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CASE REPORT

Angi M. Christensen,[1] *Ph.D. and David J. Icove,*[1] *Ph.D., P.E.*

The Application of NIST's Fire Dynamics Simulator to the Investigation of Carbon Monoxide Exposure in the Deaths of Three Pittsburgh Fire Fighters*

ABSTRACT: A case is reported in which computer fire modeling was used to reevaluate a fire that killed three fire fighters. NIST's Fire Dynamics Simulator (FDS) was employed to model the fire in order to estimate the concentration of carbon monoxide present in the dwelling, which was the immediate cause of death of two of the fire fighters, who appear to have removed their face pieces in order to share available air. This estimate, along with an assumed respiration volume and known blood carboxyhemoglobin, was plugged into a standard equation to estimate the time of exposure. The model indicated that 27 min into the fire, the carbon monoxide concentration had already reached approximately 3600 ppm. At this concentration, and a respiration of 70 L/min, an estimated 3 to 8 min of exposure would have been required to accumulate the concentrations of carboxyhemoglobin (49, 44, and 10%) measured on the fire fighters at autopsy.

KEYWORDS: forensic science, fire modeling, Fire Dynamics Simulator, carbon monoxide exposure, death investigation

Fire hazard analysis involves estimation of the effects of a specific fire. While the benefits of quantified hazard analysis with respect to product assessment, fire prevention, and cost savings are widely recognized, few have considered the potential of applying such analyses to fire death investigations. Here we explore the possible application of fire modeling programs, specifically the National Institute of Standards and Technology's Fire Dynamics Simulator (1), to the reevaluation of a Pittsburgh house fire that killed three fire fighters. Specifically, the purpose of this report is to describe how FDS was used in the investigation to estimate the carbon monoxide concentration in the house during the fire. This estimate, along with information on respiration volume and blood carboxyhemoglobin saturation, will then be plugged into a standard equation to estimate the time of exposure.

Several programs quantify hazards to occupants of burning buildings through a combination of expert judgment and calculations. The goals of such programs are to be able to calculate the development of hazardous conditions over time, calculate the time needed by occupants to escape under those conditions, and estimate the resulting loss of life based on assumed occupant behavior and tenability criteria (the ability to occupy a fire prior to incapacitation or death). Applications of fire modeling include a wide range of problem sets from single-family dwellings to industrial conditions such as control rooms in electrical power plants. Such programs provide fire protection engineers with an invaluable tool for predicting the consequences of fires in order to improve public fire safety, detection technology, and fire safety education, as well as developing strategies for reducing fire losses through improved building design and arrangement.

The three most commonly examined incapacitating effects of thermally produced smoke and gas are impaired vision as a result of smoke density or painful irritants in the smoke, pain and burns to exposed skin and upper respiratory tract as a result of heat transfer, and asphyxiation by inhalation of toxic gases. While limited visibility and heat have been shown to significantly impair escape and can themselves result in incapacitation, the effects of toxic gases are the major deterrents of escape and the primary cause of fire-related death.

Carbon monoxide is the most important asphyxiant formed in fires (because it is always present irrespective of the materials involved or the stage or type of fire) and is the major cause of death in fires (2). Effects of carbon monoxide exposure are dependent on the concentration and duration of exposure and include lightheadedness, confusion, loss of consciousness, neurological effects, and even death. The varying severity of these effects is important to the ability of a fire occupant to seek and pursue an effective escape route. The toxic effects of carbon monoxide result from its binding with hemoglobin in the blood, forming carboxyhemoglobin. The presence of this substance reduces the amount of oxygen supplied to the tissues in the body, particularly the brain, causing toxic asphyxia. Because hemoglobin's affinity for carbon monoxide is about 200 to 240 times that for oxygen (3), carboxyhemoglobin levels continue to increase as carbon monoxide is inhaled.

Case Description

Carbon monoxide toxicity appears to have been the key issue involved in the 1995 deaths of three Pittsburgh fire fighters who were

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[1] U.S. Tennessee Valley Authority Police, 400 W. Summit Hill Dr., WT-3D, Knoxville, TN.

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unable to escape from the interior of a burning dwelling. Details of the few minutes prior to the deaths of the fire fighters are unclear, but it appears that at some point they realized they were running short of air and needed to leave but were unable to find a window or any other exit and exhausted their air supplies. Two of the fire fighters are believed to have removed or loosened their face pieces and made attempts to share the air that was available by "buddy breathing," or alternating the use of the breathing apparatus. All three were eventually rendered unconscious due to carbon monoxide inhalation or oxygen deficiency.

Several tests confirmed that there were some performance deficiencies in the fire fighters' breathing apparatus (4), though it does not appear that these deficiencies were primary causal factors in their deaths. Buddy breathing, which intermittently exposed at least two of the fire fighters to toxic gasses, is more likely the major contributing factor. It is not uncommon for fire fighters to attempt to share available good air when supplies are low. Some breathing units are equipped with special fittings to allow air to be shared, but more commonly face pieces are simply transferred, quickly exposing both individuals to high concentrations of carbon monoxide. Such exposures are known to quickly cause disorientation and compromise motor skills, making it more difficult to find a means of escape. Previous situations where buddy breathing has been practiced have shown results similar to those indicated in the autopsies of the three fire fighters.

The autopsy reports indicated that all three fire fighters died from asphyxiation. Two of the three fire fighters had carboxyhemoglobin concentrations of 44 and 49%, which is consistent with concentrations known to cause unconsciousness, coma, or death (2), indicating death as a direct result of inhalation of carbon monoxide. The third firefighter had a lower carboxyhemoglobin concentration of only 10%. This suggests a likely scenario where two of the fire fighters were practicing buddy breathing while the third simply ran out of air in his breathing apparatus and never removed his face piece, resulting in an oxygen deficiency sufficient to cause death.

Computer Model Investigation

One of the many unanswered questions in the investigation of this case was: How long were the two fire fighters practicing buddy breathing before becoming incapacitated? While a rough estimate can be generated based on when the fire fighters entered the dwelling and when their bodies were discovered, we were asked to suggest a more accurate estimate based on some computer-modeling techniques that were not available at the time of the original investigation.

The following equation describes the relationship between blood carboxyhemoglobin, the concentration of carbon monoxide, the volume of inspired air, and time of exposure (5):

$$COHb = (3.317 \times 10^{-5})(CO)^{1.036}(RMV)(t)$$

where:

$COHb =$ carboxyhemoglobin (%)
$CO =$ carbon monoxide concentration (ppm)
$RMV =$ respiration minute volume (L/min)
$t =$ time of exposure (min)

Here we know the carboxyhemoglobin concentrations since they were measured at autopsy, and estimates for RMV during extremely heavy exercise such as firefighting can easily be derived from respiratory studies involving a human subject (6). Since we are interested in how long the fire fighters were practicing buddy breathing, we need to solve the equation for t, or time of exposure. This requires that we somehow derive the remaining variable, the concentration of carbon monoxide in the room where the fire fighters were found. For this, we employed the fire modeling program FDS.

FDS, developed in-house by NIST in 1997, is a computational fluid dynamics (CFD) fire model that uses large eddy simulation techniques to predict the thermal conditions resulting from a compartment fire (7,8). The user specifies the dimensions and properties of the structure of interest, dividing it into small rectangular control volumes or computational cells. Input is initially entered in a text file, which is run in DOS. Additional features about the furnishings, walls, floors, etc., can be entered and/or altered using FDS's graphical editor. (Instructions on programming a specific fire can be found in the User's Guide (1).) The model then computes the density, velocity, temperature, pressure, and species concentration of the gas in each cell based on the conservation laws of mass, momentum, and energy to model the movement of fire gasses. It also utilizes material properties of the furnishings, walls, floors, and ceilings to simulate fire growth and spread. The output of the FDS program consists of several data files including visualization files and spreadsheets. Smokeview is a visualization program that displays the results of FDS computed data by animating time-dependent variables such as particle movement, temperature, heat flux, and species (CO, O_2, CO_2, etc.) concentrations (1).

The accuracy with which FDS predicts temperatures and heat release rates has been validated by large-scale fire tests (9). Testing has shown that FDS temperature predictions were within 15% of the measured temperatures, and heat release rates were within 20% of measured values (9). Results, however, are often presented as ranges to account for some uncertainty. FDS is the primary fire-modeling tool used by NIST and has been used in major fire investigations involving large loss and death (10–13).

The first step in producing the model of the Pittsburgh fire was to construct a representation of the dwelling (i.e., input the computational cells). This was done with the assistance of floor plans and sketches of the house derived from a technical report produced by the Federal Emergency Management Agency (4) (Fig. 1). According to the report, the fire occurred in a single-family dwelling that was approximately 6 m wide by 10 m deep and had three occupied floor levels above a partially finished basement. The fire was believed to have been caused by arson and originated in the basement directly under the kitchen.

Our model included only the major obstructions in the house and the origin of the fire and did not include furniture or other combustibles in the house. While this approach has the problem of likely underestimating the heat release rate and oxygen consumption, it has the advantage of decreasing processing time as well as providing a likely underestimate (conservative) exposure time. A 0.7 by 0.5-m area was designated as the fire's "burner," or point of origin. Since this fire is believed to have been the result of arson involving an accelerant (4), the fire was designated as having a heat release rate of 2000 kW/m^2 (Fig. 1).

Since we are specifically interested in carbon monoxide concentrations, we enhanced our hazard analysis with the addition of a carbon monoxide slice in our data input file. This allowed us to specify a plane within the structure at which we could monitor the concentration of carbon monoxide. We were interested in the carbon monoxide concentration on the first floor family room, where the bodies of the three fire fighters were discovered, so our CO slice was made to intersect this room. A detailed timeline presented in the technical report indicated that the fire fighters were recovered approximately 45 min after the fire was detected. Our model indicates that even

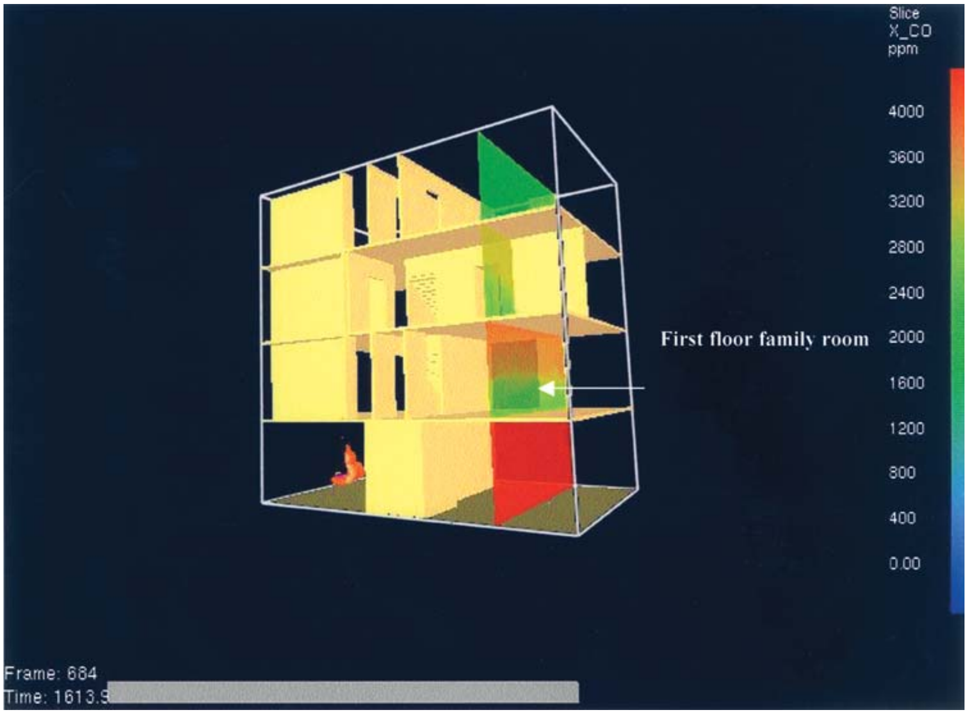

FIG. 1—*Modeled fire 27 min after ignition.*

27 min into the fire the carbon monoxide concentration had already surpassed lethal concentrations in the first floor family room.

In calculating time to incapacitation, we used the average carboxyhemoglobin measured on two of the fire fighters at autopsy of 47%. We used a conservative estimate of 3600 ppm of carbon monoxide based on the results of the computer fire model 27 min into the fire. An estimate of 70 L/min was derived from known respiration volumes during extremely heavy exercise (6). This indicates a total exposure time of 4.2 min, suggesting that, following removal of the face pieces, only a few minutes of exposure would have been required to produce the lethal concentrations of carboxyhemoglobin observed at autopsy. If we assume that some good air was left in the breathing apparatus and that each firefighter was breathing it intermittently with the toxic air, we may assume that incapacitation required perhaps several additional minutes.

$$COHb = (3.317 \times 10^{-5})(CO)^{1.036}(RMV)(t)$$

$$47\% = (3.317 \times 10^{-5})(3600)^{1.036}(70)(t)$$

$$t = 4.2 \text{ min}$$

Given some inherent uncertainty within the model as well as the limited precision and accuracy of the assumed and estimated values, the calculation was performed for varying concentrations of CO, as shown in Table 1.

TABLE 1—*Time to incapacitation given varying concentrations of CO.*

CO Concentration, ppm	Time to Incapacitation, min
2000	7.7
2400	6.4
3600	4.2
4200	3.6
5000	2.9

Conclusions

These results are consistent with the previous extremely broad estimate from the timeline provided in the FEMA report. The report does not indicate how long the fire fighters were in the dwelling, but suggests that they were on the scene for about 40 min before being reported missing or down. Our analysis based on the fire modeling results and other data provides significantly more information regarding how long incapacitation required following air supply exhaustion.

While an increasingly reliable investigative tool, the success of computer-generated fire models depends largely on the expertise of the user and poorly or improperly modeled fires can produce misleading results. Models only incompletely represent a component, system, or process and therefore may be led astray by uncertainties in variables on which they are based (14). Fire models also rely upon the knowledge of the fire phenomenon being modeled. The single most important variables (and those that, if inaccurate, may produce misleading model results) are the heat release rate and duration of the initial design fire placed into the model.

Furthermore, even when used by the most experienced engineers, fires are exceptionally difficult to replicate and predict. Inherent mathematical uncertainties exist within the model, and while these have been evaluated using actual tests and shown to be minimal, computer-generated models remain a less reliable form of evidence than physically observed data. Often, arriving at a satisfactorily modeled fire involves several attempts and revisions in order to produce a model that fits well with witnessed accounts and observed physical data. Nonetheless, this example does demonstrate the potential for fire investigators and engineers to work together to improve fire death investigation by using computer fire-modeling programs.

While this is still a relatively novel tool, the potential for success with the application of FDS and other fire models to fire death investigations will likely increase as more engineers become proficient at using fire-modeling techniques and modeling programs become increasingly accurate. In the case reported here, the quality of the original investigation was significantly enhanced by providing greater detail to the timeline and suggesting a more accurate assessment of how long the fire fighters were exposed to carbon monoxide.

References

1. McGrattan KB, Forney GP, Prasad K, Floyd JE, Hostikka S. Fire Dynamics Simulator (Version 3) user's guide. Gaithersburg: National Institute of Standards and Technology; 2002 Report No.: NISTIR 6784.
2. Purser DA. Toxicity assessment of combustion products. In: DiNenno PJ, Beyler CL, Custer RLP, Walton WD, Watts JM, Drysdale D, et al., editors. SFPE handbook of fire protection engineering. 2nd ed. Quincy: National Fire Protection Association, 1995;2.85–2.146.
3. World Health Organization. Carbon monoxide. Environmental health criteria 213. Geneva: World Health Organization, 1999.
4. Routley JG. Three fire fighters die in Pittsburgh house fire. Pittsburgh: Federal Emergency Management Agency; 1995 Report No.: 078 of the Major Fire Investigation Project.
5. Stewart RD, Peterson JE, Fisher TN, Hosko MJ, Baretta ED, Dodd HC, et al. Experimental human exposure to high concentrations of carbon monoxide. Arch Environ Hlth 1973;26:1–7.
6. McHardy GJR, Shirling D, Passmore R. Basic techniques in human metabolism and respiration. Oxford: Blackwell Scientific Publications, Ltd., 1967.
7. McGrattan KB, Baum HR, Tehm RG, Hamins A, Forney G. Fire dynamics simulator—technical reference guide. Gaithersburg: National Institute of Standards and Technology, 2000 Report No.: NISTIR 6467.
8. McGrattan KB, Baum HR, Rehm RG. Large eddy simulations of smoke movement. Fire Safety Journal 1998;30:161–78.
9. McGrattan KB, Hamins A, Stroup D. Sprinkler, smoke & heat vent, draft curtain interaction—large scale experiments and model development. Gaithersburg: National Institute of Standards and Technology, 1998 Report No.: NISTIR6196-1.
10. Madrzykowski D, Vettori RL. Simulation of the dynamics of the fire at 3146 Cherry Road NE, Washington D.C. on May 30, 1999. Gaithersburg: National Institute of Standards and Technology, 2000 Technical Report No.: NISTIR6510.
11. Madrzykowski D, Forney GP, Walton WD. Simulation of the dynamics of the fire in a two-story duplex, Iowa, December 22, 1999. Gaithersburg: National Institute of Standards and Technology, 2000 Technical Report No.: NISTIR6854.
12. Rehm RG. Pitts WM, Baum HR, Evans DD, Prasad K, McGrattan KB, et al. Initial model for fires at the World Trade Center Towers. Gaithersburg: National Institute of Standards and Technology, 2000 Technical Report No.: NISTIR6879.
13. Robertson JL, Stambaugh H. Fire at Watts Bar Hydroelectric Plant. Emmitsburg: Major Fires Investigation Project, U.S. Fire Administration, Federal Emergency Management Agency, 2003 Report No.: USFA-TR-147.
14. Mowrer FW. The right tool for the job. J Fire Protection Engineering 2002;13:39–44.

Additional information—reprints not available from author:
Angi M. Christensen
301 Taliwa Dr.
Knoxville, TN 37920