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Preliminary Findings Concerning the Validity of "BFIRES": A Comparison of Simulated With Actual Fire Events

Fred I. Stahl

Environmental Design Research Division
Center for Building Technology
National Engineering Laboratory
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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*

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PREFACE

The Environmental Design Research Division, Center for Building Technology, National Bureau of Standards (NBS), addresses problems of accessibility to - and egress from - the built environment. Research into the responses of building occupants during fire emergencies is a vital component of this effort. Under the sponsorship of the Center for Fire Research at NBS, this investigator conducted research into the computer simulation of emergency egress behavior. That effort culminated in the development of BFIRES/VERSION 1, a program written in FORTRAN V. An enhanced version of this program is under development. Under the sponsorship of the Center for Building Technology, the predictive validity of BFIRES and its usefulness as a building design and regulatory tool are being addressed. This report presents data contributing to the validation of the computer program.

The author expresses his appreciation to Mr. Harold E. Nelson and to Dr. Bernard M. Levin of the Center for Fire Research, for their support of the BFIRES project. In addition, the author thanks Dr. Edward Arens, Dr. Belinda Collins and Mr. Sanford Adler of the Environmental Design Research Division, and Ms. Patsy Saunders of the NBS Center for Applied Mathematics, for their comments on the manuscript. Finally, the staff of the Center for Building Technology Word Processing Center is gratefully acknowledged.

ABSTRACT

This report presents preliminary findings regarding the validity of BFIRES/ VERSION 1, a computer program developed at the National Bureau of Standards to simulate egress movement by building occupants during fires. A computer simulation experiment was conducted in order to compare outcomes from BFIRES runs with data selected from an archival file summarizing actual fire results. Findings from this experiment suggest that BFIRES is capable of reproducing such important fire outcomes as loss-of-life and numbers of persons ultimately escaping. In addition, patterns of egress behavior produced by BFIRES were compared with those found in the literature, with professional opinions, and with impressions gathered from anecdotal accounts. With few exceptions, these comparisons illustrate agreement between simulations and other data sources.

Key Words: Architectural research; building fires; computer-aided design; computer simulation; environmental psychology; fire research; fire safety; human performance; modeling technique; simulation.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

1.1 PROBLEM AND OBJECTIVE

Numerous attempts to simulate pedestrian movement in buildings appear in the literature (Krystiniak, 1972; Studer and Hobson, 1973; Baer, 1974; and Lozar, 1974, are important examples). In addition, several investigators addressed the specific problem of emergency egress during fire conditions, using computer simulation techniques (Wolpert and Zillmann, 1969; Edmondo, Hahin, and Sinay, 1969; Korkemaz, 1977; and Stahl, 1976, 1978, 1979).

These studies represent a wide variety of approaches to conceptualizing pedestrian movement behavior. For example, the discrimination learning model employed by Studer and Hobson contrasts with the information processing approach used by Wolpert and Zillmann, and by Stahl. Similarly, a broad spectrum of simulation techniques have been employed. Almost the entire range from deterministic input/deterministic simulation, through stochastic input/stochastic simulation, is represented in the literature.

None of the investigators discussed above, however, has published results of research illustrating the predictive validity[1] of a simulation program. As a result, it is not yet possible to make specific statements regarding the usefulness of these programs to building design, regulation, and evaluation. The objective of this report, therefore, is to report preliminary findings concerning the external validity of BFIRES/VERSION 1. This computer program was designed to simulate egress movement behavior by building occupants, and was developed at the National Bureau of Standards (Stahl, 1978, 1979).

1.2 OVERVIEW OF BFIRES/VERSION 1: STATE-OF-THE-ART

The conceptual development, structure, and function of the BFIRES computer simulation program was presented in detail by Stahl (1978). In brief, the model underlying this program was derived from a nonstationary, discrete time Markovian analysis of the building fire problem. The model postulates that occupants formulate strategies, make decisions, and take actions dynamically, in response to social and environmental information fields which change over time. The model recognizes the transactional relationship between occupants and their environment, which results when the responses of humans are influenced by features of the environment which the occupants themselves change or control. The computer simulation of these processes is accommodated through BFIRES, a library of FORTRAN V routines. This report presents an analysis of outputs from BFIRES/VERSION 1. A second generation of this program is currently under development at the National Bureau of Standards.

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[1] Predictive validity concerns the ability of a simulation to predict future real-world events.

Stahl (1979) documented results of experiments designed to calibrate BFIRES, to determine its range of applicability, and to assess the program's sensivity to important parameters. That study illustrated a number of important findings. Namely:

(1) a variety of general egress situations could be simulated by BFIRES;

(2) every such event is unique, and is defined by the set of user-supplied parameter values which describe the building, the fire threat, and the occupants;

(3) BFIRES is useful in simulating environments of known (or desired) spatial dimension, and events of known (or anticipated) temporal duration; and

(4) BFIRES outcomes are sensitive to variations in a number of parameters of immediate interest to the building designer (e.g., floorplan configuration, exit arrangment, occupants' locations).

2.0 AN EXAMINATION OF THE EXTERNAL VALIDITY OF "BFIRES"

2.1 LEVELS OF EXTERNAL VALIDITY, AND GENERAL APPROACH

Two criteria are essential to the validation of computer simulation models. These involve questions of predictability and plausibility: Does the computer program generate outcomes predictive of those found in the real-world under the conditions allegedly simulated? Are behavioral scenarios and outcomes produced by the program reasonable, or likely to occur in the real world (i.e., do they exhibit face validity)?

The predictive validity of BFIRES outcomes was tested indirectly, not by attempting to predict results of future fires, but rather by measuring the degree to which the program could replicate actual historical fire events for which appropriate data was available. The plausibility criterion was examined by comparing simulation outcomes with conclusions drawn by other investigators.

2.2 TEST OF PREDICTIVE VALIDITY: A CASE STUDY

2.2.1 Description and Objective

The objective of this case study was to determine whether data describing simulated fire outcomes conformed with those found for real events. Meyers (1977) reviewed the NFPA-FIDO[1] data base in order to determine whether certain trends were strong enough to justify various design recommendations. Data in the FIDO files are derived from news media,

[1] National Fire Protection Association Fire Incident Data Organization

reviews of accounts published in trade and technical journals, NFPA investigative reports, fire department reports, and insurance company reports.

This data base contains information in a number of categories, primarily: (a) property identification; (b) fire origin; (c) fire spread; (d) casualties; and (e) physical losses. For some incidents, floor plans of residential units are also provided. Three types of data were of particular interest in this study:

(1) dwelling unit floor plan;
(2) dwelling unit loss-of-life index;
(3) adjacency of dwelling unit exit to room-of-origin entry.

These are explained below, and in section 2.2.2.

Meyers reviewed the FIDO files, and selected those incidents in which residential fires originated in kitchens. All dwelling units chosen had substantially similar floor plans and numbers of occupants, and varied primarily in the degree of exit adjacency. For such cases, he recorded loss-of-life index data reported in the files. For this study of predictive validity, the floor plans reported in the FIDO files were idealized for input into BFIRES, and to as great a degree as possible, the fire events were recreated.

2.2.2 Experimental Design

All simulated fire events were run for several variations of a basic floor plan. These variations were constructed to simulate those found in the FIDO files. In all cases, four occupants were assumed to inhabit the dwelling units. It was also assumed that the events occurred during the night hours, and that the occupants were located in the bedrooms. The floor plans varied across classes of events, in order to reflect: (a) adjacency of dwelling unit exit to kitchen entry; and (b) number of exits from the dwelling unit. The floor plans are exhibited in Figure 1.

Two levels of the adjacency variable were studied. In the adjacent condition (Condition A), an occupant would be forced to pass within a single "step" (in BFIRES terms)[1] of the kitchen entry in order to reach the dwelling unit exit. In the non-adjacent condition (Condition B), an occupant could reach the dwelling unit exit without even entering a space adjacent to the kitchen entry.

Floor plans with both one and two dwelling unit exits were studied. In the two-exit case (Condition C), one exit was relatively near the kitchen

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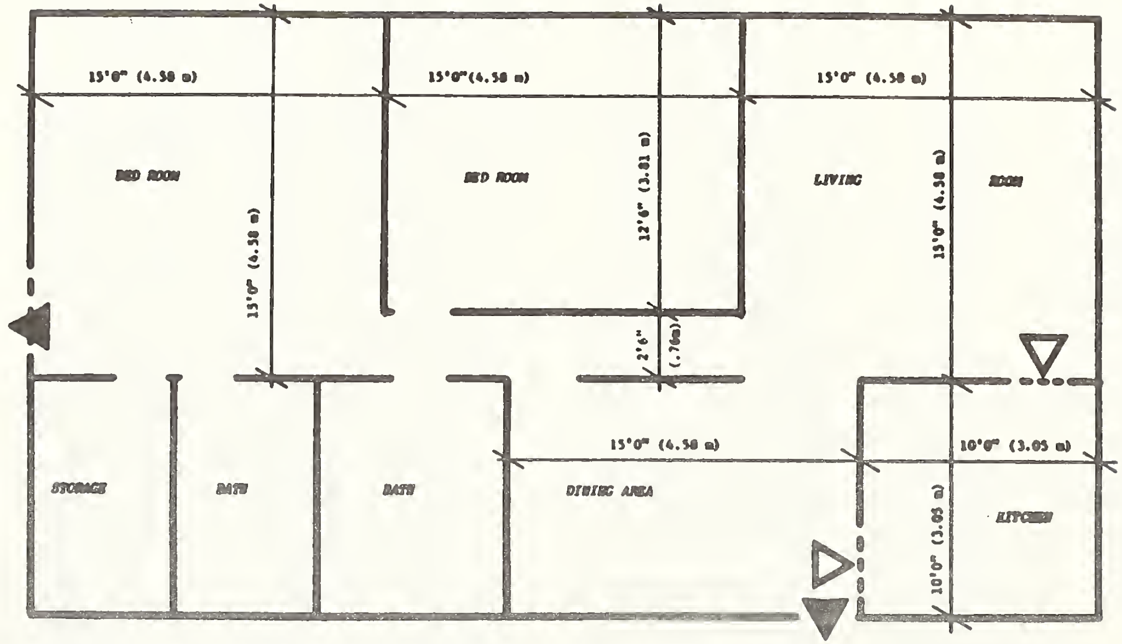
[1] BFIRES simulates pedestrian movement as a sequence of discrete spatial relocations, or "steps." In the current experiment, such a step is equivalent to 30 inches (0.76 m).



LEGEND:

(A) Optional alternatuve d.u. exit

(B) Primary d.u. exit

(C) Alternative kitchen entry locations

Figure 1 Schematic Plan of Dwelling Unit Showing Variations in D.U. Exit and Kitchen Entry Locations entry, while remote from the sleeping areas. The second exit was located within one of the bedrooms, and was remote from the room of fire origin (the kitchen).

In order to make direct comparisons with data reported in the FIDO files, dwelling unit loss-of-life (D.U. LOL) indices were computed from simulated fire outcome data. The loss-of-life index was intended by NFPA as an indicator of the number of fire fatalities relative to the total number possible for a given dwelling unit. Since the actual number of occupants must be expected to vary from time to time for any dwelling, the index was defined in terms of average potential occupancy (determined by the number of bedrooms present). Thus:

$$LOL = \frac{1}{b + 1} \quad (1)$$

where:

LOL = dwelling unit loss-of-life index;
f = number of fatalities in the dwelling unit;
b = number of bedrooms in the dwelling unit.

Simulated events were run for 200 time frames, corresponding to approximately four minutes of real time. Most fire professionals agree that, in general, a person who has not been removed from a fire in a small area (such as an apartment) within four minutes has a very low chance of survival at all. Thus, the simulated D.U. LOL index was computed as:

$$LOL' = \frac{f'}{b + 1} \quad (2)$$

where:

LOL' = simulated dwelling unit loss-of-life index;
f' = number of simulated occupants in the dwelling unit at the 200th time frame;
b = number of bedrooms in the dwelling unit.

Comparisons between simulated events, and those reported in the NFPA-FIDO files were studied through the examination of three hypotheses:

(1) In simulated one-exit dwelling units, LOL' is greater in cases where there is kitchen entry/d.u. exit adjacency, and lower in cases where no adjacency exists.

(2) In simulated cases where there is kitchen entry/d.u. exit adjacency, LOL' is lower when an alternative d.u. exit is provided, and higher when no alternative is available.

(3) For all exit and floor plan arrangements, simulated data does not differ significantly from actual fire data reported in the NFPA-FIDO files.

2.2.3 Data Collection and Analysis

As mentioned above, LOL data for cases corresponding to the experimental design were extracted from the FIDO files (Meyers, 1977). Data from simulated cases were obtained by establishing computer input files corresponding to each hypothetical condition, and then by replicating each condition ten times[1]. Because the FIDO sample was quite small, comparisons were made using only five of the original ten computer replications, and in particular, zero values of LOL' were selectively omitted. This was done to bring the balance between cases having fatalities and those having no fatalities more closely in line, beteween the simulated and real situations. It is recognized, however, that the selective omission of cases may have biased results reported below. The hypotheses enumerated above were examined by means of one-tailed t-tests for independent groups.

2.2.4 Findings and Discussion

Simulated data are reported in Table 1. Comparisons between simlulated and FIDO data are shown in Table 2. When comparing differences between simulated fire conditions, it was found that: (a) the dwelling unit loss-of-life index was significantly greater for the plan exhibiting kitchen entry/d.u. exit adjacency, than for the plan in which no such adjacency was present (t=16.00, 18 degrees of freedom (d.f.), significant at the .01 level); and (b) the loss-of-life index was significantly lower for the floor plan which provided a second means of egress from the dwelling unit, than for the plan containing only a single exit adjacent to the kitchen entry (t=10.00, 18 d.f., significant at the .01 level).

When simulated data were compared with those obtained from the FIDO files, the following results were found: (a) no significant difference in D.U. LOL was noted for the one exit/adjacency condition (t=-1.29, 6 d.f., n.s.); (b) D.U. LOL was significantly higher in simulated fires than in the actual events, for the one exit/non-adjacent condition (t=13.00, 6 d.f., significant at the .01 level); and (c) no significant difference in LOL was noted for the two exit condition (t=-1.40, 7 d.f.).

The analyses of comparisons between the simulated conditions support hypotheses (1) and (2), and indicate that, for the environmental and occupancy situations specified, BFIRES produces trends conforming to those found in an actual historical data base. For two of the three conditions studied, analyses of comparisons between simulated and historical data support hypothesis (3), and suggest that BFIRES is capable of reproducing certain kinds of event outcomes.

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[1] BFIRES generates stochastic simulations. Thus, numerous runs conducted under identical starting conditions result in a distribution of outcomes.

Table 1. Loss-of-Life Indices for Simulated Residential Fires

Replication	Condition A	Condition B	Condition C
1	.00	.33	.33
2	.00	.00	.33
3	.00	.00	.00
4	.67	.33	.00
5	.00	.00	.00
6	.33	.00	.33
7	.33	.00	.00
8	.00	.00	.00
9	.33	.00	.00
10	.67	.00	.33
Means	.23	.07	.13
Std. Devs.	.28	.14	.16

Note: Condition A: kitchen entry/d.u. exit adjacency

Condition B: no adjacency

Condition C: two d.u. exits

Table 2 Comparisons of Loss-of-Life Indices Between Real and Simulated Residential Fires

	Condition A		Condition B		Condition C	
Replication	Simul.	Real	Simul.	Real	Simul.	Real
1	.67	.67	.33	.00	.33	.00
2	.33	1.00	.33	.00	.33	1.00
3	.33	.67	.00	.00	.33	.00
4	.33		.00		.33	.33
5	.67		.00		.00	
Means	.47	.78	.13	.00	.26	.33
Std. Devs.	.20	1.10	.14	.00	.10	.47

Note: Condition A: kitchen entry/d.u. exit adjacency

Condition B: no adjacency

Condition C: two d.u. exits

These comparisons with the NFPA-FIDO data reinforce the possibility that BFIRES is sensitive to certain important parameters, as illustrated earlier by Stahl (1979). In particular, variations in factors under the direct control of building designers and regulators (floor plan and exit arrangement, and numbers of exits) seemed to have a substantial impact upon the likelihood of escape.

The study illustrating the sensitivity of BFIRES also suggested that this effect should be especially pronounced in cases where occupants could be assumed not to vary in such factors as exit knowledge (familiarity with the building's layout) and mobility. In the comparisons described here, occupants were assumed not to vary in both the simulated and historical cases. A test of the hypothesis that occupant factors interact with environmental variables, such that under certain conditions variation in occupant factors <u>wash out</u> environmental effects, is left for future study.

Finally, it must be noted that while simulated fire outcomes (i.e., loss-of-life indices) generally conformed to those found in an actual historical data base, these findings offer only indirect evidence of the correctness of the behavioral processes simulated by BFIRES. Important tasks for future research will be, therefore, to examine BFIRES-simulated behavior under a very wide spectrum of cases, and similarly to examine alternative models and explanations of emergency egress behavior.

2.3 AN EXAMINATION OF FACE VALIDITY

Comparisons such as the one discussed above provide primary evidence concerning the validity of a computer simulation program, and help to delineate the boundaries and conditions of its application. Of somewhat less obvious value are analyses of a simulation's "face validity," in which correspondence between simulated events and results reported in the literature is sought, and in which comparisons between simulations and conventional and professional wisdom are considered.

2.3.1 Comparisons With the Literature

Comparisons between BFIRES outcomes and phenomena reported <u>independently</u> by other investigators may be of value in determining (at least on some qualitative level) the external validity of the simulation model. Moreover, such comparisons should further illuminate the boundaries within which BFIRES is applicable.

Perhaps the most important contribution by the London Transport Board researchers (London Transport Board, 1958) was their realization that complex pedestrian systems must be studied in their entirety, since various segments of such systems tend to vary in terms of their carrying capacities and other characteristics. BFIRES sensitivity analyses reported by Stahl (1979) appear to conform with the overall opinions of the former investigators. 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 (1976) reported that stress, fatigue, and indecision all had negative effects on rescue performance during a mock evacuation on an actual hospital ward. Although rescue activities are not accommodated by BFIRES, sensitivity tests reported by Stahl (1979) suggest that, in general, indecision and mobility impairments act to increase occupants' egress times, and reduce their overall performance during computer-simulated fire events.

Finally, Wood (1972) and Bryan (1977) reported that evacuation often is not the first action taken during residential fires, and that it often occurs in conjunction with such other actions as alerting other occupants, rescuing others, and calling the fire department. BFIRES directly simulates pedestrian movement only, and 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 the simulated events frequently deviated from an optimal path toward a safe exit, even when simulated individuals were "familiar" with the building (i.e., knew the location of the safe exit), were mobile, and were making decisions on the basis of unambiguous and correct information. Although simulated occupants did not "investigate the fire," "alert others," etc., per se, 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 uni-directed exiting behavior is not necessarily an outcome of a fire alert. Occupants may choose to traverse a less direct--but equally purposeful--route to that final exit goal.

Bryan and Wood also reported that, on the basis of their findings, familiarity with the building layout correlated with neither evacuation speed nor 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.

2.3.2 Conventional/Professional Wisdom About Egress Behavior During Fires

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/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 many of 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. As a rule, a minimum of two exits are therefore provided 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 simulated data presented in Section 2.2 of this report.

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 was partially replicated by BFIRES simulations, which suggest that well-defined paths result in short egress times when people 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 amply supported by BFIRES data presented earlier by Stahl (1979).

2.3.3 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 investigation. Fires in various types of residential facilities were selected for content 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:

(1) 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.

(2) Where dead-end corridors were present, some occupants reported overshooting emergency exit doors.

(3) 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.

(4) Evacuees tended to move toward the most familiar exit.

(5) Mid-stream direction changing was often reported, even in cases where such behavior could not be traced to any sudden change in environmental circumstances.

(6) Indecision was frequently reported.

3.0 SUMMARY AND CONCLUSIONS

The external validity of the BFIRES simulation program was evaluated. An analysis comparing outcomes from BFIRES simulation runs with data selected from an archival file was discussed. Results of this analysis suggest that, within the boundaries established by the sample, BFIRES is capable of reproducing certain important fire outcomes, such as numbers of persons ultimately escaping, and loss-of-life.

In addition, the general patterns of emergency egress behavior produced by BFIRES were 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, and suggest that convergence is possible. 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 (1972) and Bryan (1977); and (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 unfamiliar occupants.

In view of the findings discussed above, several directions for future research are anticipated. First, additional simulation studies of the type presented in Section 2.2 will be conducted over as broad a range as permitted by available data bases. These studies will provide BFIRES users with much needed empirical evidence concerning the boundaries within which the simulation program may be considered valid and applicable. Further, as the program is validated against a broader range of occupancy categories, these boundaries will themselves be expanded. Second, other methods of validating BFIRES will be examined and applied, in order to demonstrate convergence more analytically than has been attempted thus far. One candidate method is a variation of "Turing's Test", in which experts in the fire field would be asked to distinguish real fire scenarios from those generated by the computer. Finally, it is expected that future validation efforts will illuminate important aspects of emergency egress behavior that either have not been accommodated by BFIRES, or have been treated incorrectly within the program. Thus, future research concerned with validating BFIRES will be simultaneously directed toward modifying and improving the capabilities of the computer simulation program.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report presents preliminary findings regarding the validity of BFIRES/VERSION 1, a computer program developed at the National Bureau of Standards to simulate egress movement by building occupants during fires. A computer simulation experiment was conducted in order to compare outcomes from BFIRES runs with data selected from an archival file summarizing actual fire results. Findings from this experiment suggest that BFIRES is capable of reproducing such important fire outcomes as loss-of-life indices and numbers of persons ultimately escaping. In addition, patterns of egress behavior produced by BFIRES were compared with those found in the literature, with professional opinions, and with impressions gathered from anecdotal accounts. With few exceptions, these comparisons illustrate agreement between simulations and other data sources.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Architectural research; building fires; computer-aided design; computer simulation; environmental psychology; fire research; fire safety; human performance; modeling technique; simulation.

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