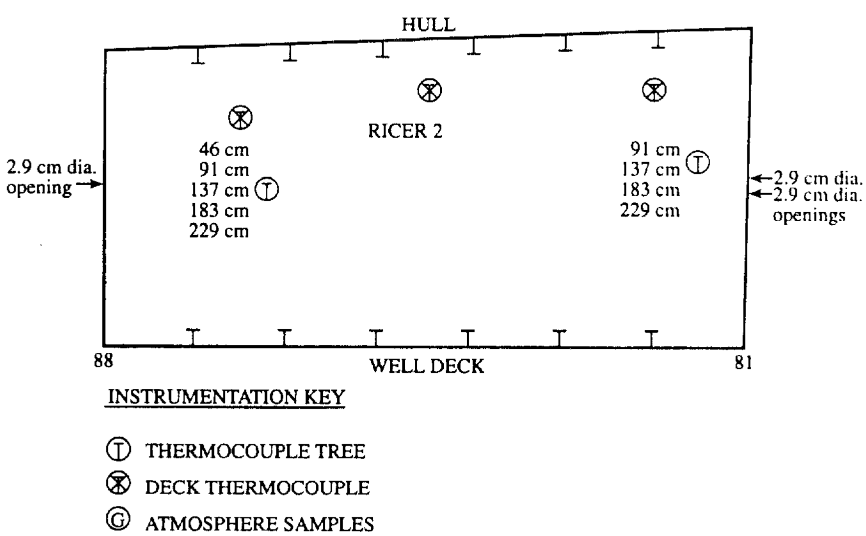

Figure 4. Plan view, Ricer 2.

openings would be important if the precise flow pattern were the issue, but it had little impact on the compartment temperature or layer height. It is the latter that determine the boundary conditions for heat conduction and therefore the effect on vertical heat transfer.

There was also an opening between the lower edge of the CIC and the main deck. The upper limit of the opening's area was estimated to be 0.03 m^2. Once again, the effect was investigated using the model and was found to be essentially nonexistent.

The final estimate to be made was the mass loss rate of fuel during the pre-burn. As mentioned, 57 liters were charged to the fuel pans and ignited, and when the pool fires began to die down, the diesel spray was started. The actual mass loss rate of the heptane during this period was not measured. Since the physical effect being measured and calculated was the combustion efficiency, the mass loss rate was estimated to produce an agreement with the measured temperature. This translates to a total of 22 liters burned from all three pans during the pre-burn. To ascertain whether this preheating period was important, the model was run with this pyrolysis rate and with a value of twice that rate. The pre-burn was short compared to the total test time, and analyzers located in Berthing 2 showed that the subsequent diesel fire was oxygen-limited. As a result of these two effects, the pre-burn had little impact on the vertical heat transfer.

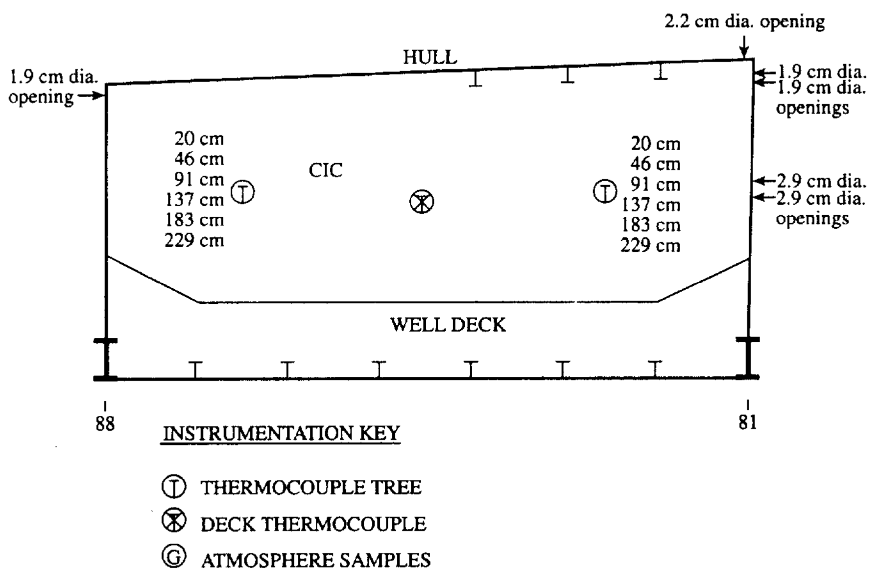

Figure 5. Plan view, CIC.

Model Limitations

CFAST models a compartment as a rectangular parallelepiped. Since none of the compartments formed this shape, the dimensions had to be adjusted for input to the model. The dimensions important for verisimilitude to the compartments are the surface area of the overheads and the volume of the compartments. For all compartments, the actual compartment length—the distance between Frames 81 and 88—was used. Effective widths were calculated so that the surface area of each overhead was the same as that of the actual compartment. The heights were then adjusted, if necessary, so that the compartment volumes were the same as the actual compartment volumes. Since heat transfer through the ceiling/floor connection was the subject of this study, the overhead surface area was the important parameter to control. The adjusted height, length, and width used as model inputs are 2.50 m, 8.52 m, and 4.02 m, respectively, for Berthing 2; 2.58 m, 8.53 m, and 4.02 m, respectively, for Ricer 2; 2.51 m, 8.53 m, and 2.77 m, respectively, for CIC; and 1.10 m, 8.53 m, and 2.77 m, respectively, for Pilot House. The actual compartment dimensions are given in Bailey and Tatem.[3]

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

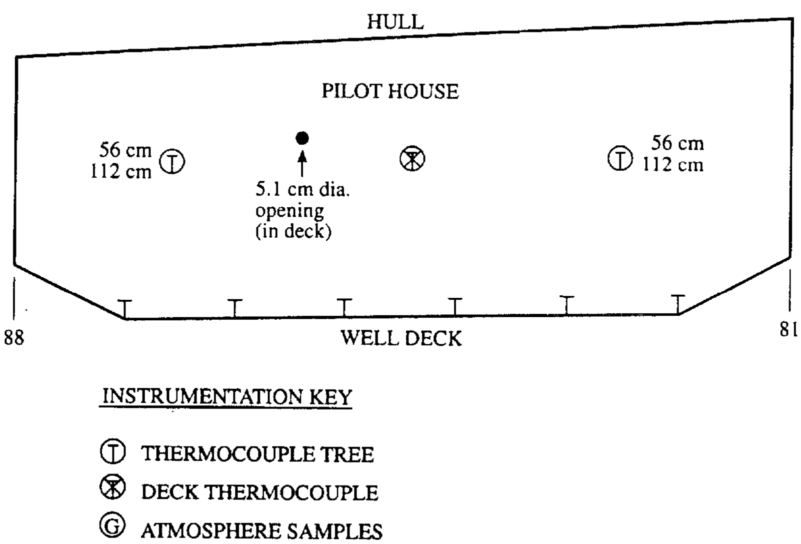

Figure 6. Plan view, Pilot House.

Results and Discussion

Before the results of the comparison are discussed, it is important to review exactly what is being compared. A zone model divides the compartments into two layers, an upper and a lower, each of which is assumed to be of uniform temperature and composition. Experimentally, however, temperatures are measured at a limited number of discrete locations. Inherent in the process of averaging these measurements to define the overall characteristics of each layer is the danger that this average does not actually represent reality. This is of particular concern when the thermocouples show that the temperatures in different parts of the compartment at the same height are not uniform. The model is still valid in these situations, since the basic conservation equations are being used, but the sensible variables being reported have a larger error associated with them.

In most cases, the experimental results given are an average of the eight experiments. Error bars that represent one standard deviation in the data obtained from the eight different experiments are also shown. This will illustrate the degree of repeatability obtained from these experiments.

Error bars for the model predictions are not shown. The primary error arises from the finite element assumption, which implies uniformity in the layers. This is 10% in the fire compartment and 15% beyond. The primary cause of this inherent error is the discretization in the cells. Only two are used, and, experimentally, there is a transition region of about 10% and 15%, respectively, of the height of the compartment. Three other sources of error in these comparisons are in the effective surface area that permits heat transfer, the thermophysical properties of the decks and bulkheads, and the actual heat release rate of the fire. Since the compartment geometry chosen was based on the height, width, and depth of the compartment, the error due to inaccuracy in the measurement of the geometry is proportional to the measured values of these spaces. Thermophysical properties are based on handbook values,[10] which are generally measured at one temperature. The properties of steel, unlike those of permeable materials, are not expected to vary much with temperature. Earlier studies have confirmed this.[11]

The primary error was in determining the actual pyrolysis of the three initiating heptane pool fires. An estimated 22 liters of heptane was burned over three minutes. The effect of this variable was investigated by running the model with this value and comparing the results with predictions obtained using 44 liters of fuel, a factor of 2. There was a difference in the initial compartment temperature, but, because the time was short, the effect did not persist. The two predictions were almost completely coincident after the pre-burn, indicating no lingering effect. The overall result is to limit the accuracy of the predictions to ±20% in the room where the fire is located and ±25% beyond, assuming the variation is independent and therefore additive.

Berthing 2 was the fire compartment. The experimental results show that nearly all of the compartment was in the upper layer during the experiments, based on the interface height as calculated from the thermocouple trees.[12] For each experiment, therefore, 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 Figure 7. The error bars reflect the deviation in the average compartment temperature among the experiments. The largest error bars were in the transition period between the pre-burn and the diesel spray fires.

The two-zone approximation was used to generate model predictions. The model also predicted that almost the entire compartment consisted of an upper layer throughout the experiments. Figure 7 shows the comparison between the model-predicted and the experimentally determined upper-layer temperatures in Berthing 2. As can be seen, the differences between the measured temperatures and the predicted temperatures are well within one standard deviation of the experimental data.

The two thermocouple strings in Ricer 2 will be designated in the following

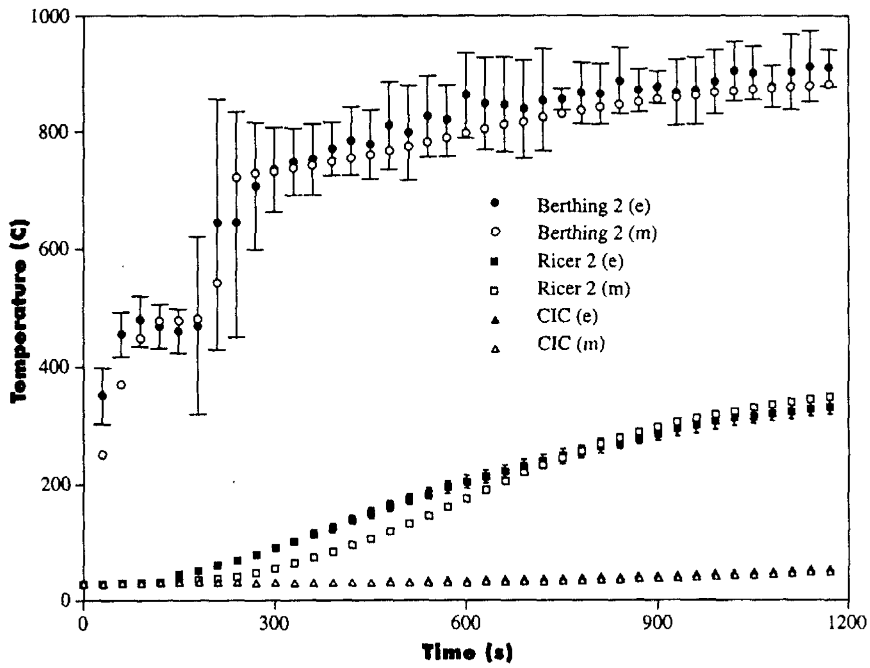

Figure 7. Comparison of measured and calculated temperatures as a function of time for Berthing 2, Ricer 2, and the CIC on ex-USS SHADWELL. The filled symbols (e), are experimental values (measured), and the open symbols (m), are the model predictions.

discussions as forward and aft, referring to their location in the compartment. The thermocouples on the forward string were averaged together for each experiment, as were the thermocouples on the aft string. Even though the thermocouples on each string were within 30°C of each other, the difference between the average of the forward string and the average of the aft string reached about 70°C toward the end of the experiments. The thermocouples on the aft string all read temperatures higher than any on the forward string. On the aft string, the hottest temperatures were near the bottom, while the cooler temperatures were near the bottom on the forward string. This suggests some type of circulation pattern in the compartment and no consistent stratification. For this reason, the single-zone approximation was used for Ricer 2.

For each experiment, all the thermocouples were averaged to determine the temperature in Ricer 2. These average temperatures from the individual experiments were then averaged and compared with model predictions in Figure 7. The error bars on the experimental data show that there was much better agreement in temperature among the experiments in Ricer 2 than there was in the Berthing 2 experiments. There was good agreement between the model-predicted and experimentally measured Ricer 2 compartment temperatures.

The three deck thermocouples in Ricer 2 were averaged together for each experiment. These values were then averaged across experiments and compared with model predictions in Figure 8. The comparison shows a delay in the rise of the model-predicted deck temperature, indicating that the effective heat capacity the model is using may be too high. Note that the delay propagates upwards and is evident in the air temperature in Ricer 2 and in the deck temperature of the CIC.

Although it is not shown, the model predicted before the addition of the vertical heat transfer algorithm that both the air and deck temperatures in Ricer 2 would rise only a few degrees Celsius above ambient. The actual increases were 300°C and 700°C, respectively. The small temperature rise in the model predictions was due to the transport of hot gases through the cracks in the Ricer 2 deck. If there had been no cracks, the model would have predicted no increase in either the air or deck temperature of Ricer 2. The addition of the new algorithm resulted in much more realistic predictions.

Since combustion products never entered the CIC, the single-zone approximation was used to depict the physical situation in the CIC. The readings from the 12 thermocouples were averaged to obtain the compartment temperature for each experiment. These averages were then averaged and compared to the model predictions in Figure 7. Reproducibility in the experimental data was excellent, as was the comparison between model-predicted and experimentally determined compartment temperatures. The error bars are so small that they are obscured by the symbols.

One thermocouple measured the temperature of the CIC deck. The readings from this one thermocouple were averaged over all eight experiments and compared to model predictions in Figure 8. The lag in the model-predicted temperature rise, mentioned above, is evident in the comparison. There was very good reproducibility in the experimental data. Again, the error bars are so small that they are hidden by the symbols.

Before the algorithm, which properly accounts for the conductive heat transfer through decks, was developed, CFAST predicted that the CIC air and deck temperatures would remain at ambient throughout the experiment.

Because the single-zone approximation was used to generate model predictions for the Pilot House, all four thermocouples were averaged for each of the eight experiments. These averages were then averaged to obtain the experimentally determined temperature, which was compared to the model predictions. The temperature increases in the Pilot House and Pilot House deck, both experimentally determined and model-predicted, were only a few degrees above ambient so they are not shown.

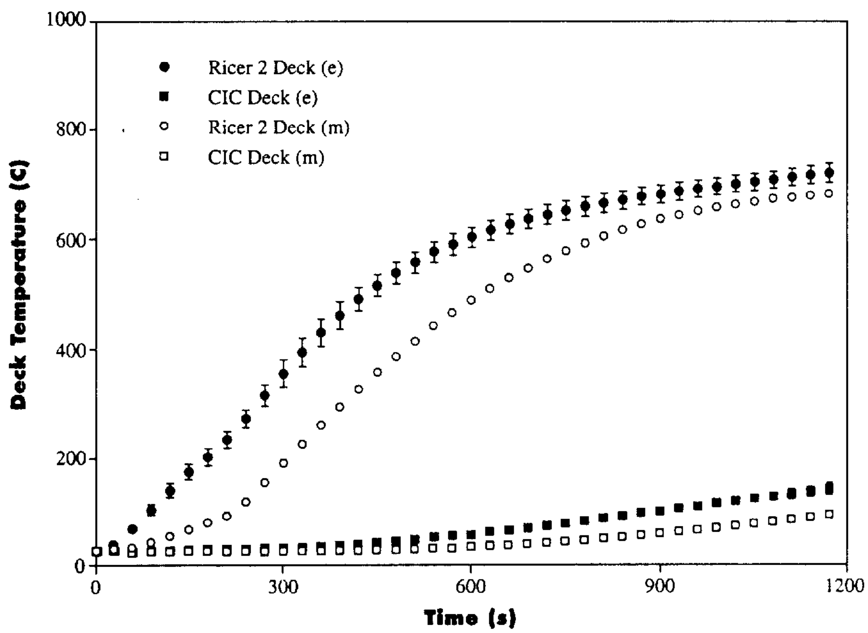

Figure 8. Comparison of measured and calculated temperatures as a function of time for Ricer 2 deck and CIC deck on ex-USS SHADWELL. The filled symbols (e) are experimental values (measured), and the open symbols (m) are the model predictions.

Conclusion

An algorithm that properly accounts for vertical heat transfer by conduction was recently incorporated into CFAST, and the model was used to simulate large-scale fire tests conducted aboard the ex-USS *Shadwell.* The test configuration consisted of three compartments vertically aligned above a fire compartment. Before the new algorithm was added, the model predicted that the temperatures in the compartments above the compartment of fire origin would remain essentially at ambient. After the algorithm was incorporated, however, the model's predicted results were much more realistic. The comparison between the predicted and measured temperatures in this series of experiments showed excellent agreement. The comparison does indicate that during the early stages of the fire, the far-side temperatures—that is, those on the unexposed surface—were underpredicted. This indicates an effective heat capacity that is too high and/or effective conductivity that is too low. This should be a subject of further investigation.

Acknowledgments

This work was sponsored by the Office of Naval Research, Surface Ship Technology Area.

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