BFIRES-II: A Behavior Based Computer Simulation of Emergency Egress During Fires

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This paper acquaints the reader with BFIRES, a computer program designed to simulate the emergency egress behavior of building occupants during fires. Use of the program is illustrated, and findings concerning the simulation's validity are presented.

SINCE 1977, the Environmental Design Research Division of the Center for Building Technology, National Bureau of Standards (NBS) has been actively developing a technique for simulating the emergency egress behavior of building occupants via computer.[1,2,3,4] Long-range goals of this ongoing activity are (a) to develop a deeper understanding of human behavior during fire situations, and (b) to develop a standardized technique for analyzing alternative building designs from an emergency egress viewpoint. The latter aim provides the focal point of this paper.

The principal result of this activity is BFIRES, a dynamic stochastic computer simulation of emergency egress behavior by building occupants during fires. The objectives of this paper are to acquaint the reader with the purpose and function of BFIRES, to illustrate the program's use, and to present preliminary findings concerning the validity of this simulation.

PURPOSE

BFIRES was specifically designed to simulate — by digital computer — the movement of people within building enclosures in response to life-threatening stimuli (i.e., fire and smoke). Originally planned for use in evaluating health care facility designs, the program permits users to simulate such special activities as rescuing non-ambulatory persons, in addition to simulating more frequent and general categories of emergency

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response (e.g., exit seeking, threat evasion, the deterioration of emergency responses resulting from inhabiting a toxic environment, etc.). In its current form BFIRES is applicable to a broad range of building occupancies.

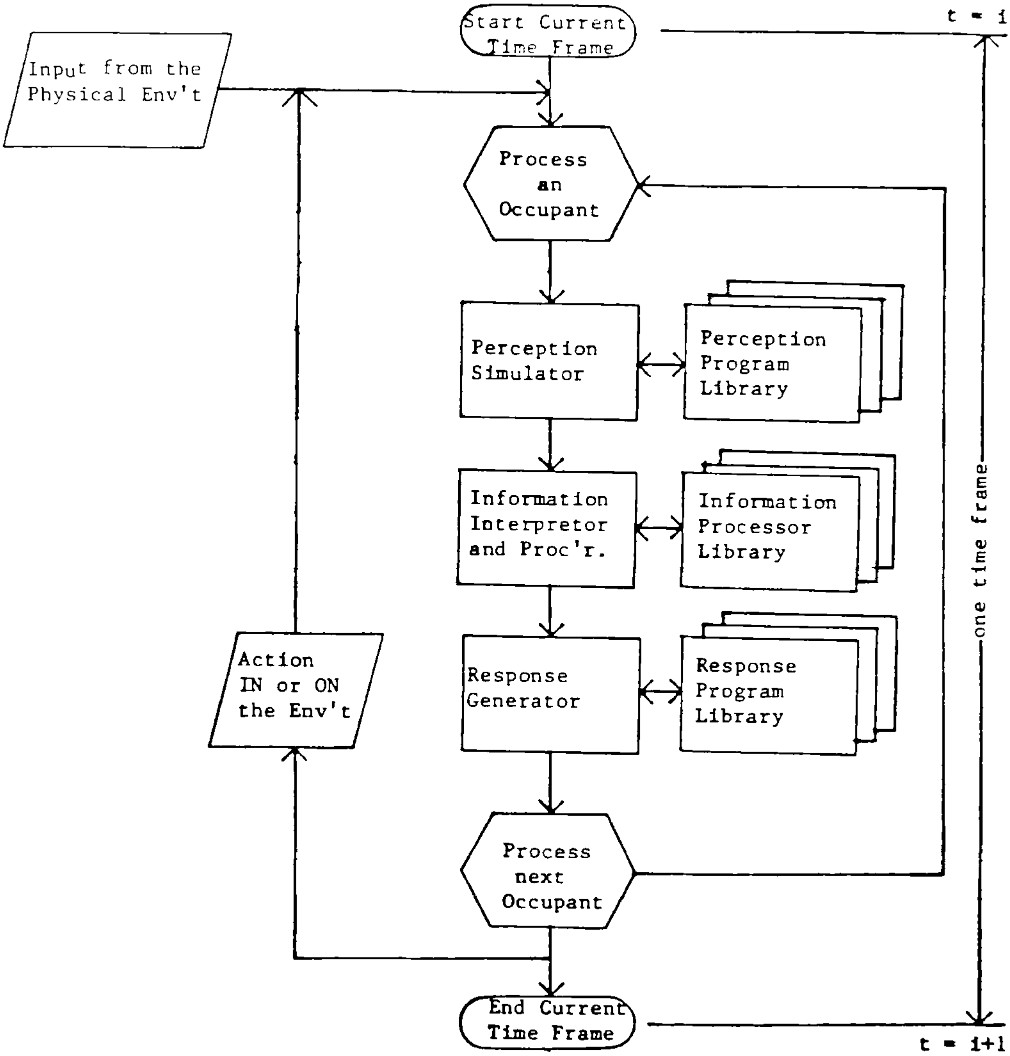
CONCEPT AND STRUCTURE

BFIRES simulates the perceptual and behavioral responses of building occupants involved in fire emergencies. As in real fires, simulated occupants may respond to a fire alert although they are quite distant from actual fire products. For example, these products may be confined to some distant part of the building. Alternatively, occupants' behavior may result from a direct confrontation with toxic agents. The program can simulate a wide variety of emergency scenarios by treating human behavior at a very fundamental level. Specifically, the basic unit of occupant behavior generated by BFIRES is the *individual momentary response* to the state of the environment at a discrete point in time, t. BFIRES conceptualizes a building fire event as a chain of discrete "time frames" (t_1, t_2, . . ., t_n) and for each such frame, it generates a behavioral response for every occupant in the simulated building. If each "frame" could be replayed sequentially as in the case of a movie or animated film, a complete "picture" of the building fire event would be seen (i.e., the simultaneous egress performance of all occupants in response to a migrating fire threat).

The response-generating capability of BFIRES is based upon an information processing explanation of human behavior, and suggests that building occupants act in accordance with their perceptions of a constantly changing environment. Between the two time frames t_i and t_{i+1} the environment undergoes change; e.g., people have altered their locations in space, smoke has advanced to new locations, and the building itself may have undergone physical changes. When preparing a behavioral response at t_i, a simulated occupant first gathers information which describes the state of the environment at this point in time. Next, the occupant interprets this information, relating it to the emergency egress goals guiding the individual's overall behavior. This is accomplished by comparing current with previous distances between the occupant, the fire threat, and the exit goal, and by comparing "knowledge" about threat and goal locations possessed by the occupant, with amounts possessed by other nearby simulated persons. Current locations of physical barriers (e.g., walls or doors) and of other occupants also are taken into account. Finally, the simulated occupant evaluates alternative responses and selects an action as the response for time t_i.

The selection of a behavioral response (i.e., the decision to move in a particular direction) results from the comparison of available move alternatives with the occupant's current move criteria. For example, an occupant who knows the locations of both the fire threat and a safe exit will favor moves which minimize his distance to the exit goal and/or maximize his distance from the threat. This response is likely to change his physical position within the building, and hence to create a new environmental information field to which all other occupants must respond during the next time frame in the chain, t_{i+1}. This cycle continues until the fire event is completed.

In order to simulate information-processing and behavior, BFIRES assumes that people have "libraries of response programs" in their memory systems.[5] In broad terms these programs are thought to be acquired through learning and experience, and undergo change over time. The simulation program makes use of a simplified version of this model, as is shown in Figure 1. Thus, the BFIRES executive program routes simulated



The BFIRES EXECUTIVE program generates one complete cycle for each simulated occupant, during each frame of simulated time. This process continues until an entire fire event has been completed.

Figure 1. General structure of BFIRES.

occupants through three behavioral processes: perception (information-gathering), interpretation, and the response processes. Each of these processes calls upon a library of computer subroutines, each of which is responsible for producing some aspect of simulated occupant behavior. Several additional "nonbehavioral" subroutines are required which enable the user to communicate with BFIRES. (i.e., to input initial scenarios and to retrieve data describing fire event outcomes from the computer). BFIRES was written in FORTRAN-V, and is currently operating on the UNIVAC 1108 and INTERDATA 7/32 computers at NBS.

AN APPLICATION OF "BFIRES"

SCENARIOS

To illustrate the possible uses of BFIRES, the example utilizes floor plans shown in Figures 2 and 3. These represent typical designs for a wing of a health care or nursing facility. The two plans are nearly identical and differ only in the location of the exit stairs. In Figure 2 the exits are remotely located at opposite ends of the floor, while in Figure 3 they are centrally located. At the moment of fire ignition, 12 occupants are assumed to be spatially distributed as shown in the figures.

In addition to considering differences in floor plans, differences in occupant distribution also will be compared in this example. Figure 2 illustrates the situation in which all occupants are fully ambulatory, and are assumed to be capable of evacuating themselves without special assistance. Figure 3,

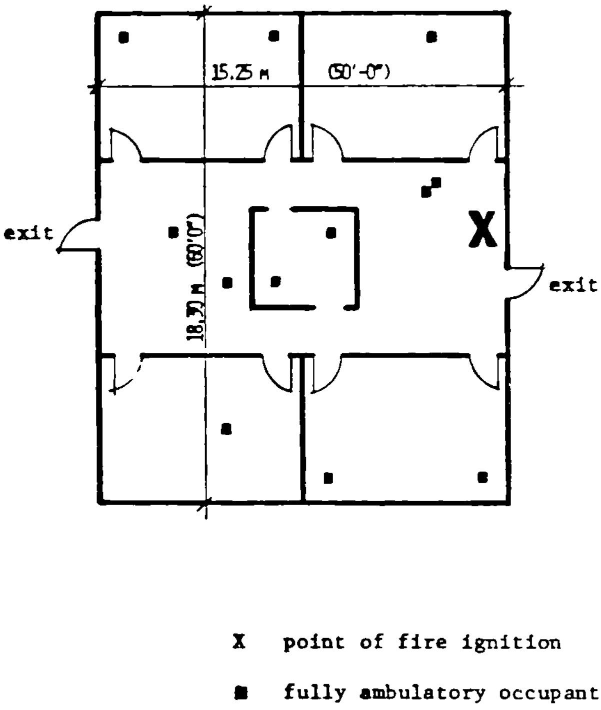


Figure 2. Floor plan with remote exits.

on the other hand, portrays a situation in which four occupants are non-ambulatory (requiring assistance to make evacuation possible), four occupants are semiambulatory (able to move at a slower-than-normal pace, yet not requiring assistance), and four occupants are specially designated as rescuers, or "helpers" (e.g., nurses on duty, whose first priority is to evacuate non-ambulatory occupants). As there are two floor plans and two occupant distributions under consideration, a total of four scenarios may be studied in this example (they are illustrated here in two diagrams for convenience only).

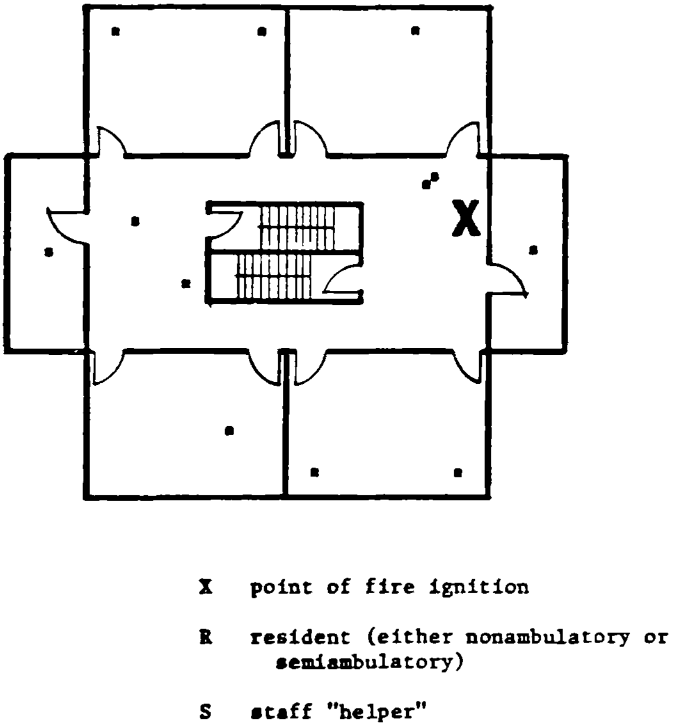


Figure 3. Floor plan with centralized exits.

In each of the four scenarios a fire is presumed to begin at the point marked "X" in Figures 2 and 3, and to migrate through the floor radially (passing through open doors, but not through walls). These descriptions of the building, the occupants, and the fire are the principal elements needed to initiate a BFIRES simulation. Of course, the delineation of each of these elements requires much more detail than described above (e.g., simulated occupants must be assigned behavioral probability estimates of various types, door locations and initial open/closed status must be specified, etc.). But for purposes of this introductory example, these details needn't be addressed.

PREPARING AN INPUT FILE

To initiate a BFIRES computer run, the user (building designer or code official) must translate actual information about fire scenarios into a form

TABLE 1. *Summary of Data from a Sample Simulation Experiment*

			No. of occs who escape[a]		*Escape score*[b]		*Egress route length*[c]		*Time spent in smoke-free env't*[d]		*Time spent in toxic env't*[d]		*Successful full pairs*
			$\bar{X}$	*s*	$\bar{X}$	*s*		*s*	$\bar{X}$	*s*	$\bar{X}$	*s*	%
Occupancy Class	All Ambulatory	Remote	10.8	1.14	0.73	0.07	19.09	5.00	21.33	2.69	26.70	7.18	
		Central	10.9	0.74	0.74	0.05	18.03	3.35	20.87	2.90	26.27	5.07	
	Mixed	Remote	4.1	1.29	0.24	0.07	20.41	2.89	37.60	2.53	76.13	7.50	25.0
		Central	2.1	1.45	0.13	0.08	19.17	3.57	39.11	2.67	86.73	8.42	2.5

Notes: [a] Maximum possible is 12.
[b] The higher the escape score, the earlier occupants escaped.
[c] Measured in units of distance which separate person-occupiable spatial locations.
[d] Measured in simulated time frames (one time frame is approximately equal to 0.025 minutes).

readable by the computer. This requires the preparation of numerical data files. Where original descriptions are in nonnumerical form (e.g., architectural drawings), conversions are necessary. For example, BFIRES cannot comprehend lines and other symbols drawn on a floor plan. However, by translating spatial locations into *x-y* coordinates, and then entering the numbers representing these coordinates into the computer, BFIRES can be given an extremely concise picture of the scenario under study.

Similar conversions are necessary when preparing descriptive data regarding the occupants and the fire. For instance, the BFIRES user will specify the *x-y* coordinates of the spatial location of fire origin, as well as a factor which determines the rate of fire and smoke spread. The *x-y* coordinates specifying initial locations of building occupants also must be read into the computer, as must several factors which describe behavioral objectives, predispositions, and probabilities. Examples of these include locations of safe exits and/or refuges, whether or not occupants are aware of exit locations, probabilities that occupants will open and/or close doors, occupants' tolerance for the toxic environment.

AN ILLUSTRATIVE CASE

To illustrate some of the capabilities of BFIRES, the four scenarios described earlier were simulated. Ten simulated fires were run for each scenario, and data describing six event outcomes were recorded from simulation runs: (1) the number of simulated occupants who escaped the floor during 100 frames of simulated time (equivalent to about 2.5 minutes), (2) escape score (an index between 0 to 1.00 such that the higher the score, the less time was required for occupants to escape the floor), (3) route length, (4) the number of time frames spent by simulated occupants in a

TABLE 2. *Summary of Statistical Analyses*[a]

Effect	*Degrees of freedom*	*No. occs who escaped*	*Escape score*	*Egress route length*	*Time in smoke-free env.*	*Time in toxic env.*
Occupancy class (O)	1, 1	F = 54.48 n.s.[b]	F = 100.83 n.s	F = 196.32 0.05	F = 305.25 0.05	F = 99.34 n.s.
Exit arrangement (E)	1, 1	F<1 n.s.	F<1 n.s.	F = 172.81 0.05	F<1 n.s.	F<1 n.s.
O X E interaction	1, 36	F = 7.89 0.008[c]	F = 5.86 0.05	F<1 n.s.	F = 1.34 n.s.	F = 5.95 0.05

Notes: [a] Based on the random effects analysis of variance model.
[b] Not significant.
[c] Level of statistical significance.

smoke-free environment, (5) the number of time frames spent in a toxic environment, and (6) the number of non-ambulatory occupants successfully evacuated by helpers (for conditions actually having such occupants). For each of these six outcome categories, results from the four floor plan-by-occupancy conditions are summarized by Table 1.

Data in Table 1 were analyzed using the random effects model analysis of variance.* These analyses are summarized in Table 2. When numbers of occupants escaping, escape score, and total time spent in the smoke-filled environment were analyzed, variation in neither occupant mix nor exit layout by themselves were found to significantly affect final event outcomes. In each of these cases, however, the interaction between the two variables *was* statistically significant.† In particular, occupant mix had a greater influence on final outcomes for the floor plan having centralized exits than it did for the plan having remote exits.

When the length of the egress routes was analyzed, variation in both occupant mix and exit layout had a significant effect upon final event outcomes. In this case, the interaction effect was not significant. Thus, egress travel routes were shortest for the floor plan containing centralized exits, regardless of the occupant mix studied. Moreover, the "fully ambulatory" groups traversed significantly shorter routes, regardless of floor plan studied.

The analysis of time spent in a smoke-free environment revealed that only variation in occupant mix affected final event outcomes. In particular

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* The random effects model is specified whenever levels of both independent variables (e.g., occupant mix and exit layout) either are in fact or are treated as having been selected at random from a larger population of levels. In this model, the interaction mean square is used as the error term when computering the main effect F rations.[a]

† As a consequence of employing the random effects analysis of variance, results of statistical tests presented in Table 2 may seem counter-intuitive. Since the interaction mean square is used as the error term (denominator) when computing values of F for main effects, the importance of a main effect will be greatly reduced whenever the interaction is significantly large. Similarly, the importance of main effects will increase where very small interactions are present. The random effects analysis of variance is also a considerably more conservative test, since many fewer degrees of freedom are associated with the interaction (as compared with the residual) mean square.

the "fully ambulatory" groups spent significantly shorter periods in the non-toxic environment than did other groups, regardless of floor plan studied. Neither exit layout variation nor the interaction between occupant mix and exit layout yielded statistically significant results.

Finally, the number of non-ambulatory residents successfully evacuated by staff helpers was examined for each exit arrangement. For each floor plan type, four resident-staff pairs were possible. Out of a maximum of 40 possible successes (four pairs times ten replications), a 25 percent success rate was found for the floor plan with remote exits. Only a 2.5 percent success rate was achieved for the plan with centralized exits. Refer also to Figure 4.

INTERPRETING THESE DATA

The interaction effects reported in Table 2 (see also Figure 4) above indicate that the degree to which the different floor plans yielded differing event outcomes depended upon the occupant mix studied. In this example, occupant mix seems an important factor to consider when planning for centralized exits, but it may be irrelevant where remote exits are concerned. Although the "fully ambulatory" groups generally had the most escapees, escaped earliest, and spent the least time in the toxic environment, these outcomes were most pronounced for the cases with centralized exits. The key point here is not necessarily that BFIRES leads the designer or regulator to one type of floor plan or another,* but rather that BFIRES is capable of surfacing factors which render some designs better under certain conditions and other superior under different conditions. In this hypothetical design situation, for example, an architect might be advised against the use of a centralized exit arrangement if he expects a mix of non-ambulatory, semi-ambulatory and ambulatory occupants.

Other results from the simulation experiment suggest that, for the sample investigated, floor plans with centralized exits may yield shorter egress routes, and that "fully ambulatory" groups typically traverse shorter routes. These are logical outcomes which support the face validity of BFIRES. In particular, shorter egress routes are expected when exits are centrally located, since the mean initial distance between occupants and exits will be shorter than it would be in floor plans featuring remote exits. Similarly, "fully ambulatory" groups are expected to traverse shorter routes, on the average. In partially ambulatory groups, occupants have been noted to meander more frequently, and thus helpers may need to seek out non-ambulatory persons before beginning to move toward exits. These factors result in more lengthy and much less direct egress travel.

The experiment also suggests that "fully ambulatory" occupant groups will typically spend less time in the smoke-filled environment than will par-

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* Since BFIRES has not yet been field validated, it is not now advocated for practical design or regulatory applications. The objective here is to illustrate the program's potential capabilities.

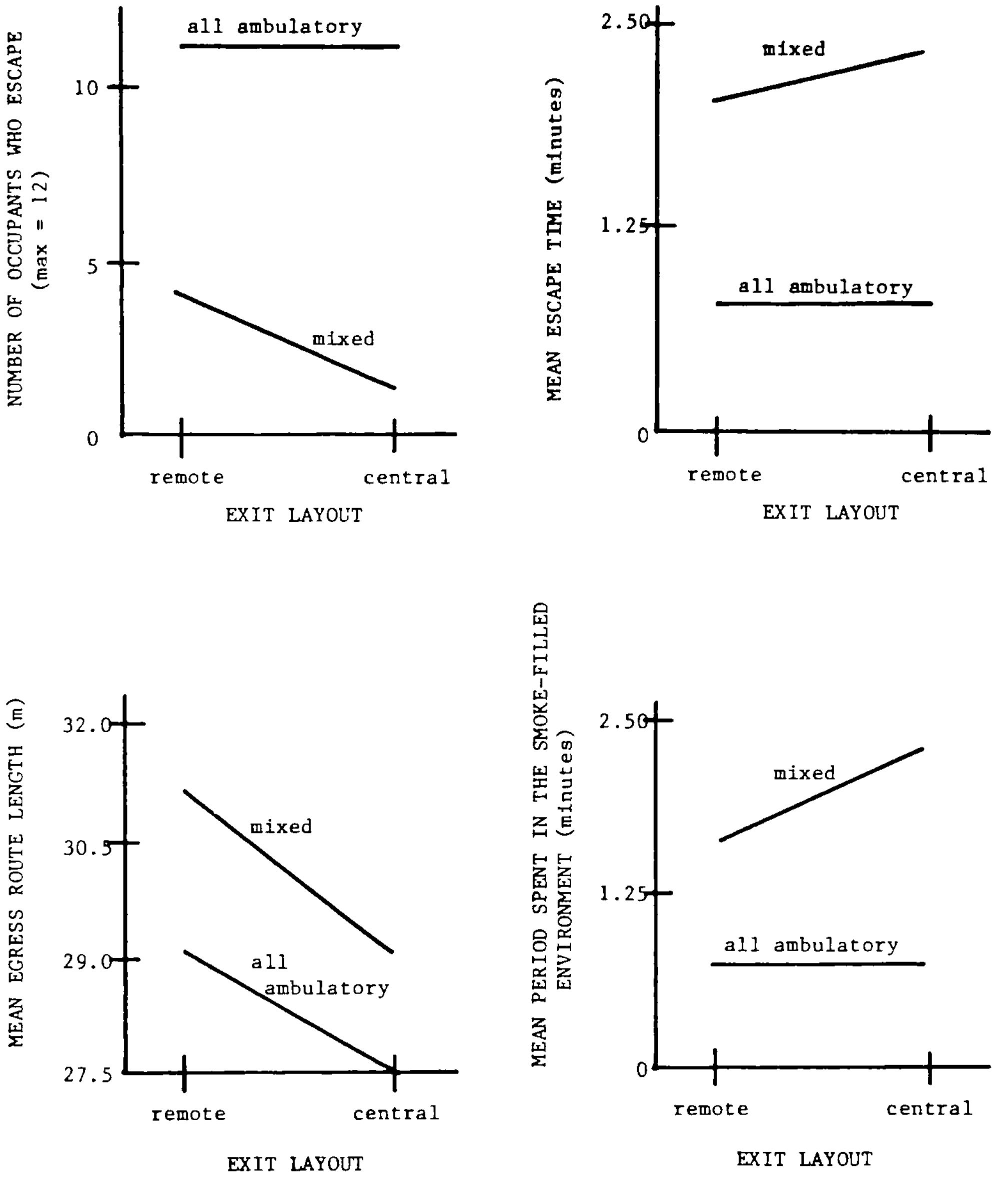


Figure 4. Effects of occupant capabilities and exit layout on egress measures.

tially ambulatory groups, regardless of exit layout. This seems logical and consistent with other evidence presented earlier, since the ambulatory groups are expected to evacuate the floor before becoming engulfed by toxic smoke. But why didn't exit layout make any difference here? Evidence discussed above suggests that centralized exits should yield shorter egress routes, and hence faster escape. Shouldn't centralized exits also result in less time spent in the smoke-filled environment? Not necessarily. With exits centralized, occupants at the end opposite the ignition point had to move toward the direction of the life threat in order to approach the exit goal.

Smoke migrating toward them made travel toward the exit more difficult, and many occupants did not move in a purposeful and straight-forward manner. Hence, while centralized exits were — on the average — closer to all occupants than were remote exits, they were not entered any faster. Again, an important capability of BFIRES is its ability to illuminate and specify such conditions and confounding factors during the design review process.

Finally, a greater resident-helper evacuation success rate was found for the remote exit plan than for the centralized exit plan. This is due to the fact that, in general, helpers seeking their residents moved away from the migrating smoke, and continued to move away from the smoke once they reached their residents and proceeded toward the exit at the opposite end of the floor. In contrast, helpers in the centralized plan often had to move directly into the smoke-filled environment, which had engulfed the exits by the time helpers reached their residents. As noted earlier, BFIRES responds to the need to move through the toxic environment with increased meandering and less direct egress movement by simulated occupants.

PRELIMINARY FINDINGS CONCERNING THE VALIDITY OF BFIRES

LITERATURE COMPARISONS

In addition to suggestions about face validity discussed above, comparisons between BFIRES outcomes and phenomena reported independently by other investigators are useful in evaluating the validity of the simulation model. Findings regarding the sensitivity of BFIRES reported by Stahl[2] appear to conform with the overall opinions and findings of the London Transport Board.[7] That is, BFIRES data suggest that varying degrees of route "constriction" produce differences in movement behavior, and variation in such important outcomes as egress time. These simulated data indicate that, to a point, increased constriction results in more direct movement toward the exit goal, and thus shorter egress time.

Appleton and Quiggen[8] reported that stress, fatigue, and indecision all had negative effects on rescue performance during a mock evacuation on an actual hospital ward. Studies reported by Stahl[2] have shown that indecision and mobility impairments act to increase occupants' egress times, and reduce their overall performance during BFIRES-simulated fire events.

Finally, Wood[9] and Bryan[10] reported that evacuation often is *not* the first action taken during residential fires, and that it often occurs in conjunction with such actions as alerting other occupants, rescuing others, and calling the fire department. BFIRES directly simulated pedestrian movement only, on the assumption that the decision to evacuate has already been made prior to the onset of a simulation run. Such movement may be construed as "evacuation." However, the movement of occupants during simulated events frequently deviates from an optimal path toward a safe exit, even when simulated individuals are "familiar" with the building (i.e., know the location of the safe exit), are mobile, and are making decisions on the basis of unambiguous and correct information. Although simulated occupants don't "investigate the fire," "alert others," etc., each of these activities has the effect of using up potentially valuable time. It is this characteristic of the Wood and Bryan findings which appears to be simulated by the deviations and detours generated by BFIRES. Thus, both the Wood and Bryan surveys and BFIRES simulations all agree that unidirected exiting behavior does not necessarily result from a fire alert.

Bryan and Wood also reported that, on the basis of their findings, familiarity with the building layout did not correlate with either evacuation speed or the directness of the egress route. These findings do not support BFIRES results which indicate that, despite the deviations and detours described above, familiarity is a necessary component of rapid and direct evacuation during simulated fires.

CONVENTIONAL WISDOM ABOUT EGRESS BEHAVIOR

Over the years, professional architects, fire protection engineers, and building regulatory officials have developed a body of opinion concerning various aspects of occupants' emergency egress behavior patterns. Much of this conventional and professional wisdom has been built into design and regulatory practice, and concerns: (a) the provision of appropriate numbers of exits; (b) the problem of blocked egress ways; (c) the clarity and simplicity of egress system design; (d) dead-end corridors; (e) occupant density; (f) familiarity and emergency training; and (g) the effects of special occupant capabilities (e.g., those of elderly or handicapped populations). In many ways, independently derived outcomes from BFIRES simulations concur with professionals' opinions and beliefs about these issues.

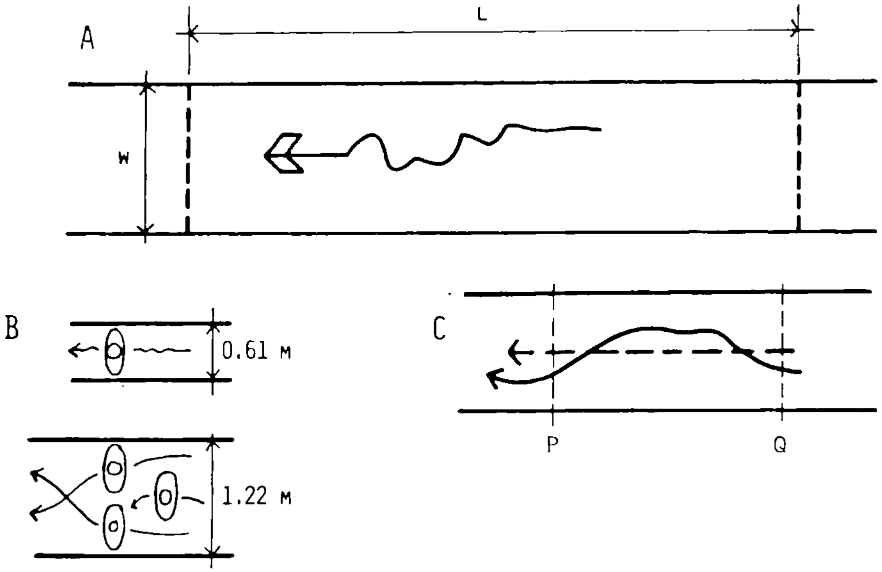
Design professionals have long agreed that no building occupant should ever be trapped in a situation where the only egress path was blocked in buildings larger than two-family dwellings. The possibility that a single exit could, if blocked, easily entrap occupants, and the notion that this problem is readily mitigated by the provision of an alternative exit, are amply demonstrated by the BFIRES-simulated data presented earlier by Stahl.[3]

Professionals have also believed that, in general, shorter and more direct pedestrian circulation paths reduce ambiguity and increase the likelihood of safe emergency escape, especially where occupants are unfamiliar with the building layout and exit locations. This belief is partially confirmed by BFIRES simulations, which show that well-defined paths result in short egress times when simulated occupants are familiar with exit locations. However, simulated occupants who are not familiar with exit locations are not likely to escape, regardless of the clarity with which the circulation system was designed.

Finally, building professionals generally agree that: (a) persons familiar with exits and egress routes (whether through continual use or through training) are more likely to escape in a reasonable period of time; and (b) mobility-impaired occupants will require more time for evacuation than will their unimpaired counterparts. Both of these expectations are confirmed by BFIRES simulations documented earlier by Stahl.[2]

CORRESPONDENCE WITH ANECDOTAL ACCOUNTS

Fire reports published by the National Fire Protection Association in the last five years were reviewed during the course of this research program. Fires in various types of residential facilities were selected for content



$$V = \frac{L}{N \times FL} \tag{1}$$

where, V = pedestrian walking speed
L = channel length
N = number of time frames required to move through channel
FL = length of time frame in real time

$$FL = \frac{SL}{V_f} = \frac{0.61\ \text{m}}{1.67\ \text{m/sec}} = 0.37 \text{ seconds} \tag{2}$$

where, SL = step length, as determined by the user
V_f = average value of "free flow" walking speed

Figure 5. Experimental analysis of pedestrian movement in linear channels.

analysis. These included: (a) multi-family dwellings; (b) hotels; (c) dormitories; and (d) nursing homes. A number of general patterns were recorded, and BFIRES-produced behaviors appear to conform with these:

- After being alerted to the fire danger, occupants frequently took time to dress and collect their belongings. In these cases, evacuation was neither immediate nor direct.
- Where dead-end corridors were present, some occupants reported overshooting emergency exit doors.
- Walking toward the fire was occasionally reported by persons specifically seeking the exit, even in cases where the safe exit was in the opposite direction.
- Evacuees tended to move toward the most familiar exit.
- Mid-stream direction changing was often reported, even in cases where such behavior could not be traced to any sudden change in environmental circumstances.
- Indecision was frequently reported.

PEDESTRIAN MOVEMENT IN LINEAR CHANNELS

Virtually no measurements describing occupants' egress paths during real fires are currently available, and as a result only qualitative assessments of the validity of BFIRES under emergency conditions thus far have been possible. When considering pedestrian movement behavior during non-emergency building use, however, a number of comparisons between BFIRES and other quantitative data bases are possible. One example involves the analysis of pedestrian flow along such linear channels as building corridors, as shown in Figure 5.

Figure 5A illustrates a corridor of length l and width w. Figure 5B shows the potential effects of variation in corridor width. For example, a channel 0.61 m (2.0 ft) wide may only permit a single file of pedestrians, allowing each individual to deviate extremely little from a straight-line path. A 1.22 m (4.0 ft) corridor, by contrast, permits two pedestrians walking abreast, and allows each individual to deviate somewhat from purely linear travel.

Several investigators have reported data from observations of pedestrian movement in building corridors. Chief among these are the London Transport Board[7] and Predtechenskii and Milinskii.[11] In addition, Naka[12] and Nakamura and Yoshioka[13] have reported data from their computer simulations of pedestrian behavior. These data address the effect of variation of pedestrian density upon flow rate and walking speed in linear channels, and were compared with findings from BFIRES simulations of pedestrian movement in such channels.

Figure 6 presents results from BFIRES simulations for both 0.61 m and 1.22 m corridors, concerning the effect of variation in density upon walking speed. Results of simple linear regression analyses are also shown. The standard errors reported may be partially explained by the vague manner in which walking speed has traditionally been measured. Figure 5C illustrates this problem. The speed with which a person traverses a linear channel is typically measured by recording the time required to pass through the zone demarked by lines p and q. A person walking along a purely linear path (denoted by the dashed line in Figure 5C) may pass through this zone in the same time period as another person traveling along a non-linear path (denoted by the solid line). Although both persons will appear to have traveled the same distance (the distance between p and q) in the same time — hence at the same computed speed — it is obvious that the person traveling the non-linear path will have actually moved at a higher rate of speed. The problem of measuring walking velocity becomes even more complex when one considers the possibility that a pedestrian may stop momentarily, or may even reverse direction for brief periods of time.

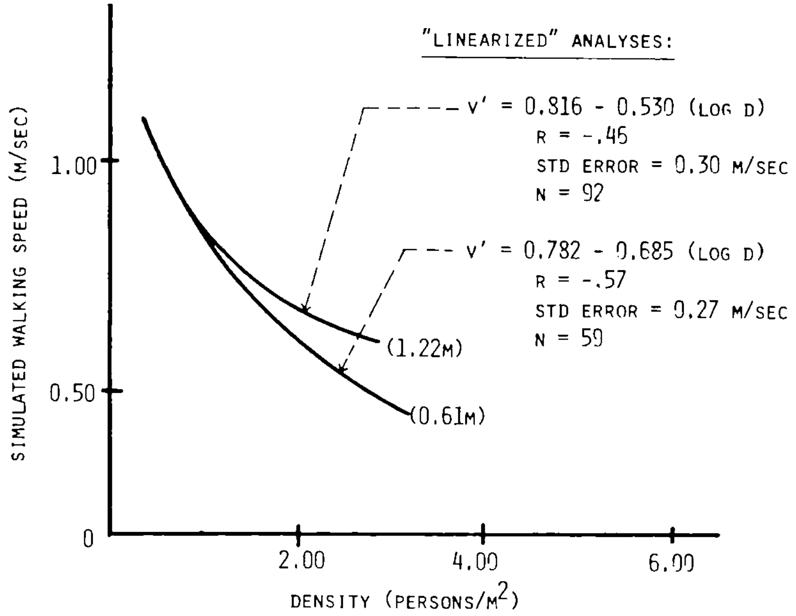


Figure 6. Effect of variation in density upon walking speed (simulated).

Figure 7 compares BFIRES-produced simulated behavior, data on actual pedestrian movement, and results from other computer simulations, concerning the effects of variation in density upon walking speed. Unfortunately, regression statistics were not provided by the other investigators, and so a detailed comparison is not possible. However, Figure 7 shows clearly that BFIRES results lie within trends established by real-world observations and other simulations, at least for the low and intermediate density ranges. This is also true for the effect of variation in density upon pedestrian flow rate,* as illustrated in Figure 8.

Only Nakamura and Yoshioka[13] discussed the effects of variation in density upon *variability* in walking speed, in connection with their observations

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* Flow rate refers to the number of persons passing through a channel of unit width (i.e., 1 m) during a unit of time (i.e., 1 sec), and is defined as density times walking speed.

of computer-simulated pedestrian movement. In general, they noted that as pedestrian density increases, the standard deviation of walking speed decreases. This is expected to occur because as density becomes greater, each individual has less freedom of choice regarding travel path, and is more likely to be moved along with the linear flow in the channel. Figure 9 compares BFIRES-produced behavior with that generated by the computer simulations by Nakamura and Yoshioka. While BFIRES produced greater variation, these results follow the trend suggested by the earlier simulation experiments.

SUMMARY AND CONCLUSIONS

Simulation modeling is appropriate for problems (a) that would otherwise require costly, time-consuming and tedious manual effort (b) that cannot be solved through experimentation because of high costs or unacceptable risks to human participants, and (c) for which intuition, past experience or available data do not provide the proper insight. The problem of evaluating the life safety potential of building designs frequently conforms with these criteria, and is therefore a candidate for simulation analysis. This paper illustrates the use of the BFIRES simulation program in evaluating building design or retrofit options, and in surfacing the effects of interact-

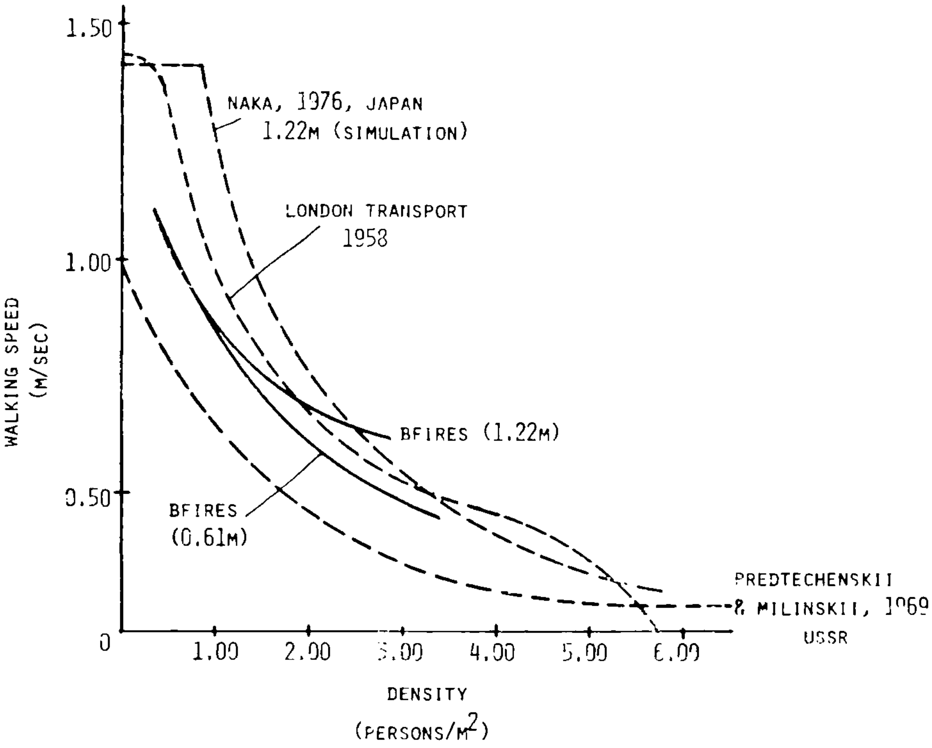

Figure 7. Effect of variation in density upon walking speed — comparisons.

ing factors which might otherwise go unnoticed during traditional design or regulatory analysis.

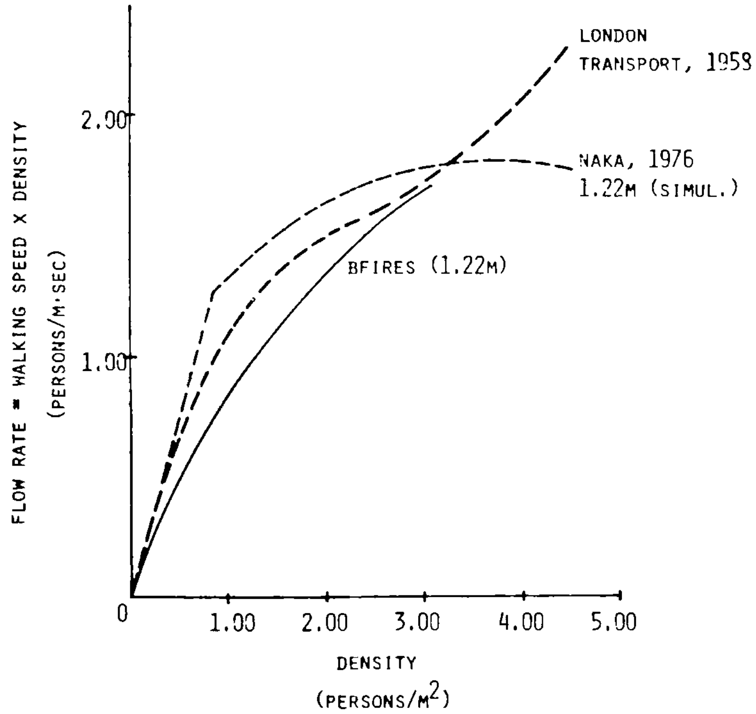

Figure 8. Effect of variation in density upon pedestrian flow rate.

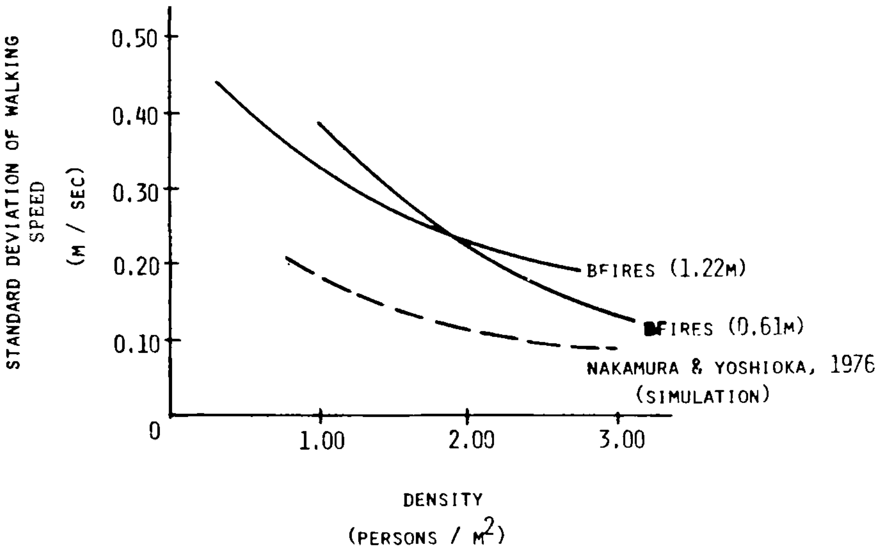

Figure 9. Effect of variation in density upon variability in walking speed.

In this paper, the general patterns of emergency egress behavior produced by BFIRES are compared with those found in the earlier research literature, with professional opinions about such behavioral patterns, and with general impressions gathered from anecdotal accounts. In general, these comparisons illustrate agreement between simulation results and various independent sources. Two important exceptions are: (1) BFIRES results exhibit a positive correlation between occupants' familiarity with the building layout, and the speediness and directness of their escape, although no such correlation was found during the field surveys by Wood[9] and Bryan;[10] (2) BFIRES results suggest that occupants unfamiliar with the physical layout of the building will not be helped by designs providing shorter and more direct egress routes, while conventional wisdom suggests that short, direct, and unambiguous routes should be especially helpful to occupants unfamiliar with the building.

Comparisons between BFIRES-produced behavior patterns and data collected by other investigators on the relationships between occupant density and pedestrian flow in linear channels are also reported. In general, pedestrian movement simulated by BFIRES lies well within trends established by observations of actual pedestrian behavior, and by other computer simulations of this behavior.

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