

PREDICTING SMOKE DETECTOR ACTIVATION USING THE FIRE DYNAMICS SIMULATOR

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ABSTRACT

This is a study into the ability of the Fire Dynamics Simulator - Version 1.0 (FDS 1.0) to predict smoke detector activation. FDS is a field computer model that has shown promise in the modeling of fire phenomena. Two methods were used to create a first order approximation of the ability of FDS to predict smoke detector activation. First, the fluid transport model of smoke within FDS was tested and compared with full scale UL217 test data. Second, a series of full-scale multi-compartment fire tests were conducted to provide a data set to further validate the results obtained from FDS. It was determined that FDS can predict smoke detector activation when used in conjunction with smoke detector lag correlations that correct for the time delay associated with smoke having to penetrate the detector housing.

INTRODUCTION

The fundamental equations that govern fluid dynamics, heat transfer, and combustion have been defined and improved upon for decades. However, the daunting task of adequately modeling fire growth and behavior has been hampered by the sheer mathematical complexity of the equations involved, the number of variables that need to be taken into account, and maybe most importantly the processing capabilities of computers. The technological revolution has provided engineers with desktop personal computers that, for the first time, may provide economically convenient methods of numerically modeling fire phenomena.

Recently, the emergence of computational fluid dynamics (CFD) fire modeling codes based on the RANS (Reynolds Averaged Navier-Stokes equations) has shown promising results when modeling fire induced flow. Exponential growth in computational clock speed has allowed the engineer with a desktop personal computer to define grids with hundreds of thousands of cells that bring approximation of fire phenomena to higher levels of accuracy.

Another emerging technology, and the most promising for capturing large-scale transient flow, is the development of the Large Eddy Simulation (LES) technique for fire modeling. The Fire Dynamics Simulator (FDS version 1.0) is the most widely used LES

model in the fire science field [1]. LES modeling assumes that turbulent motion can be separated into large eddies and small eddies. “The large eddies (grid-scale) motion is directly simulated and the small eddies (sub-grid scale) motion is modeled. [2]” FDS has demonstrated good agreement with experimental data in numerous validation studies.

The scope of this effort was to determine the ability of FDS to predict smoke detector activation. A two-step approach was used to determine a first order approximation of the smoke detection predictive capabilities of FDS. First, the smoke transport fluid model within FDS was tested against the repeatable smoke transport criteria that Underwriters Laboratories (UL) 217 (1985) dictates for non-fire retardant polystyrene foam. Second, FDS was used to model a series of full-scale multi-compartment fire tests that were instrumented with ionization smoke detectors, thermocouples, light extinction measurements, and other equipment.

UL 217 TEST

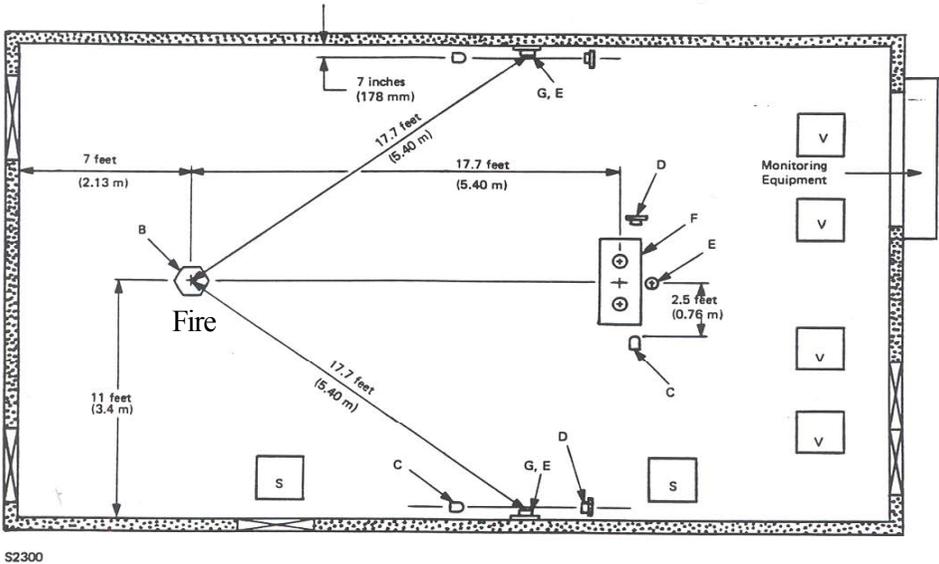
To determine if FDS had the ability to accurately model the fluid transport of the products of combustion, UL 217 was used as a test criterion. The 1985 edition of UL 217 (Single and Multiple Station Smoke Detectors) provides a rigid test setup that consists of a room with multiple locations for photocell assemblies and smoke detectors [3] (Figure 1). For the purpose of this phase of the study, the propagation of the smoke was of the most concern. UL 217 test D (Polystyrene Fire) was chosen as the test fire to be considered in this study.

To determine the input parameters within the FDS model, oxygen consumption calorimetry was used to find the exact heat release profile of the polystyrene test sample used in the UL 217 test D. This profile was determined by burning a prescribed sample of foam polystyrene type packing material with a density between 24-32 kg/m³ and no flame inhibitor, under a collection hood with oxygen sampling. It is known that approximately 13.1 kJ of heat is released per gram of oxygen consumed. By monitoring the reduction of oxygen present in the hood exhaust, a measure of the heat release profile for the foam was determined for the duration of the test.

$$\dot{Q}_{foam} = \dot{m}_{oxy} \cdot \Delta H_{c(oxy)} \quad (1)$$

The heat release profile was then mapped into FDS by using the RAMP function, which allows the user to define the percentage of the peak heat release at various time intervals, thus producing a heat release rate curve. The smoke production properties of non-flame retardant polystyrene foam were taken from existing literature [4].

Figure 1: UL217 Test Setup (Taken from UL 217 – 1985) [3]



A method of using FDS to accurately model smoke generation for small grid cells within the computational mesh was used. This technique involved defining a species, labeled ‘smoke’, with an initial mass fraction equal to zero and a molecular weight that was specified the same as air (29 g/mol). In the definition of the fire SURFACE line within the code, a species YIELD was defined that had the same properties found from the literature [4] for the percentage of smoke produced from a polystyrene foam fuel source.

In essence, this method treats smoke as one of the gases generated from the surface of the fire and allows for a better approximation of the smoke concentration within a given cell in the computational domain. On the contrary, the function that is built into FDS for tracking smoke movement (SMOKE_YIELD) assigns a fraction of smoke to each thermal particle that is released from the combustion zone. The presence of a thermal element within a cell determines how much smoke is present. For small cell sizes, there is a greater chance of there not being at least one of these elements present at a given time, which would lead FDS to assume that there is no smoke present at that moment. This creates very erratic results, which are uncharacteristic with real smoke movement. For a detector activation analysis an average smoke presence is desired, therefore tracking the smoke production as a species yield proves to be more accurate. This application of FDS is a technique that this study sought to validate.

UL 217 prescribes a rigid test scenario in which smoke must reach each of the sampling locations within the test room during a certain window of elapsed time. Furthermore, the test standard dictates the level of smoke obscuration at different times within the test at each location. The prescribed fire for the test is designed to provide this smoke profile. This kind of repeatable, well-documented test provided a solid set of data to compare

with the FDS model results. The following are the results of the FDS data compared to UL 217 stipulations:

Table 1: Comparison of FDS Predictions vs. UL 217 Requirements.

UL Smoke Profiles

Smoke buildup shall occur:	UL requires (s)	FDS (s)
Ceiling Detector	35-45	40
Sidewall Detector	25-35	34

33% obscuration per meter smoke shall occur:	UL requires (s)	FDS (s)
Ceiling Detector	70-90	74-97
Sidewall Detector	60-80	66-78

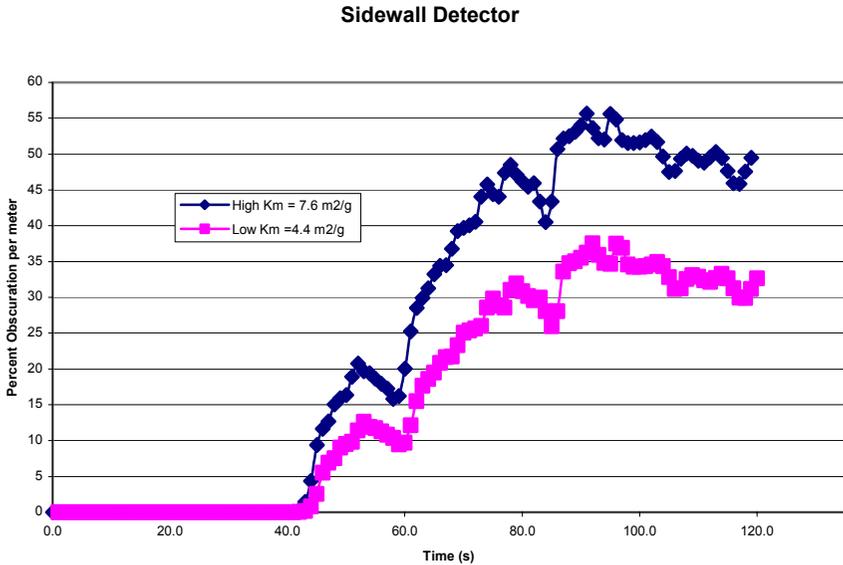
33 – 43% obscuration per meter smoke shall remain:	UL requires (s)	FDS
Ceiling Detector	90-120 (end)	yes

33 - 56% obscuration per meter smoke shall remain:	UL requires (s)	FDS
Sidewall Detector	80-120 (end)	yes

The FDS data demonstrates excellent agreement with the smoke profile requirements of UL 217. The range of times produced by FDS is directly correlated to the specific extinction coefficient (K_m) of the smoke produced. The specific extinction coefficient is a function of the size distribution and optical properties of smoke [5]. For smoke produced during flaming combustion of wood and plastics, the value of K_m has been found to equal approximately $7.6 \text{ m}^2/\text{g}$ [6]. For the smoldering production of smoke from these materials, K_m has been found to equal approximately $4.4 \text{ m}^2/\text{g}$ [6]. The burning of polystyrene foam in the configuration prescribed by UL 217 is a combustion process that involves both flaming and pyrolysis of the fuel. Because of this ‘dual’ combustion process, the exact K_m value for the smoke produced is really a function of time during the burning process.

Figure 2 is a graph of the range of values produced by FDS for the sidewall detector in the modeled UL 217 test. Bouguer’s law was used in conjunction with data obtained by FDS and the K_m values to determine the percent optical density per meter at each location. It is postulated that because the UL time requirements fall within the range of times produced by FDS using the K_m range mentioned above, this is an excellent validation of the fluid smoke transport model within FDS.

Figure 2: Graph of FDS Output for UL217 Test – Sidewall Detector



FULL SCALE TEST

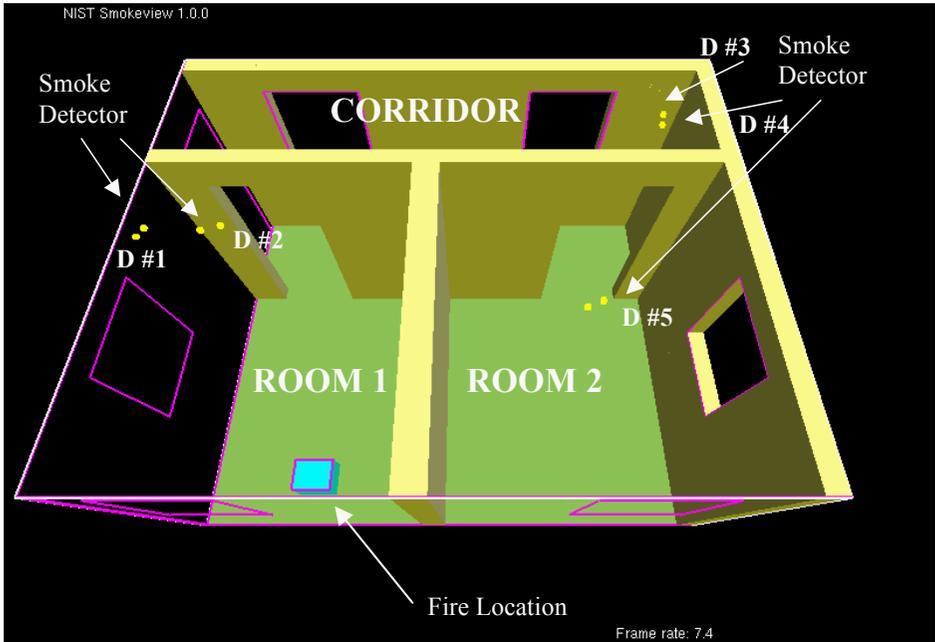
The second phase of the validation study was to test the ability of FDS to predict smoke detector activation in a full scale, multi-compartment test setup. To accomplish this, three full-scale tests consisting of hydrocarbon pool (75% heptane / 25% toluene) fires were conducted. The test geometry consisted of two 2.4 m × 2.4 m × 2.4 m compartments connected by a 4.9 m corridor with 2.4 m high ceiling. The doors to both rooms were open during the tests, but the entire test geometry (both rooms and the corridor) was sealed, except for a small amount of construction leakage. Every attempt was made to seal construction gaps and minimize this leakage to the outside.

The test fires were located near the back wall of room 1 (see Figure 3). For each test, a 15.25 cm diameter pan was filled with 75% heptane / 25% toluene by volume. The test pans were placed on scales that measured mass loss data in the event that a better heat release profile was needed for input into FDS. Coupling the known net heat of combustion for the two fuels with the mass loss data would provide this data. The test fires were ignited using a standard butane lighter.

For each test, a series of ionization smoke detectors were placed on the wall 6 cm down from the ceiling in room 1 and the corridors, and on the ceiling of rooms 1, 2, and the corridor (see Figure 3 for detector placement). At each location where the smoke detectors were placed, a laser-photo diode pair was installed to measure the optical smoke density. A data acquisition system was used for recording data at a rate of one measurement per second. Temperature, optical density, smoke detector voltage output, and mass loss data were gathered by a Kiethley® DAS-800 board with four EXP-800

expansion boards. Two cameras were also included in the test setup; one recorded the smoke layer at the ceiling of room 1 and the other recorded the smoke layer at the ceiling of room 2.

Figure 3: Multi-Compartment Test Setup



The input into FDS to model these tests consisted of the heptane/toluene effective heat release rate, heat of combustion, and smoke yield. This data is readily available in the literature for both of these fuels [4] (Table 1). The optical density and smoke velocity were sampled at each detector location within the FDS model, and were used in determining the predicted time to activation. Utilizing the previous outlined procedure for modeling smoke production, a two-step approach that coupled the model outputs of smoke velocity and optical density was used to determine detector activation.

Table 1: Soot Yields and Heats of Combustion of Experimental Fuels [4].

Fuel	Soot Yield (g/g)	ΔH_c (MJ/kg)
n-Heptane	0.037	48.07
Toluene	0.178	42.43

The first step was to determine when FDS predicted the optical smoke density to be at a threshold that was deemed critical for detector activation. From the UL 217 fire tests, this

range can be from approximately 23-56 percent obscuration per meter (% Obs/m). Because these tests involved a flaming fire (with no smolder), a K_m value of $7.6 \text{ m}^2/\text{g}$ was used in the analysis. This procedure was repeated for each detector within the model to determine the time required for the necessary concentration of smoke to travel to each location.

When this criterion was fulfilled, a smoke detector delay time associated with the time it takes for smoke to navigate and enter into the sensing chamber within the detector housing was factored into the calculation. This delay time is directly correlated to the velocity of the smoke when it reaches the smoke detector. Several studies have tried to quantify this detector lag time. Three different correlations for detector lag time (Brozovsky et. al [7] (2) & Cleary et. al [8] (3 + 4)) were compared in the analysis for two different critical optical densities (23% Obs/m, and 56% Obs/m). These correlations were chosen because they provide an analysis that is independent of a characteristic length scale that typically attempts to assess the physical construction of a particular detector. The Brozovsky et. al correlation is listed below:

$$\Delta t = \exp(-1527U^3 + 918.1U^2 - 187.7U + 14.84) \quad (2)$$

Where: Δt = Detector delay time
 U = Smoke velocity at detector location

For the two correlations extracted from a study conducted by Cleary et. al, a two-parameter model was used to describe the lag time of the detectors. Two correlations were presented for two different, unidentified, ionization smoke detectors. The first parameter is the dwell time, which is the time for the smoke to reach the sensing chamber. The second parameter is the mixing time in the sensing chamber. These two times are assumed to act in series (i.e. one after the other). Therefore the lag time of a detector is the sum of these two parameters. The two sets of correlations that were used for ionization type smoke detectors are listed below:

Ionization Detector Correlation #1 (3)

Dwell time = $2.5 U^{-0.71}$
Mixing time = $0.76 U^{-0.87}$

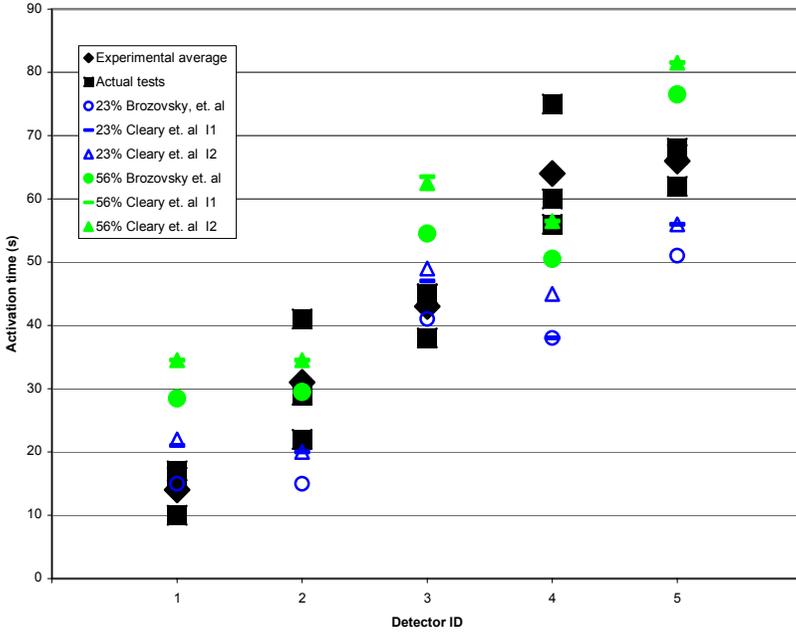
Ionization Detector Correlation #2 (4)

Dwell time = $1.8 U^{-1.10}$
Mixing time = $0.98 U^{-0.77}$

The final predicted detector activation time is equal to the transport time associated with the flow of smoke, at the specified concentration, to a specific detector in addition to the time delay associated with one of the detector lag correlations.

The results are presented in Figure 4. The data suggests that when using a detector lag correlation, FDS can be used to predict detector activation time.

Figure 4: FDS Predicted Detector Activation Time vs. Experimental Data



CONCLUSION

The UL 217 validation test confirmed that the fluid transport model within FDS operates very effectively given a well defined input fire. The data suggests that the importance of choosing an accurate specific extinction coefficient has a significant effect on the predicted level of smoke obscuration. It is important to note that the specific extinction coefficient is a function of the different stages of combustion, and therefore a more accurate method of modeling fire would be to incorporate an iterative calculation of K_m within the model.

The FDS model of the full-scale multi-compartment fire tests shows an encouraging agreement with the experimental data. From the existing data, it is apparent that the incorporation of a delay time is significant [7,8]. For detectors located far from the fire source, the optical density requirements necessary for detector activation may be satisfied, but the smoke velocity is so low that the delay time can be significant. FDS was able to predict the detector activation of these distant locations with reasonable accuracy when coupled with the detector lag correlations.

FUTURE WORK

There is currently an effort to model test data from experiments involving complex geometries and detector locations far from the fire source (i.e. full scale house burns). Test configurations of this nature yield smoke flow velocities at the most distant detectors that are slow enough to make the detector lag correlations more significant in a detector

activation analysis. There is also work being done to determine the grid dependency of boundary layer effects near the wall. This additional analysis is important because smoke detectors are typically placed on walls where viscous boundary layer effects could be significant.

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