COMMUNITY RISK ASSESSMENT MODELING: RESULTS OF RESIDENTIAL FIREGROUND FIELD EXPERIMENTS

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ABSTRACT

This paper presents an overview of a large multi-year, multi-partner research study on Firefighter Safety and Deployment of Resources as well as specific results from more than 60 laboratory and residential fireground experiments designed to quantify the effects of various fire department deployment configurations on the most common type of fire—a low hazard residential structure fire. The goal of the residential fireground field experiments is to provide an in-depth understanding of how different deployment factors affect time to fire department interventions. In the field experiments, fire crews performed a series of 22 key fireground tasks that were timed while the thermal and toxic environment inside the structure was measured. Report results quantify the effectiveness of crew size, first-due engine arrival time, and apparatus arrival stagger on the duration and time to completion of the 22 fireground tasks and the effect on occupant and firefighter safety. The overarching goal of the full project is to enable fire departments and city/county managers to make sound decisions regarding optimal resource allocation and service based upon scientifically-based assessment; safe, efficient and effective emergency response system design; and the local government's service commitment to the community.

INTRODUCTION

Service demands and public expectations placed upon local fire departments continue to rise as threats to communities from both natural and man-made disasters (including terrorism) reach new highs. Historically, the fire service has been based solely on those activities related to fire prevention and fire suppression; however, over the past three decades fire department response has expanded to include emergency medical services, terrorism response, hazardous materials response and mitigation, natural disasters, specialized rescue and other community risks. This expansion of responsibility has not always been matched with an adequate deployment of resources. Firefighters are often asked to do more with less rather than having the burden of work expected coordinated with the allocation of resources required.

The overall project objective is to produce a validated computer model for use by fire departments to assess and optimize resource allocation. The ability of the model to aid the end-users in decision making is predicated substantially on the capability of the model to produce technically defensible assessments of the risks inherent to the community under assessment, as well as produce an objective, intuitive assessments of policy changes under consideration for the community by the assessment team.

OVERVIEW OF COMMUNITY RISK ASSESSMENT MODELING PROJECT

Studies on firefighter safety and the adequate deployment of resources are needed to enable fire departments, cities, counties, and fire districts to design an acceptable level of resource deployment based upon community risks and service provision commitment. These studies should assist in strategic planning and the budgetary process involved in making good decisions locally. To meet this need, a research partnership of the Commission on Fire Accreditation International (CFAI), International Association of Fire Chiefs (IAFC), and International Association of Firefighters (IAFF), National Institute of Standards and Technology (NIST), and Worcester Polytechnic Institute (WPI) was formed to conduct a multiphase study of the deployment of resources as it affects firefighter and occupant safety. Starting in FY 2005, funding was provided through the Department of Homeland Security (DHS) / Federal Emergency Management Agency (FEMA) Grant Program Directorate for Assistance to Firefighters Grant Program—Fire Prevention and Safety Grants.

The research plan is split into three phases, each with multiple tasks and subtasks to be completed over multiple years. This introduction will provide background on the overall three year research plan. This introduction reviews the motivation for initiating the project, describes the project's vision and goals for each of the three phases.

Phase 1: Model and Survey Design and Development

Task A. Establish a network of partnerships and stakeholders

Three distinct partnership groups were established: the partnership council, the technical advisory team, and the stakeholder group.

- The project council described above meets at least quarterly to discuss the status of the project and any issues that have arisen in the course of the project. All decisions concerning the overall direction of the project are made by consensus of partners.
- The project technical advisory team consists of representative experts in disciplines germane to the project. Expertise in mechanics of firefighting and operations, public policy, statistics, modeling, and fire science is available to the project team
- Stakeholders are those people who play a role in the establishment, operation, and staffing of the fire service. Stakeholders meet with the project council regularly and are provided information to share with their respective or organizations.

Task B. Development of Community Risk Assessment Model Structure

Based upon extensive literature review, consultation with technical advisors and stakeholders, in-situ fire department immersion by principal investigators, and peer review, the theoretical structure of the model was developed in Year 1. The model encompasses 11 primary concepts of community risk. Each of these concepts have multiple dimensions for evaluation and measurement. The 11 principal concepts are categorized into five boundary concepts (hazards present in the community to which the fire department must respond), five decision concepts (resources the fire department employs to mitigate the hazards), and a measure of community risk (the unmitigated residual).

Three objective variables were selected to reflect the primary measurable concept which corresponds to the actual risks observed in the community under consideration: (1) number of first responder injuries and deaths; (2) number of civilian injuries and deaths; and (3) total economic consequences to community. Optimization of the levels of the three dependent variables will be conducted by the community assessor rather than a priori within the model in order to reflect the fact that priorities of economic and life safety concepts may be variable across otherwise similar communities.

The study will collect the data which will form the foundation of the model. There are two principal components of data collection: fire department survey and time-to-task field experiments. While the fire department experience survey will form the principal basis for the computational model, the field experiments will ensure a controlled, in-depth understanding of fire department response which would not be possible using survey statistics alone.

Task C. Fire Department Experience Survey: Methods and Design

The fire department experience survey will populate the regression database. With the assistance of the IAFF and the IAFC, more than 400 fire departments were invited to participate in the study. The sample of participating departments was stratified on five concepts (response, special hazards, pre-plans, emergency responders, and apparatus and equipment). Stratification will ensure sufficient variation to produce reliable statistical estimates from the subsequent regression analysis. A priori estimates for these stratification concepts should be apparent by reviewing standard operating procedures (SOP) or community characteristics for a candidate department. Finally, once stratified, participating departments will be randomly selected from a larger sample of willing departments to ensure adequate representation. Once a fire department is participating in the full-scale collection, every (actual emergency) response will be inputted to the database, independent of whether the outcome is positive or negative. A trained fire department representative will log into the project database (http://www.fddata.org) and key in the appropriate responses.

Phase 2: Data Collection

Task A. Field Experiments

The field experiments will ensure repeatable, reliable conclusions for components of the model at a level of detail not achievable in the fire department experience survey. For example, time to put water on a fire, a critical component of predicting community risk, is not readily measured by most fire departments given the hazardous and taxing nature of the task. Documenting (and controlling for) the myriad of events which can impede fire ground operations is difficult for a responder tasked with other important duties. This study will use conduct a parametric study of factors which influence time to intervention, including crew size (2, 3, 4 and 5 person companies) with early and late arrival time and close and far stagger as well as replicates to assess uncertainty. EMS field experiments, with two response scenarios (trauma and cardiac) and 15 crew compositions, will also be conducted to assess EMS intervention times.

Task B. Data Analysis

Once the data collection is complete, standard statistical software packages, such as SPSS, will perform the multiple regression analysis. The model may then be simplified to eliminate variables which have little or no explanatory power. This will ease the input burden on end-users and increase the ability to understand the implications for public policy decision making. In Year 3 (future work), the final version of the model, along with all of the regression equations, will then be provided to Emergency Reporting, Inc. for programming into a user-friendly, GUI-driven software package, suitable for widespread usage. The third and final technical component of this project will be to verify and validate the model.

RESIDENTIAL FIREGROUND EXPERIMENTS

The following research questions guided the experimental design of the low-hazard residential fireground experiments documented in this report:

1) How do crew size and stagger affect overall start-to-completion response timing?
2) How do crew size and stagger affect the timings of task initiation, task duration, and task completion for each of the 22 critical fireground tasks?
3) How does crew size affect elapsed times to achieve three critical events that are known to change fire behavior or tenability within the structure
   a) Entry into structure?
   b) Water on fire?
   c) Ventilation through windows
4) How does the elapsed time to achieve the national standard of assembling 15 firefighters at the scene vary between crew sizes of four and five?

Research Plan for Residential Fireground Experiments

The research was divided into four distinct, yet interconnected parts:

Part 1—Laboratory experiments to design the fuel load for field experiments. The purpose the laboratory experiments, was to characterize the burning behavior of the wood pallets as a function of:

- number of pallets and the subsequent peak heat release rate
- compartment effects on burning of wood pallets
- effect of window ventilation on the fire
- effect on fire growth rate of the loading configuration of wood excelsior (slender wood shavings typically used as packing material)

Based on the results of the laboratory experiments, the fuel load was sized appropriately such that no risk of flashover of backdraft would be present for fire fighter participants in the field experiments to follow.

Part 2—Field Experiments to measure the time for various crew sizes and apparatus on-scene arrival stagger to accomplish key tasks in rescuing occupants, extinguishing a fire, and protecting property. For each experiment, three engines, a ladder-truck and a battalion chief and an aide were dispatched to the scene of the residential structure fire. The crew sizes studied included two-,three-, four-, and five-person crews assigned to each engine and truck dispatched. Resultant on-scene staffing totals for each experiment follow: (FF = firefighter)

- Two Person crews = 8 FFs + Chief and Aide = 10 total on-scene
- Three Person crews = 12 FFs + Chief and Aide= 14 total on-scene
- Four Person crews = 16 FFs + Chief and Aide = 18 total on-scene
- Five Person crews = 20 FFs + Chief and Aide = 22 total on-scene

Part 3—Room and contents experiments with enhanced fuel load that prohibited firefighter entry into the burn prop and allowed for measurements of conditions within the building as a function of time.

Part 4—Fire modeling to correlate time-to-task completion by crew size and stagger to the increase in toxicity of the atmosphere in the burn prop for a range of fire growth rates.

Literature Review

Studies documenting engine and ladder crew performance in diverse simulated environments as well as actual responses show a basic relationship between apparatus staffing levels and a range of important performance variables and outcome measurements such as mean on-scene time, time-to-task completion, incidence of injury among fire service personnel, and costs incurred as a result of on-scene injuries[1-6]. Numerous studies of local departments have supported this conclusion using a diverse collection of data, including a report by the National Fire Academy (NFA) on fire department staffing in smaller communities, which showed that a company crew staffed with four firefighters could perform rescue of potential victims approximately 80 % faster than a crew staffed with three firefighters[3].

During the same time period that the impact of staffing levels on fire operations was gaining attention, investigators began to question whether staffing levels could also be associated with the risk of firefighter injuries and the cost incurred as a result of such injuries at the fire scene. One early analysis by the Seattle Fire Department for that city's Executive Board reviewed the average severity of injuries suffered by three-, four-, and five-person engine companies, with the finding that "the rate of firefighter injuries expressed as total hours of disability per hours of fireground exposure were 54 % greater for engine companies staffed with 3 personnel when compared to those staffed with 4 firefighters, while companies staffed with 5 personnel had an injury rate that was only one-third that associated with four-person companies"[1].

Two separate studies of local fire department performance, one from Taoyuan County in Taiwan and another from the London Fire Brigade, have drawn ties between fire crews'staffing levels and total water demand as the consequence of both response time and fire severity. Field data from Taoyuan County for cases of fire in commercial, business, hospital, and educational properties showed that the type of land use as well as response time had a significant impact on the water volume necessary for fire suppression, with the notable quantitative finding that the water supply required on-scene doubled when the fire department response increased by ten minutes[7]. Time as a predictor of residential fire outcomes has received less study than the effect of crew size. A Rand Institute study demonstrated a relationship between the distance the responding companies traveled and the physical property damage. This study showed that the fire severity increased with response distance, and therefore the magnitude of loss increased proportionally[8]. Using records from 307 fires in nonresidential buildings over a three-year period, investigators in the United Kingdom correspondingly found response time to have a significant impact on final fire area, which in turn was proportional to total water demand[9].

In light of the existing literature, there remain unanswered questions about the relationships between fire service resource deployment levels and associated risks. For the first time this study investigates the effect of varying crew size, first apparatus arrival time, and response time on firefighter safety, overall task completion and interior residential tenability using realistic residential fires. This study is also unique because of the array of stakeholders and the caliber of technical advisors involved.

Additionally, the structure used in the field experiments included customized instrumentation for the experiments; all related industry standards were followed; robust research methods were used; and the results and conclusions will directly inform the *NFPA 1710* Technical Committee, as well as public officials and fire chiefs.

Study Limitations

1) The scope of this study is limited to understanding the relative influence of deployment variables to low-hazard, residential structure fires, similar in magnitude to the hazards described in *NFPA 1710.*
2) Every attempt was made to ensure the highest possible degree of realism in the experiments while complying with the requirements of *NFPA 1403*, but the dynamic environment on the fireground cannot be fully reproduced in a controlled experiment.
3) The number of responding apparatus for each fireground response was held constant (three engines, one truck, plus the battalion chief and aide) for all crew size configurations.
4) The fire crews who participated in the experiments typically operate using three-person and four-person staffing. Therefore, the effectiveness of the two-person and five-person operations may have been influenced by a lack of experience in operating at those staffing levels. Standardizing assigned tasks on the fireground was intended to minimize the impact of this factor.
5) The design of the experiments controlled for variance in performance of the incident commander. In other words, a more-or less-effective incident commander may have a significant influence on the outcome of a residential structure fire.
6) Although efforts were made to minimize the effect of learning across experiments, some participants took part in more than one experiment, and others did not.
7) All experiments were conducted during the daylight hours.
8) Fire spread beyond the room of origin was not considered in the room and contents tests or in the fire modeling. Therefore, the size of the fire and the risk to the firefighter may be somewhat underestimated for fast-growing fires or slower-response configurations.

Fire Department Operations - Tasks

Twenty-two fireground tasks were completed in each experiment. Meticulous procedures gathered data to measure key areas of focus, such as individual task start times, task completion times, and overall scenario performance times. Each task was assigned a standardized start and end marker, such as crossing the threshold to enter the building with a hose line or touching a ladder to raise it to a second story window. Several control measures were used to collect data, including crew cue cards, radio communications, task timers, and video recording. The 22 tasks, with the events for measuring start and stop times, are shown in the table below.

Table 1: Twenty-two fireground tasks measured in field experiments

Task:
Conduct size-up
Position attack line
Establish 2 in - 2 out
Establish RIT
Gain forced entry
Advance line
Advance line
Advance backup line to door
Advance backup line to stairwell
Advance backup line 2
Conduct primary search 1
Ground ladders in place
Horizontal ventilation, second story, window 3
Horizontal ventilation, second story, window 2
Horizontal ventilation, second story, window 1
Horizontal ventilation, first story, window 2
Control utilities interior
Control utilities exterior
Conduct secondary search
Check for fire extension walls
Check for fire extension ceiling

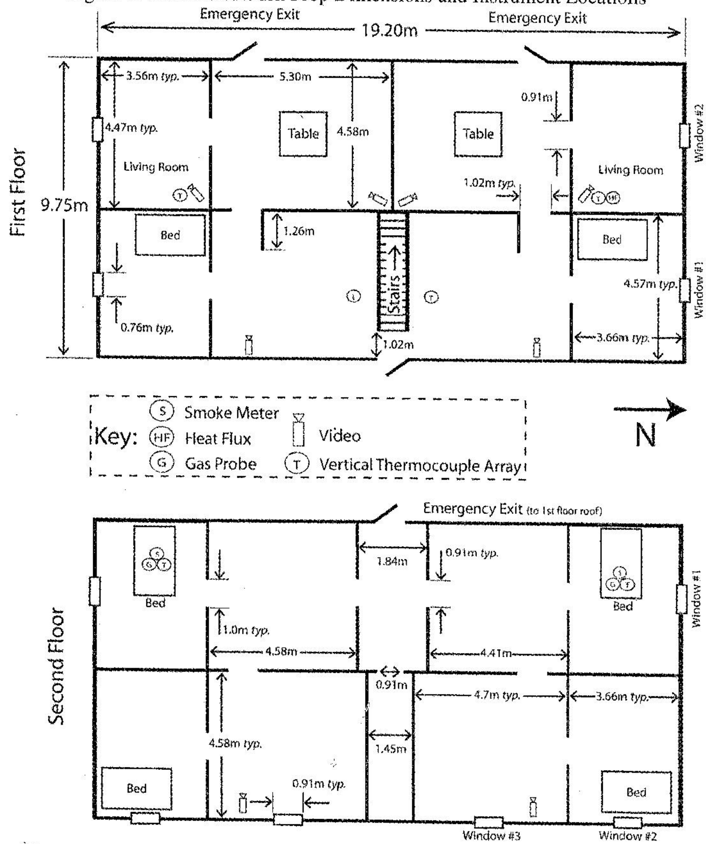
Experimental Layout

The fireground field experiments were conducted in a residential-scale burn prop constructed as a two-story duplex with a common stairwell. Symmetric construction of each unit allowed for multiple tests daily. Each two-story unit totaled 2,000 ft^2 (186 m^2), without a basement —each therefore a typical model of a low-hazard* single-family residence identified in *NFPA 1710*. Instrumentation to

*A low-hazard occupancy is defined in the NFPA Handbook as a one-, two-, or three-family dwelling and some small businesses. Medium hazards occupancies include apartments, offices, mercantile and industrial occupancies not normally requiring extensive rescue or firefighting forces. High-hazard occupancies include schools, hospitals, nursing homes, explosive plants, refineries, high-rise buildings, and other highlife hazard or large fire potential occupancies.

measure gas temperature, gas concentrations, heat flux, visual obscuration, video, and time during the experiments was installed throughout the burn prop. Figure 1 shows the building dimensions and the approximate location of instruments and non-combustible furniture fashioned to represent obstacles of realistic size and location for firefighters navigating the interior of the structure.

Figure 1: Residential Burn Prop Dimensions and Instrument Locations



Test Procedure

The field experiments consisted of two parts (the second and third parts of the four described in the research plan). In the first of the two parts, firefighter participants simulated an initial alarm assignment response to the burn prop. For each experiment, the fire source designed in part one of the research plan was ignited in the living room in one of the units. Trained timing staff recorded the start and completion times of 22 tasks deemed essential for mitigation of a residential fire incident by the study's technical experts. The staffing level of fire apparatus was varied incrementally from two to five personnel per piece. The interval between apparatus on-scene arrival times was varied at either 60 s or 120 s. This resulted in eight different configurations of deployments. With each experiment replicated three times, 24 total experiments were conducted in total.

Although the fire source in part two of the research plan created a realistic amount of heat and smoke for a fire incident simulation, the requirements of *NFPA 1403* prevented use of a fire source which could potentially reach flashover or backdraft condition with fire fighters inside the structure. Part 3 of the fire experiments was conducted in order to change the fuel package to be representative of realistic fuel loading that could be found in a living room in a residential structure (upholstered furniture, etc). This larger fuel package was used to focus on seven ventilation or suppression related tasks that could change the interior environment and affect tenability conditions (listed in chronological order): 1.) Forced entry of the front door, 2.) Water on fire, 3.) 2nd floor window #1 ventilated, 4.) 2nd floor window #2 ventilated, 5.) 2nd floor window #3 ventilated, 6.) 1st floor window #1 ventilated, 7.) 1st floor window #2 ventilated. The times that these seven tasks were performed were derived from the averages of times recorded in the first part of the field experiments. Ventilation was performed exterior to the structure and suppression was performed with a remotely controlled hose stream in order to comply with *NFPA 1403.*

In order to maximize repeatability, nominally identical sets of furniture (manufacturer, style, and age) were used for each test. 16 full sets of furniture were available, so eight experiment scenarios were conducted — each with a replicate. The time to untenable conditions was a primary variable of interest in the room and contents fires, so the arrival time of the first due engine was a paramount consideration. Because the effects of the subsequent apparatus stagger were explored in the time-to-task tests, the stagger was fixed at the "close arrival" time. Additionally, a baseline measurement was required to compare the effectiveness of fire department response to the absence of a fire department response. Therefore, a five-person, later arrival combination was eliminated in favor of a no-response scenario (with replicate).The first due engine arrival times were determined using the following assumptions: ignition of the fire occurs at time zero. Smoke detector activation and a call to 9-1-1 occurs at 60 seconds after the fire starts. Call intake and processing requires an additional 90 seconds. The firefighters take 60 seconds to complete their turnout at the station and begin travel to the scene. Thus travel time begins 3.5 minutes into experiment. The two levels of arrival time are then determined by two different travel times: early arrival assumes a three-minute travel time, while later arrival assumes a five-minute travel time. For all scenarios in the room and contents experiments, the close stagger (60 seconds) between subsequent apparatus times was used.

Part four of the research plan used the NIST Fire Dynamics Simulator (FDS) to correlate response times to the tenability inside the structure. In order to calibrate the computer fire model, simulations were performed to replicate the experimental results observed in the room-and-contents fires. Model inputs include building geometry and material properties, ventilation paths (doors, windows, leakage paths), and heat release rate of the fuel package. Three fire growth rates were used to assess the effectiveness of different fire department deployment configurations in response to fires that were similar to, faster growing, and slower growing than the fires observed in the room-and-contents fires. The slow, medium, and fast fire growth rates are defined by the Society of Fire Protection Engineers according to the time at which they reach 1 megawatt (MW). The fire models used the average suppression and ventilation timings obtained from the time-to-task experiments under specific deployment configurations as inputs to the model. The resulting "computational" fire is repeatable, and therefore, any differences in occupant exposure to toxic gases will be due to the intervention times associated with a specific deployment configuration rather than the random variation that naturally occurs from fire to fire.

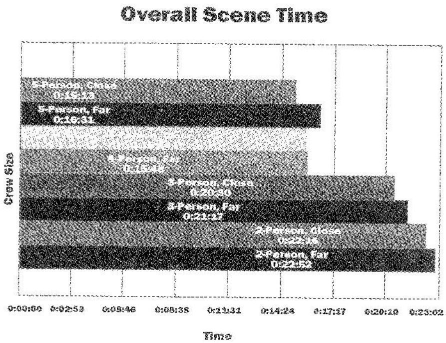
RESULTS

Of the 22 fireground tasks measured during the experiments, results indicated that the following factors had the most significant impact on the success of fire fighting operations. All differential outcomes described below are statistically significant at the 95 % confidence level or better.

Overall Scene Time

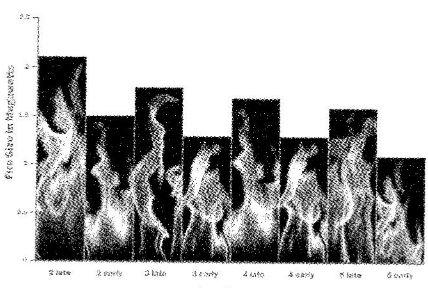
Figure 2 shows that the four-person crews operating on a low-hazard structure fire completed all the tasks on the fireground (on average) seven minutes faster—nearly 30 %—than the two-person crews. The four-person crews completed the same number of fireground tasks (on average) 5.1 minutes faster—nearly 25 %—than the three-person crews. On the low-hazard residential structure fire, adding a fifth person to the crews did not decrease overall fireground task times. However, it should be noted that the benefit of five-person crews has been documented in other evaluations to be significant for medium- and high-hazard structures, particularly in urban settings, and is recognized in industry standards.

Figure 2: Overall Scene Time



Time to Water on Fire

Figure 3: Size of Fire at Time of Suppression

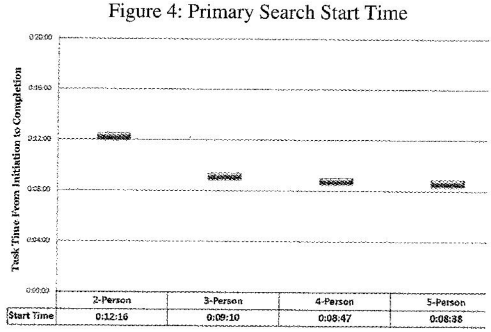


There was a 10% difference in the "water on fire" time between the two- and three-person crews. There was an additional 6% difference in the "water on fire" time between the three- and four-person crews. (i.e., four-person crews put water on the fire 16% faster than two person crews). There was an additional 6% difference in the "water on fire" time between the four- and five-person crews (i.e. five-person crews put water on the fire 22% faster than two-person crews). Figure 3 shows the estimated fire size (determined from fire modeling) at the time of water application.

Primary Search

As seen in Figure 4, three-person crews started and completed a primary search and rescue 25 % faster than the two-person crews. The four- and five-person crews started and completed a primary search 6 % faster than the three-person crews and 30 % faster than the two-person crew. A 10 % difference was equivalent to just over one minute.

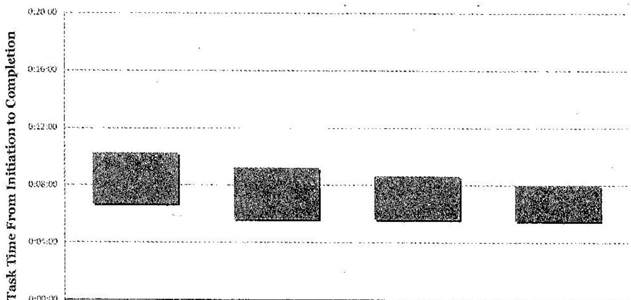
Figure 4: Primary Search Start Time



Hose Stretch Time

In comparing four-and five-person crews to two-and three-person crews collectively, the time difference to stretch a line was 76 seconds. Figure 5 shows the performance of each deployment type. In conducting more specific analysis comparing all crew sizes to the two-person crews the differences are more distinct. Two-person crews took 57 seconds longer than three-person crews to stretch a line. Two-person crews took 87 seconds longer than four-person crews to complete the same tasks. Finally, the most notable comparison was between two-person crews and five-person crews—more than 2 minutes (122 seconds) difference in task completion time.

Figure 5: Advance Attack Line Time

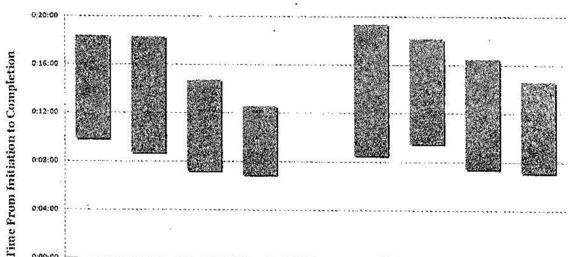


	2-Person	3-Person	4-Person	5-Person
End Time	0:10:16	0:09:15	0:08:41	0:08:01
Duration	0:03:34	0:03:36	0:03:02	0:02:29
Start Time	0:06:43	0:05:39	0:05:39	0:05:33

Ground Ladders and Ventilation

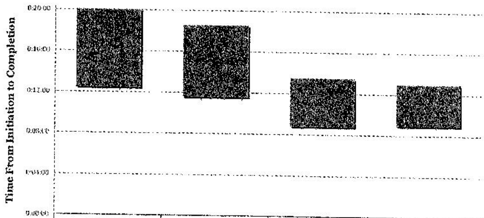
Figures 6 and 7 show deployment configuration performance for laddering and ventilation. The four-person crews operating on a low-hazard structure fire completed laddering and ventilation (for life safety and rescue) 30 % faster than the two-person crews and 25 % faster than the three-person crews.

Figure 6: Laddering Time



	2-Person Close	3-Person Close	4-Person Close	5-Person Close		2-Person Far	3-Person Far	4-Person Far	5-Person Far
End Time	0:18:24	0:18:19	0:14:45	0:12:34		0:19:23	0:18:12	0:16:29	0:14:38
Duration	0:08:31	0:09:35	0:07:31	0:05:40		0:10:51	0:08:40	0:09:03	0:07:31
Start Time	0:09:54	0:08:44	0:07:14	0:06:54		0:08:31	0:09:32	0:07:26	0:07:07

Figure 7: Venting Time

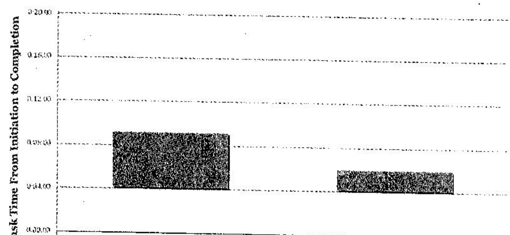


	2-Person	3-Person	4-Person	5-Person
End Time	0:20:02	0:18:33	0:13:30	0:12:59
Duration	0:07:36	0:07:01	0:04:42	0:04:04
Start Time	0:12:26	0:11:32	0:08:48	0:08:55

Industry Standard Achieved

As defined by NFPA 1710, the "industry standard achieved" time started from the first engine arrival at the hydrant and ended when 15 firefighters were assembled on scene. An effective response force was assembled by the five-person crews three minutes faster than the four-person crews, as shown in Figure 8. Based on the study protocols, modeled after a typical fire department apparatus deployment strategy, the total number of firefighters on scene in the two- and three-person crew scenarios never equaled 15 and therefore the two- and three-person crews were unable to assemble enough personnel to meet this standard.

Figure 8: Effective Response Force Assembly Time

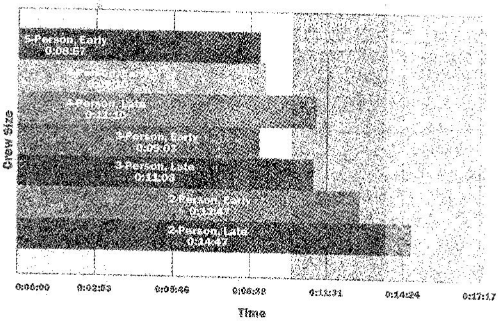


	4-Person	5-Person
End Time	0:09:10	0:05:57
Duration	0:05:02	0:01:48
Start Time	0:04:09	0:04:09

Occupant Rescue

Three different "standard" fires were simulated using the Fire Dynamics Simulator (FDS) model. Characterized in the *Handbook of the Society of Fire Protection Engineers* as slow-, medium-, and fast-growth rate, the fires grew exponentially with time. The rescue scenario was based on a non-ambulatory occupant in an upstairs bedroom with the bedroom door open. Independent of fire size, there was a significant difference between the toxicity, expressed as fractional effective dose (FED), for occupants at the time of rescue depending on arrival times for all crew sizes. Occupants rescued by early-arriving crews had less exposure to combustion products than

Figure 9: Toxic Dose at Rescue for a Medium Fire Growth Rate



occupants rescued by late-arriving crews. Figure 9 summarizes the fire modeling results for a medium growth rate fire. The fire modeling showed clearly that two-person crews cannot complete essential fireground tasks in time to rescue occupants without subjecting them to an increasingly toxic atmosphere. For a slow-growth rate fire with two-person crews, the FED was approaching the level at which sensitive populations, such as children and the elderly are threatened. For a medium-growth rate fire with two-person crews, the FED was far above that threshold and approached the level affecting the general population. For a fast-growth rate fire with two-person crews, the FED was well above the median level at which 50%of the general population would be incapacitated. Larger crews responding to slow-growth rate fires can rescue most occupants prior to incapacitation along with early-arriving larger crews responding to medium-growth rate fires. The result for late-arriving (two minutes later than early-arriving) larger crews may result in a threat to sensitive populations for medium-growth rate fires. Statistical averages should not, however, mask the fact that there is no FED level so low that every occupant in every situation is safe.

CONCLUSIONS

More than 60 full-scale fire experiments were conducted to determine the impact of crew size, first-due engine arrival time, and subsequent apparatus arrival times on firefighter safety and effectiveness at a low-hazard residential structure fire. This report quantifies the effects of changes to staffing and arrival times for residential firefighting operations. While resource deployment is addressed in the context of a single structure type and risk level, it is recognized that public policy decisions regarding the cost-benefit of specific deployment decisions are a function of many other factors including geography, local risks and hazards, available resources, as well as community expectations. This report does not specifically address these other factors. The results of these field experiments contribute significant knowledge to the fire service industry. First, the results provide a quantitative basis for the effectiveness of four-person crews for low-hazard response in *NFPA 1710*. The results also provide valid measures of total effective response force assembly on scene for fireground operations, as well as the expected performance time-to-critical-task measures for low-hazard structure fires. Additionally, the results provide tenability measures associated with a range of modeled fires. Future research should extend the findings of this report in order to quantify the effects of crew size and apparatus arrival times for moderate- and high-hazard events, such as fires in high-rise buildings, commercial properties, certain factories, or warehouse facilities, responses to large-scale non-fire incidents, or technical rescue operations.

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