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Distributed Sensor Fire Detection

1. Introduction

Most fire detection systems, even those with 100's of individual detectors reporting to a fire panel, are designed to alarm on a single detector, be it a single sensor or multi-sensor design. The stochastic nature of fire dictates that no single location for a detector is preferred. In current design, detectors are sited such that each detector "protects" a given fraction of the building space. While there may be some threshold alarm value adjustment if adjacent detectors start to sense fire conditions for particular designs, the concept of distributed sensor fire detection **has** been pursued no further. Distributed parameter systems, i.e., systems where the state vectors depend on spatial position, are frequently encountered in the field of process control and give rise to control theories dedicated to those systems. The fire detection problem is similar to control of distributed parameter systems in that both address a problem stated as: what are the number of measurements required and where are their locations to guarantee either early fire detection or stable control of the system? Also taking a cue from distributed parameter control where the distributed sensors need not be, and frequently are not, measuring the same state values (e.g., a mixture of temperature, concentration, pH, and pressure measurements, etc. for process control), different types of sensors distributed in space may afford an economical, optimized fire detection system. The concept put forth here is multi-sensor, multi-criteria detection with distributed sensing elements.

There are three conceivable reasons to integrate distributed sensing elements for fire detection. First, a sensor primarily used for another purpose may provide useful information related to early fire detection. An example might be a carbon dioxide sensor used for demand-controlled ventilation in a building, and located either in a return **air** duct common to several rooms, or in a single room. Second, cost may limit a particular sensor to either a single location or a limited number of locations; other types of sensors would be needed to fill in the gap in space coverage. Third, a particular sensor may not be suitable for a particular location due to naturally-high ambient levels it would sense there (i.e., a CO sensor located next to a parking garage). This paper details a case study that utilized model simulations to assess the relative performance benefits of distributed sensing over single-station, single-sensor smoke detection and co-located multi-sensor detection.

2. Fire Model Runs

This study utilized 500 individual CFAST fire simulations performed by Notarianni [1]. CFAST is a multi-room zone fire model developed at NIST [2]. The space configuration considered was a seven room arrangement representing a single-floor apartment (Figure 1).

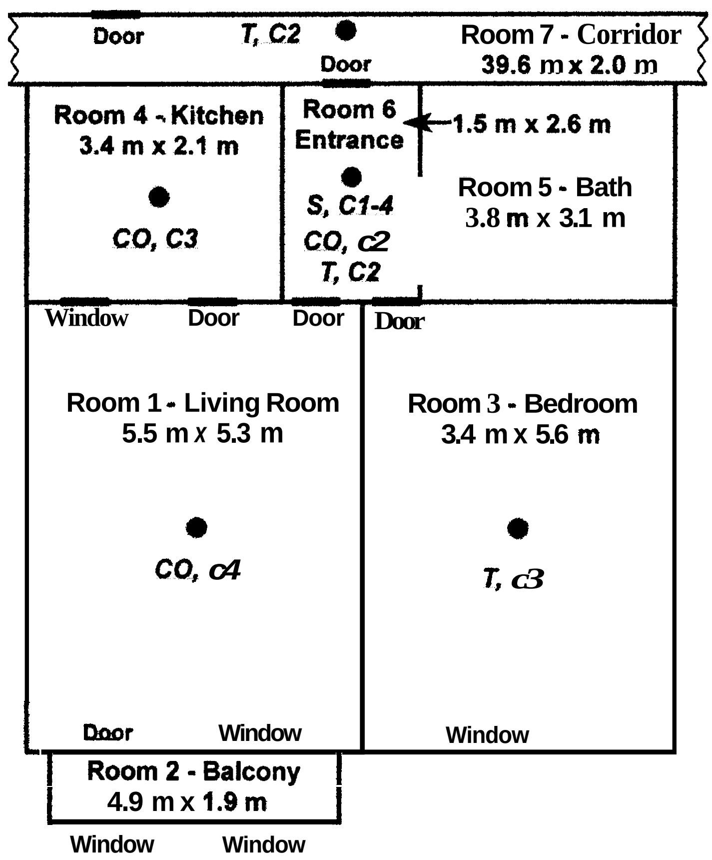

Figure 1. Schematic of apartment layout. The distribution of smoke (S), temperature (T), and carbon monoxide (CO) sensors are shown for the various cases (C#).

The 500 simulations encompassed a realistic distribution of potential fire scenarios. The set included a combination of scenarios that represent statistically, both the types of fires and the frequency at which they occur in a given occupancy type. Design fires were made up of fire events (heat release rate and location) and the characteristics of the material burning. Building geometry, properties of construction materials, and seasonal weather conditions, (outside ambient temperature) were used to **fix** initial and boundary conditions. Information about the uncertainty, variability, and correlational structure of the input parameters was used to define the fire scenarios. Fire growth rate inputs were one of the "t^2" fires: slow, medium, or fast. **A** "t^2" fire is a modeled fire where the heat release rate increases from zero **as** a function of time to the **2^{nd}** power. Standard pre-exponential values are defined **as** slow, medium, fast, etc. The fire location was moved to different rooms for different simulations. Model output included smoke concentration, **CO** concentration, and temperature in the upper layer **as** a function of time in each room. There are significant limitations in zone-model simulations with relation to detector response (instantaneous uniform mixing in the layers, no flow velocity information, etc.). Here it was assumed that the detector instantaneously sees the computed upper-layer value of smoke, CO, or temperature. Thus, the computed results were used **as** the sensor response for smoke, CO and temperature sensors. Given the model limitations and the assumption of instantaneous detector response, it was decided not to consider rate-of-rise of any of these computed values in the alarm rules. It is noted however that rate-of-change and other real sensor signal features contain a wealth of information that could be exploited in advanced pattern recognition algorithms developed for distributed sensor detection systems.

Figures 2-4 show the computed upper-layer values of smoke optical density, CO concentration and temperature **as** a function of time in each room for one simulated fire, a slow t^2 fire located in the bedroom.

3. Detection Rules and Sensor Distributions

Four sensor spatial configurations were examined along with **4** different rules governing the alarm state. Each sensor configuration and rule set constitutes a **CASE** for dentification purposes. The sensor configurations are shown in Figure 1. Configuration 1 is the base case of a single smoke detector in the entrance (room *6)* which represents the **minimum**

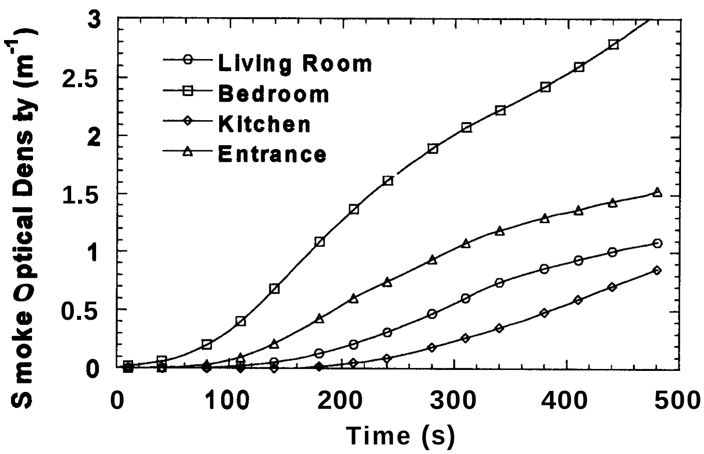

Figure 2. Smoke optical density for a slow t^2 fire located in the bedroom.

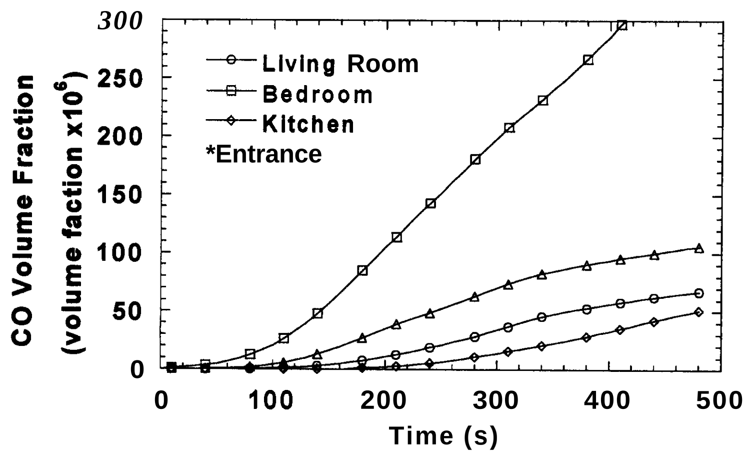

Figure 3. CO volume fraction for a slow t^2 fire located in the bedroom.

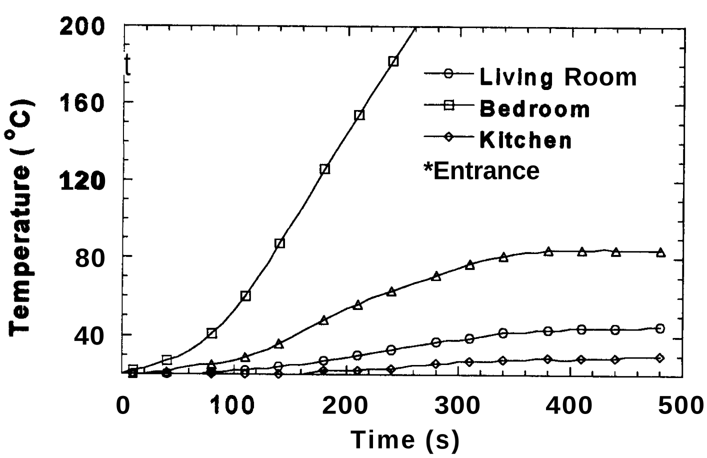

Figure 4. Upper-layer temperature for a slow t^2 fire located in the bedroom.

code requirements for existing residential dwellings. Configuration **2** is a detector consisting of three sensors: smoke, CO, and temperature, co-located in the same space, the entrance (and presumably in the same detector housing). Configuration **3** is a smoke detector in the entrance, a heat detector in the bedroom, and a CO detector in the kitchen. A detector in the bedroom is a logical addition based on **U.S.** code requirements for new construction. The CO sensor in the kitchen is logical if gas appliances (water heater, dryer, etc.) are located there. Configuration 4 moves the heat sensor to the corridor, and moves the CO sensor to the living room.

The four rules consist of fixed thresholds or threshold adjustments based on other sensor signals. They are:

Rule 1 - If smoke optical density > 0.06 m^{-1} (4 %/ft obscuration), then alarm is on

Rule 2 - If CO volume fraction > 1.0 x 10^{-5} and smoke optical density > 0.015 m^{-1} (1 %/ft obscuration), then alarm is on

Rule 3 - If $\Delta T > 5$ °C and smoke > 0.015 m^{-1}, then alarm **is** on

Rule 4 - IF $\Delta T > 15$ °C, then alarm **is** on.

AT is the temperature difference between initial ambient room temperature and the upper-layer temperature. At each time step the rules were checked to see if an alarm condition was indicated. If so, the time to alarm was noted along with the rule that yielded the alarm. The following Cases were examined:

CASE 1: Configuration 1 and Rule 1, (Base Case)

CASE **2:** Configuration **2** and Rules 1-4

CASE 3: Configuration 3 and Rules 1-4

CASE 4: Configuration 4 and Rules 1-4.

4. Results and Analysis

Figure **5** shows the alarm time versus simulation run for CASE 1. The mean alarm time was **88 s.** It is more illustrative to compare other CASES to their improvement from the CASE 1. Figures **6-8** show the difference between the base case alarm time and the alarm time for CASES **2, 3,** and 4 respectively. The mean alarm time for CASES **2, 3,** and 4 were 50 **s, 81 s,** and **67 s** respectively. The distributed sensor configuration with the temperature

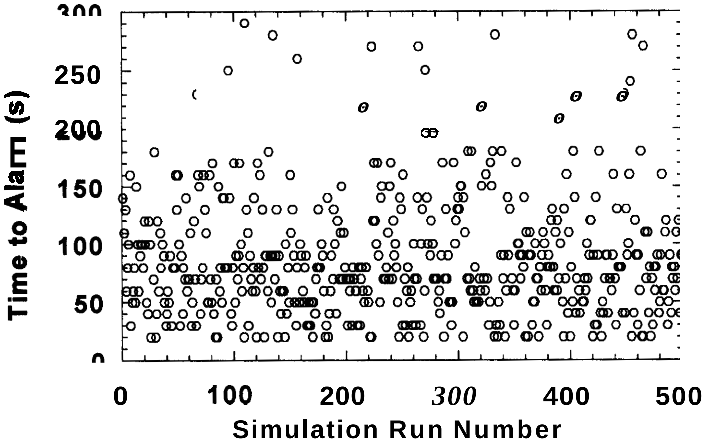

Figure 5. Time to alarm for CASE 1 (base case - a single smoke detector in the entrance).

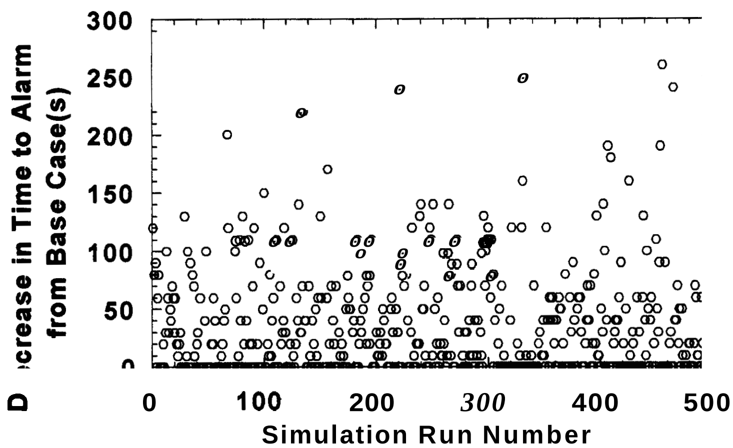

Figure 6. Decrease in time to alarm between CASE 2 (co-located smoke, CO, and temperature sensors in the entrance) and CASE 1 (base case).

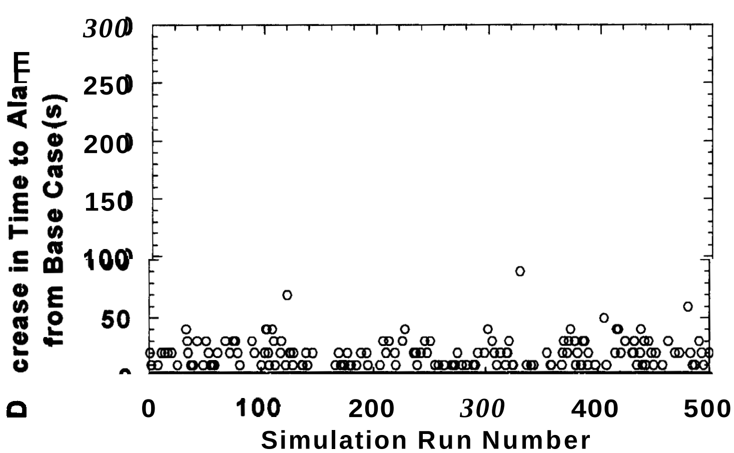

Figure 7. Decrease in time to alarm between CASE 3 (smoke, CO, and temperature sensors in entrance, kitchen, and bedroom respectively) and CASE 1 (base case).

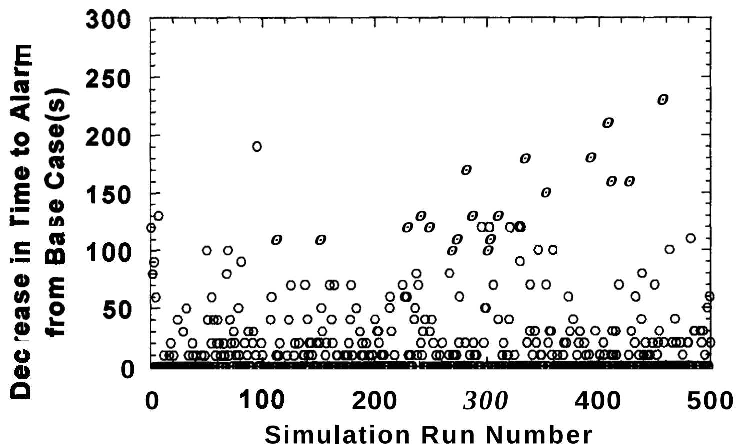

Figure **8.** Decrease in time to alarm between CASE 4 (smoke, CO, and temperature sensors in the entrance, living room, and corridor respectively) and CASE 1 (base case).

sensor located in the bedroom, (CASE **3)** performed only slightly better than the single smoke sensor CASE 1. The co-located sensor configuration, CASE **2,** performed the best, on average, over all simulations.

Figures 9-11 show the decrease in alarm time from the base case (CASE 1) versus the rule that yielded the alarm in each simulation for CASES **2,** 3 and 4 respectively. In Figure 9, notice that rule **2** ***(CO*** and smoke) was never first to yield an alarm in the co-located sensors configuration, and that significant reductions in alarm time were obtained with the temperature criterion (rule 4). Figures 10 and 11 show that rule **2** was first to yield an alarm a number of times in these distributed sensor configurations, though the decrease in time to alarm **was** less than 50 **s** for each time that rule **was** first.

The reason rule **2** was never the first to indicate alarm in Configuration **2,** co-located sensors, is due to the selection of the CO and smoke yields used in the simulations. Smoke was always present in sufficient quantity to invoke rule 1 prior to CO volume fraction reaching the threshold in rule **2.**

The preceding analysis considered only the reduction in alarm time for each fire scenario. **A** better metric would be to consider the life safety impact of the detection schemes. Here, a simple tenability criterion, a threshold upper-layer temperature in the room of (fire) origin, **was** used to compare the relative performance of the detection schemes. Two

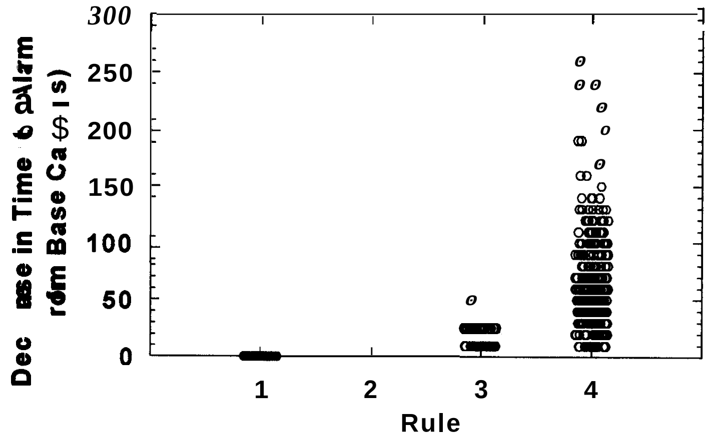

Figure **9.** Decrease in base case time to alarm versus the rule indicated for **CASE 2 -** the co-located sensors in the entrance.

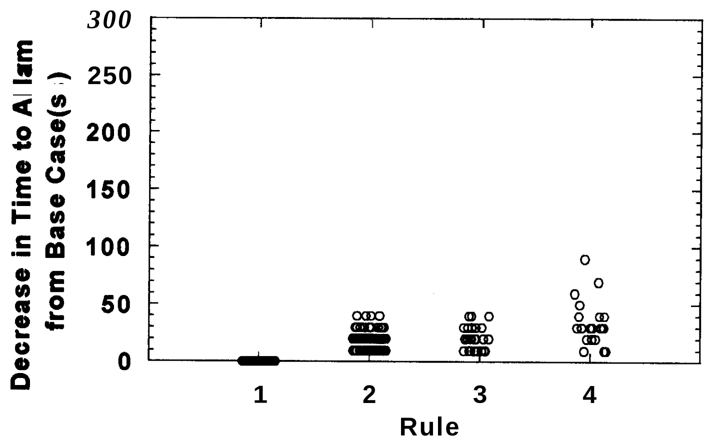

Figure 10. Decrease in base case time to alarm versus the rule indicated for **CASE** 3 - smoke, **CO,** and temperature sensors in the entrance, kitchen, and bedroom respectively.

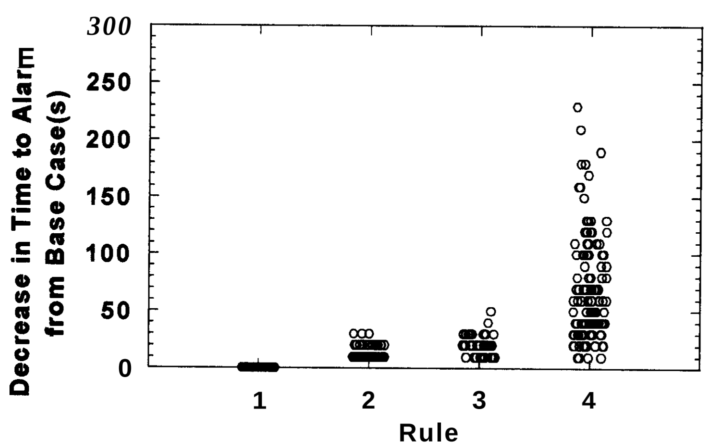

Figure 11. Decrease in base case time to alarm versus the rule indicated for **CASE 4 -** smoke, **CO** and temperature in the entrance, living room, and corridor respectively.

threshold upper-layer temperatures, **65** °C and **150** °C were specified **as** distinct limits indicating untenable conditions, with the lower value representing a more conservative criterion. A more complete hazard analysis would include multiple tenability criteria evaluated along egress paths.

Figures **12-15** show the difference between the time to reach the upper-layer threshold in the room of origin and the time to alarm for each simulation. A positive time difference represents the length of time after alarm but before a hazardous condition is reached in the room of origin, and conversely a negative time difference represents the length of time a hazardous condition exists in the room of origin before alarm. For both threshold temperatures all cases show positive and negative differences. The average difference over all simulation runs for each threshold and CASE is given in Table **1.**

Threshold Temperature Criterion (°C)	Average of $T_{untenability}$ - T_{alarm} (s)			
	CASE 1	CASE **2**	CASE **3**	CASE **4**
65	**-2**	**35**	**5**	**19**
150	**61**	**98**	**67**	**81**

Table **1.** Average difference between time to reach threshold temperature in the room of origin and the time to alarm for all simulations.

For the **65** °C threshold, the base case average time difference was less than zero, meaning on average the room of origin reached hazardous conditions before alarm. For a **150** °C threshold, the base case average time difference increased to over a minute. For both threshold temperatures CASE **2,** the co-located sensor configuration yielded the longest average time difference, **37 s** longer on average than the base case. The next best was CASE **4, 20 s** to **21 s** longer on average than the base case. The distributed sensor configuration CASE **3** performed only slightly better than the base case. Maximizing the average time to escape hazardous conditions would be a goal of an optimized sensor configuration. Another constraint would be to reduce or eliminate negative time differences and increase small positive time differences between hazardous conditions and time to alarm (i.e., maximize the number of fire scenarios where an alarm allows for adequate escape from the hazard).

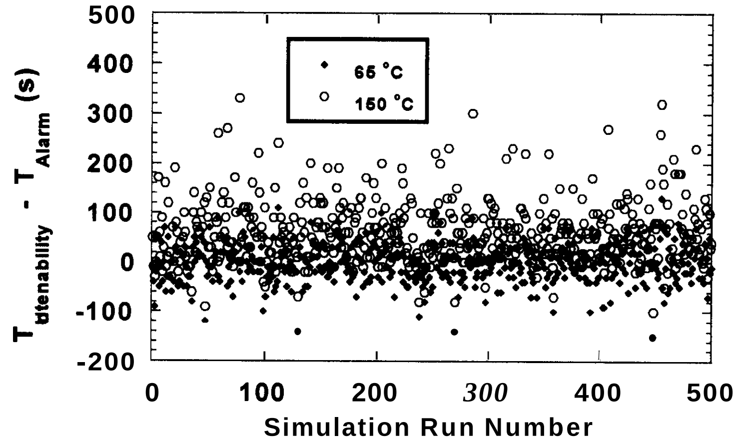

Figure **12.** The difference between the time to untenable temperature in the room of origin and the time to alarm for **CASE 1** (base case).

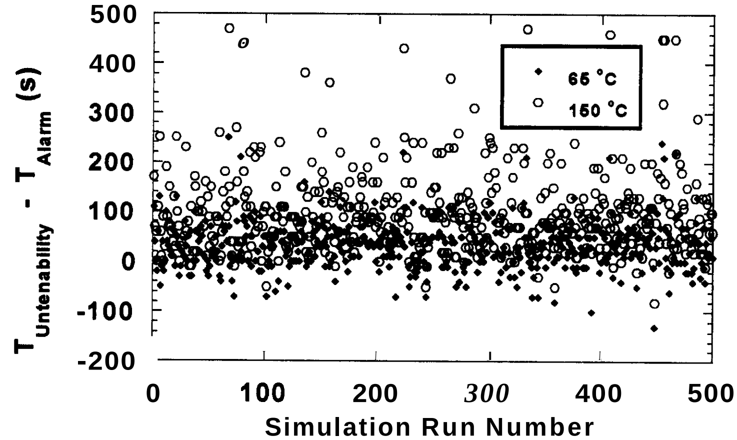

Figure **13.** The difference between the time to untenable temperature in the room of origin and the time to alarm for **CASE 2** (co-located sensors).

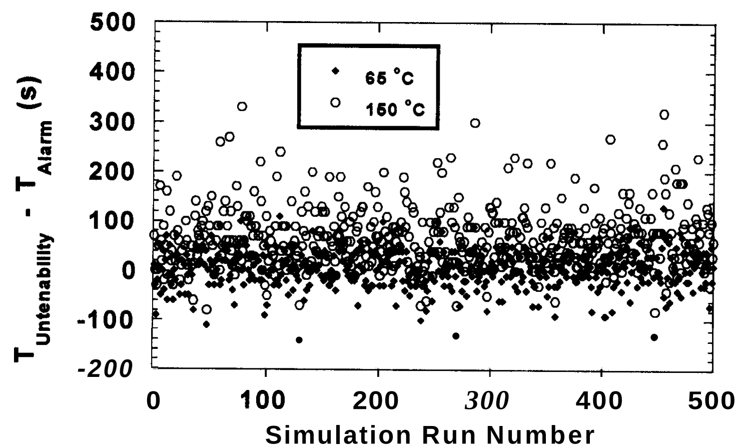

Figure **14.** The difference between the time to untenable temperature in the room of origin and the time to alarm for **CASE 3** (distributed sensors).

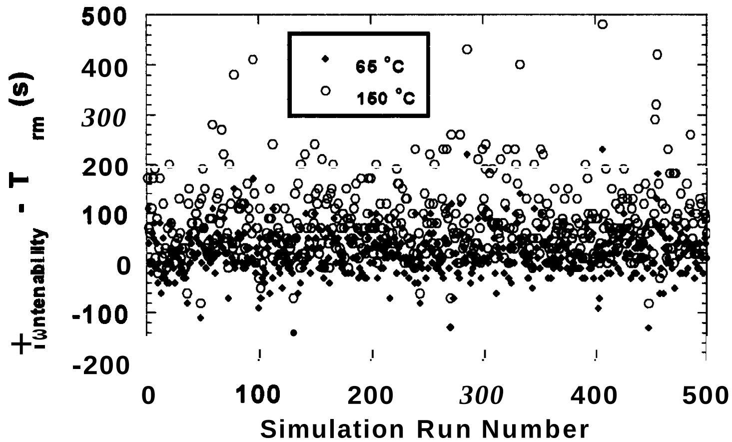

Figure 15. The difference between the time to untenable temperature in the room of origin and the time to alarm for **CASE 4** (distributed sensors).

While the distributed sensor configurations did not perform as well as the co-located sensors configuration, the results were still encouraging. The rule base was not optimized for the distributed sensor configuration, nor were all three sensor/room combinations tried. Also, this set of simulations was skewed toward rapidly growing fires compared to fire sensitivity test fires developed for detectors (even a "slow" t^2 fire reaches **29** kW in 100 **s).** Slower growing fires or smoldering fires would not have the rapid smoke and temperature rise associated with these simulated fires, and could produce higher CO yields. The fact that the apartment entrance was centrally located was particularly beneficial to the co-located sensor configuration.

5. Conclusions

From this modeling exercise and analysis, it is concluded the distributed sensing may improve time to alarm over single-station detectors, however, the location of sensors, their type, and the rules for processing multiple sensor signals need to be tailored for each specific application. More work is needed to develop simulation data that includes many more very slow growing fires with properties reflecting both smoldering and flaming conditions. Sensor environments obtained from simulations need to more closely follow actual temporal and spatial variations expected in real cases. With such **data** realistic sensor response models can be employed. Nuisance source simulation data is needed to assess the ability of sensor combinations and algorithms to reject nuisance alarms. **HVAC** flow needs to be included since it affects transport of combustion products. The most appropriate models need to be selected and tested to assess their ability to produce "good" simulation data sets. If this research evolves to point where a rich set of statistically valid fire and non-fire simulations can be generated for given building configurations and occupancies, such data could be exploited by using it to develop and train distributed-sensor, pattern recognition algorithms for early fire detection.

6. References

[1] Notarianni, **K.** A., "The Role of Uncertainty in Improving Fire Protection Regulation," Ph.D. Thesis, Carnegie Mellon University, Pittsburgh, PA, May, **2000.**

[2] Jones, **W. W.,** Forney, G.P., Peacock, R.D., and Reneke, P.A., "A Technical Reference for CFAST: An Engineering Tool for Estimating Fire and Smoke Transport," Tech. Note **1431,** National Institute of Standards and Technology, Gaithersburg, MD, January, **2000.**