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MODELING EMERGENCY EGRESS BEHAVIOR
DURING RESIDENTIAL BUILDING FIRES

by

FRED IAN STAHL

A dissertation submitted to
the Graduate Faculty in Psychology
in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILSOPHY

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1979

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August 20, 1979
Date

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Chapter 1

INTRODUCTION

OBJECTIVES AND OVERVIEW

This investigation considers the practical problem of emergency egress behavior by occupants during fires in residential buildings. Moreover, it deals with the theoretical problems of conceptualizing and modeling this unique and complex phenomenon. An immediate objective was to provide a basis for developing useful tools for building design, regulation, and evaluation. But the research was guided by other goals of equal importance. Primarily, these were: (1) to demonstrate an approach to organizing and analyzing substantive theory in environmental psychology, and (2) to illustrate the notion that our understanding of discrete substantive areas can be furthered through the study of their interaction within a given milieu.

Tools for Building Design, Regulation, and Evaluation

The importance of this objective will be better understood when one considers the current states of knowledge and practice regarding architectural design for life safety. In general, codes and standards which regulate building design are based upon physical principals and professional engineering judgment. Expectations regarding human behav- during fire situations have historically been couched in broad generalizations and untested assumptions. The soundness of regulatory provisions is typically evaluated only in connection with studies of major disasters: If code-complying features of a building or its mode of occupancy are found not to have performed as anticipated, then some alteration to the provisions is considered necessary. Such changes in regulatory codes generally result from a consensus of professional (engineering) judgment.

Unfortunately, few efforts have been undertaken to assure that lessons learned from each disaster will contribute to a systematic understanding of building fire events. This problem is especially acute when considering occupants' emergency egress behavior. At present, an enormous gap exists between what researchers have yet to learn about emergency egress responses, and the assumptions about these phenomena which typically guide building design.

This thesis suggests that such a gap can only be reduced through the introduction of a general model of emergency egress behavior. The purposes of such a model are to: (a) provide the building regulatory community with a framework through which to interpret and apply results of actual fire disasters; (b) provide architectural designers with a mechanism through which life safety problems can be logically anticipated and evaluated while a building is still under design; and (c) provide researchers with a framework for expanding knowledge in this problem area.

Organizing and Analyzing Substantive Theory in Environmental Psychology

The Problem of Theory Development: Similarities Between Environmental Psychology and Sociology

Persistent difficulties for environmental psychologists have involved the development, validation, and application of theories structuring their work (Ittelson, Proshansky, Rivlin and Winkel, 1974; Ittelson, 1976). In general, there has been little disagreement over the roles of theory in guiding the development of specific research strategies, and in suggesting procedures for collecting data. However, to the extent that theory has emphasized a transactional relationship in which persons are viewed as active participants within ongoing socio-physical environments they themselves help create, traditional laboratory experimentation has become theoretically inappropriate. What remains is the enormous task of finding alternative methodological orientations (Proshansky, 1976).

In seeking to understand real-world systems by observing them directly (and by thus rejecting the laboratory paradigm), environmental psychologists have frequently sought parallels in the field of sociology. For example, sociologists Glaser and Strauss (1965) advocated methods of qualitative analysis in the study of social systems, not merely as a prelude to eventual quantitative research (seen to be only rarely necessary), but rather as a basis for developing substantive theoretical statements about those systems. For most practical needs of sociologists, in fact, Glaser and Strauss virtually rejected rigorous quantitative research, suggesting that qualitative data and analyses are sufficient for guiding inquiry, and for dealing with "everyday" questions with which the sociologist might have to deal.

Special Concerns of Environmental Psychologists

To what degree are qualitative methods sufficient for dealing with the "everyday" questions confronting environmental psychologists? Increasingly, these professionals are required to deal with problems cast in specific contractual language (e.g., the language of building design programs and specifications), and laden with far-reaching legal or regulatory implications. When working in such domains as architectural design, urban planning, and governmental regulation, the consulting environmental psychologist is frequently compelled--if not required--to offer recommendations that can be shown to derive from quantitative and rigorous analyses of specific environmental problems. To guide the development of specific methodological approaches in such cases, the practitioners of environmental psychology require quantitative models which can be stated in some empirically testable form.

Quantitative Solutions

Thus, although the qualitative approach to theory construction suggested by Glaser and Strauss and others seems sufficient in the development of tentative, general models, quantitative methods for analyzing such models may nevertheless be required. Where correlational data has been obtained from historical documents, anecdotal accounts, or uncontrolled field studies, for example, behavioral scientists have begun to conduct so-called path analyses, based on statistical techniques which enable investigators to draw weak causal inferences from nonexperimental data. Path diagrams, and their associated path coefficients, permit researchers to construct static descriptions of a given environmental system.

Moreoever, where a description of a dynamic process is required, or when it is necessary for a problemsolver to make predictions about the future behavior of a system, computer simulation offers an alternative approach to constructing and analyzing models. Models so constructed may be induced from qualitative investigations of a system's behavior, or where such investigations are impractical to conduct, they may be deduced from some higher order theory or conjecture. Where theoretical guidance is unavailable, computer simulations may even be constructed on the basis of an investigator's speculation about a system's behavior. The remainder of this dissertation details the analysis of a model of emergency egress behavior during fires in residential buildings, via computer simulation methodology. While somewhat speculative, this model is based upon an "information processing" explanation of human cognitive behavior.

Furthering Understanding of Relevant Substantive Areas

Perhaps the most important requirement of computer simulation methodology is that the investigator must explicitly define the parameters and relationships believed to comprise the system under study. Computer programs are themselves totally closed systems, and if any parameter or relationship is left undefined, a program cannot function. But when attempting to model such complex environmental systems as the building fire, the investigator is quickly overloaded with variables and relationships describing decisionmaking under stress and uncertainty, environmental stressors, the role and use of information, the effects of information overload, etc. Often, concepts and data in such substantive areas are not immediately transferable to the study of a particular environmental phenomenon, and so simulation program writers must "improvise"; that is, they must often fabricate their models from elements specifically modified to fit immediate requirements.

Therefore, when developed to model complex systems, computer simulation programs require investigators to speculate about the interaction of numerous parameters emanating from seemingly disparate substantive areas. The resulting configurations (now in the form of programming logic) may themselves be viewed as hypotheses about specific relationships, under the unique conditions established by the problem under study. So viewed, experiments on the computer simulation model serve not only to illuminate the main problem, but to further our understanding of contributing substantive areas as well. The remainder of this chapter details the problem of emergency egress behavior during fires, and establishes a basis for dealing with this problem through computer simulation methodology.

PROBLEM CONTEXT

According to estimates by the National Fire Prevention and Control Administration (NFPCA), some 8000 to 12000 Americans died in fires annually, during the past 20 years (NFPCA, 1978). This represents a rate of approximately 55 deaths per million citizens. The fire fatality rate in the United States remains the highest of all industrialized nations.

According to the NFPCA (1978), there are approximately 10 times as many injuries from fire in the U.S. as there are deaths. In 1974, for example, approximately 123,000 injuries were recorded representing a rate of 620 injuries per million persons. Fire-related injuries tend to be extremely serious: they are frequently quite painful, are often disfiguring, and victims often incur severe costs emotionally, financially, and in the form of lengthy recovery periods. Fire-related casualties most often result from the inhalation of noxious smoke, and also from burns, falls, being struck by debris, etc.

Children under age 14 and elderly persons over age 65 have incurred disproportionately high numbers of fire fatalities and injuries--some 70 to 80% of the annual totals. Moreover, some 93% of all fire casualties occur in residential environments. Although this investigation focused specifically on the residential fire problem, the modeling of occupants' emeregency egress behaviors did not look at the effects of age on egress success.

Statistics showing relationships between age, occupancy, and injury or death from fire suggest that while present building design regulations specifically provide for emergency exits and other safety features in buildings, other factors may be operating which somehow vitiate their intended effectiveness. For example, although fire-resistive residential buildings must utilize special doors to separate apartment units from corridors, and two acceptable means of egress must be provided from apartments or floors, very young children are not likely to have been trained in the appropriate use of such architectural features in an emergency. Similarly, elderly persons may be comparatively slow to respond to ambiguous danger signs, and thus their emergency egress behavior may appear less deliberate and of lower overall effectiveness.

Moreover, recent research has begun to suggest that many people, upon initial fire alert, do not respond as though speedy evacuation from the danger zone was their sole objective (Wood, 1972; Bryan, 1976, 1977). Rather, goal-seeking hierarchies appear to operate, which account for the consumption of much-needed time for safe egress. Examples from actual fire cases include the findings that people in burning buildings have returned to the danger zone to retrieve items of financial or sentimental value, to alert or aid others, etc. In other cases, persons have been noted to deviate from seemingly effective egress strategies, reducing the possibility for safe egress (miscellaneous fire service investigations).

Reviews and research efforts focusing specifically on emergency egress behavior during fires have begun to raise serious questions about the concepts underlying present architectural design requirements (Breaux, et al., 1976; Rubin and Cohen, 1974; Stahl and Archea, 1977). Recent arguments have suggested that:

(a) During the very brief period immediately following fire alert, confusion over the location and severity of the threat, location of exits, and selection of egress strategy may result in the elevation of psychological stress and resultant emotional responses. If true, these factors bring into question the general assumption that building occupants, upon receiving an alert, will proceed immediately, purposefully, and directly to designated areas of safety.

(b) While the provision of adequate numbers of properly designed exit facilities is a necessary condition for effective emergency egress, it may not be sufficient. The factors which predispose area occupants to move from threatened zones to areas of relative safety are diverse and complex. The quality of information through which occupants perceive the threat-laden environment, and their beliefs about the building's fire-resistiveness, may be as essential to egress success as is the provision of adequate exits.

(c) When moving through corridors or on stairs, persons have been noted to exhibit interpersonal spacing behavior which casts into doubt the efficacy of the standard 22-inch channel width unit (based on the shoulder-to-shoulder width of the "average" human) as an appropriate requirement for architectural design (Pauls, 1975).

PRESENT RESEARCH ON THE EMERGENCY EGRESS BEHAVIOR OF BUILDING OCCUPANTS

Extremely little research into emergency egress behavior has been conducted. Over the last few decades, however, several studies have been undertaken. These investigations cluster into two principal categories: (a) studies measuring the flow capacity of egress ways (e.g., corridors and stairs); and (b) post-incident surveys in which survivors from actual fires were interviewed.

Investigations of the Flow Capacity of Egress Ways

In general, the carrying capacity literature has stressed the measurement of flow velocities and rates in buildings of various types. Two overall objectives involved the construction of predictive models of building egress, and the establishment of egress facility design standards. Accordingly, researchers concentrated on the various physical components of egress routes, and evaluated differences in flow characteristics between, for example, downward and upward travel on stairs and ramps, along corridors, and through doors.

The work of Togawa (1955) in Japan is regarded as one of the most detailed analyses of egress flow capacity. Togawa's objective was to survey walking velocities and flow rates on stairs, through doorways, and along corridors in department stores, apartment houses, theaters, museums, hotels, and commuter train stations.

Togawa conducted field studies at the various sites, observing pedestrian movement during periods of normal occupancy (i.e., in the absence of emergency conditions). Both individual and group movement patterns were recorded, and the numbers of persons passing between fixed points were noted.

Like Togawa, Fruin (1971) studied pedestrian movement in various channels. His specific goals were to measure pedestrian volume and density, walking velocity and flow rate, interpersonal spacing, conflict, and queuing. Fruin conducted field studies in public buildings of various types, in which actual users were observed during non-emergency periods. Pedestrians were timed during their journeys between fixed points along various paths, as had been done by Togawa. In addition, Fruin included more general observations of pedestrian movement behavior.

Another example of laboratory research on carrying capacity was provided by Peschl (1971), who investigated the capacity of door openings during simulated "panic" situations. Peschl simulated various doorway configurations in the laboratory, and then asked groups of varying numbers of subjects to press against the door openings until all persons had moved through. Subjects were student volunteers, and large group experiments were assumed to be analogous to, and representative of, "panic" conditions which might be expected during real building emergencies. On the basis of his findings, Peschl concluded that humans may be assumed to behave, during a panic situation, as granular material flowing from bins. Accordingly, he recommended that floors be sloped toward the exit doors, and that a safe minimum door width be about four feet.

While Peschl advocated the "granular", or particle model of egress behavior, Henderson (1971) introduced a more rigorous form of analysis. In particular, he suggested, *a priori*, that the movement of human crowds should be analogous to the propogation of gas molecules, and that such movement should be predictable by the classical Maxwell-Boltzman gas model.

Henderson distinguished between low- and high-density crowd flow, and suggested that each had a counterpart in a model of particle movement. In particular, while low-density crowd flow could be treated as a gaseous medium, high-density flow could be construed as a fluid. His study was confined to an experiment in "low-density" human crowd movement.

Henderson's investigation primarily involved two phases. First, he observed human movement patterns in actual settings, and made measurements of directional and velocity vectors. He studied several settings to test various implications of the gas theory: College students on a campus thoroughfare, adults in a traffic intersection, and children in a playgound. Second, he ran computer-simulations using the Maxwell-Boltzman gas equations to generate "particle behavior" in analogous spatial configurations. He then analyzed his data by testing for agreement between movements of humans in real environments, versus those predicted by the simulation.

Interestingly, the Maxwell-Boltzman gas model did predict real-world crowd measures somewhat accurately. Of greater interest is the fact that Henderson attributed much of the variance to sex differences in walking habits of humans (males were found to move faster than females). When interpreting these findings, it is important to bear in mind that the humans observed by Henderson were neither confined to the rigid environmental structures of building interiors, nor were they exposed to life-threatening elements of any kind.

The flow of passengers in London subway stations was investigated by the London Transport Board (1958), in a study which recorded the numbers of persons passing over selected pedestrian ways during fixed periods of time. In addition, population densities and movement velocities were also recorded. In a parallel study, this organization conducted field experiments at a boy's school, in which rates of flow were measured under varying conditions of density in corridors.

Two conclusions resulted from the London Transport studies. First, the investigators concluded that pedestrian "systems" must be studied in their entirety, since different segments may contribute differential degrees of constriction. This contrasts with most other carrrying capacity research, in which segments for detailed study were arbitrarily designated.

Second, the researchers concluded that the mechanisms of crowd flow could not be considered analogous to either liquid or granular flow. Instead, they found that the speed of pedestrian movement with respect to density, was represented by an equation which, in the important middle ranges of density, reduced to the form:

$$k = \frac{v}{d} \tag{1}$$

where: k = a constant

v = speed of pedestrian movement

d = pedestrian density

The investigators argued that this relationship is not analogous to liquid or granular flow, since liquids and granules are virtually incompressible, and their densities may be considered as constants independent of speed.

Pauls (1975) documented the movement of people on exit stairs and other egress facilities under various circumstances. Of major importance is his study of some 40 evacuation drills, conducted in high-rise office buildings in Canada. Pauls distinguished between two types of evacuation: total evacuation, in which all occupants are presumed to attempt egress simultaneously via the exit stairs, and phased evacuation, in which the various floors are cleared according to some prearranged sequence. The principal variables evaluated by Pauls included density and personal space utilization on stairs, speed of descent, and evacuation time. Data collected during fire drills included voice-taped observer comments, taped background sounds, and visual records of stair and corridor activity. It was generally assumed that the drills occurred without prior warning to building occupants.

On the basis of his field studies, Pauls argued that the traditional assumptions which govern stair design in building regulations be reconsidered. He found, for example, that:

(a) Evacuees did not walk in a highly regimented fashion, shoulder-to-shoulder, nor even in staggered files. Side-to-side body sway, individual concern for interpersonal separation, and varying need for handrail support all influenced the utilization of exit stairs by evacuees.

(b) Speed of descent on stairs tended to be more variable, and generally slower, than architects have been led to believe.

(c) Evacuation time in total-evacuation drills appeared to depend upon total building population and available stair width: A 10 story building with 100 occupants per width unit could be evacuated in less than 5 minutes (+/- 20%). By contrast, a 30 story building with 1,000 occupants per unit might take more than 30 minutes to evacuate. Even these estimates assume that evacuees have had prior drill training, that they are not aware of the reason for the evacuation (i.e., that it is only a drill), and that trained supervisory personnel ("floor wardens") are present on each floor.

Pauls' analysis of phased-evacuation methods diverges even further from a traditional "particle" approach to emergency egress. According to his observations, phased evacuation required trained supervisors and the maintenance and utilization of emergency communications systems.

The efficient use of exit stairs was seen to depend not only upon evacuees' movements, but also upon the organization and management of the evacuation.

Appleton and Quiggen (1976) simulated emergency egress procedures at a British hospital. Data gathered from the mock evacuations included patient preparation times, travel times, and travel speeds. The chief objectives of the study were to recommend improvements to decrease total evacuation times, and to develop a general model of evacuation for hospitals.

During the simulations, professional actors role-played both ambulatory and non-ambulatory patients. Two potential fire situations were evaluated: a daytime incident, with all staff members on hand, and a nighttime fire, during which only a skeletal staff was present. The simulated escapes were filmed, and special attention was paid to such activities as: patient preparation, travel across the ward, shunting patients through the exit, movement on stairs, and the staff members' return to the ward to assist other patients.

As did Pauls, Appleton and Quiggen suggested factors operating during fire situations which cannot be adequately explained by particle models. Examples include stress and fatigue, which influenced the performance of staff members, as well as indecision, which occurred when alternative exits were necessary.

Post-incident Investigations

Recently, several investigators have attempted to examine emergency behavior in the context of actual building fires. In these studies, facility design per se was not at issue. Rather, researchers emphasized the need to understand the network of behavioral patterns leading to egress success. The major studies are summarized below.

Wood (1972) had fire department personnel interview victims at the scene of fire incidents. Nearly 1,000 fires were investigated in the United Kingdom. Approximately 50% of these occurred in single-family dwellings, while another 22% occurred in factories and shops. About 2% involved more than 250 occupants.

In preparing his interview schedule, Wood was concerned with the following issues: (a) How occupants first became aware of the fire; (b) The location of occupants at the time of ignition; (c) The first, second and third actions taken by occupants, after being alerted; (d) Whether, and how, occupants attempted to leave the building; (e) Whether occupants had difficulty moving through smoke; and (f) The location of occupants upon arrival of the fire department.

Wood found that most persons interviewed became aware of the fire either when they actually saw smoke, or through having been alerted by others. A few respondents indicated that they were initially alerted by the sight of flames, or by hearing distant shouts. Still others said that vague noises, fire alarm signals, and increases in ambient heat accounted for their initial alerting.

The following factors accounted for about 80% of all first actions reported: Fire fighting, calling the fire department, investigating the fire, warning others, evacuating oneself, and evacuating others. Fighting the fire, remaining in place, calling the fire department, leaving the building, and shutting doors accounted for about 60% of all second actions, and approximately 73% of all third actions reported.

Most actions were found to be similarly distributed across the three sequential categories. An interesting exception is remaining-in-place. This activity was virtually absent as a first action, was found to account for some 15% of the second actions reported, and was finally noted to account for nearly half of all third actions reported.

Wood found that familiarity with the building did not correlate with the directness and immediacy with which a person left the building. However, persons who were familiar with the building: (a) Were more likely to call the fire department; and (b) Were more likely to fight the fire. More people were found to leave the building immediately when smoke levels were minimal. In contrast, immediate egress was less likely for persons who had previously experienced building fires.

Sex differences were also found to influence emergency actions taken. For example, women were less likely than men to fight the fire, or to take other steps to minimize the actual danger. They were more likely than men to warn others, leave immediately, or request assistance.

Replicating Wood's study, Bryan (1977) attempted to describe the behaviors of fire victims in incidents in the Washington, D.C., vicinity. As with Wood, Bryan focused upon reports of action patterns, and correlated these with such other factors as sex differences, mode of initial alert, and prior experiences in building fires.

Bryan generally corroborated Wood's findings on issues concerning mode of initial alert, reasons reported for not leaving the building, reasons reported for re-entry into the burning building, and sex differences in re-entry behavior.

However, findings reported by Bryan failed to corroborate Wood's concerning first action as a function of previous fire experience, and first action as a function of sex. Regrettably, data reported by Bryan were not always presented in a format consistent with Wood's. Consequently, opportunities for comparison along a variety of other factors were lost.

A similar research strategy was employed by Haber (1976), who interviewed survivors of fatal fires in total-care institutions. These included hospitals, nursing homes, and a home for elderly persons. Her principal objective was to determine how social structures changed as a result of fires in these facilities. Haber found that most of the buildings surveyed met all the applicable construction and design codes, and that they had not been criticized as fire hazards.

Rather than building or floor "size", the social structure and institutional organization on floors emerged as important factors. In five of the seven fires investigated, the room of origin was in the extreme corner of the fire floor, far removed from the nurses' station. It was also found that the occupants of such corner rooms tended to be the most deviant and chronically ill patients on the floor. "Undesirable" patients were often assigned to rooms far distant from nurses' stations and the least attention tended to be paid to the most distant patients (in terms of surveillance and supervision).

While it was extremely difficult to reconstruct the pre-fire socio-environment structures in a post-hoc study, Haber found indications that the fires she studied were preceded by changes in normal routine, or by the occurrence of some highly unusual problem in the building.

General Conclusions from the Literature

The two principal bodies of literature relevant to the problem of emergency egress were reviewed. On the basis of this review, several general observations about the state-of-the-art emerge:

(a) Investigations of egress facility carrying capacity were conducted either under contrived laboratory conditions, or in real buildings during non-emergency periods. In no case were subjects under any threat of injury or death, nor did they believe they were. Inferences from these investigations regarding optimal channel widths or configurations have, however, often been assumed to generalize to the case of emergency egress.

(b) Investigators studying the carrying capacity of egress ways were primarily concerned with the design and protection of egress-related building components. Their analyses took no account of other less protected portions of building floors, where life-threatening stimuli are likely to be most acute, and where patterns of emergency behavior usually begin.

(c) Survey research in which fire victims were interviewed has not emphasized the design and configuration of the physical environment. Rather, the reconstruction of behavioral networks was stressed.

(d) While survey research has attempted to describe gross outcomes of building fires, no investigators have focused on the cognitive processes of individual occupants during the emergency event.

INADEQUACIES OF THE PREVIOUS RESEARCH, AND THE NEED FOR THEORETICAL DEVELOPMENT

It was stated earlier in this Chapter that a critical gap exists between what researchers have yet to learn about emergency egress behavior, and assumptions about such behavior which are built into current building design and regulatory practice. It was also suggested that this gap exists, at least in part, because no theoretical framework is available to unify and guide research efforts, to help interpret findings, and to help identify and evaluate life safety design problems. The need for such a framework forms an important argument of the current thesis. Another key argument, also outlined earlier, involves the requirement that theory be developed through a deductive approach, because certain peculiarities and inconsistencies inherent in the previous research did not make available data amenable for use in deriving models empirically. Having reviewed the literature on egress behavior, we can now summarize these difficulties.

First, available data shed virtually no light on the cognitive processes at work during building fire emergencies. For example, while Wood (1972) and Bryan (1977) attempted to identify action sequences, neither described specific processes through which such sequences were determined. Accordingly, there remains no direct knowledge of: (a) occupants' perception of the building-scale emergency environment; (b) mechanisms for gathering and interpreting information about the emergency situation; (c) mechanisms for evaluating alternative action patterns; and (d) strategies for making decisions about action in or upon the emergency environment.

Second, the literature is characterized by several important methodological shortcomings. Taken as a whole, for example, the body of research on egress behavior and human responses during fires was not guided by any single set of objectives. Consequently, individual efforts were neither cumulative nor purposefully directed toward theory development. Instead a collection of discrete studies exists in which it is often difficult to even compare results for ostensibly similar variables. Moreover, many of the studies discussed above suffer problems of reliability and validity. Included are the following:

(a) Such complex constructs as "egress behavior" were often operationalized in terms of pedestrian flow measures (e.g., velocity, flow rate, density). Variance due to social and cognitive factors could not be assessed, and variance attributed to physical design features may therefore have been overrated.

(b) With few exceptions (experiments by Peschl and Henderson), field investigations of the carrying capacity of egress ways were characterized by a lack of experimental controls (comparison groups and/or experimenter manipulations). In fact, most studies involved no tests of explicit hypotheses, and may consequently be viewed as exercises in data collection technique.

(c) Even where meaningful trends might have been found in the carrying capacity data, investigators rarely attempted to describe these trends in a statistically rigorous fashion.

(d) Surveys of fire survivors consisted of scaled, structured, and open-ended questionnaire items. The reliability and validity of the various protocols employed have not, to date, been examined.

(e) Survey researchers never systematically controlled for effects arising from the temporal proximity of the interview and the actual experience. Where too long a period lapsed, for example, respondents' impressions of the event may have changed due to media reports and interactions with other victims. Moreover, the emotional impact of the event may, over time, have altered the individual's memory of the fire experience. Conversely, if the event was traumatic, too short a time lapse could have resulted in distorted reports. For the available data base, the extent of such effects--and hence the validity of findings--are largely indeterminate.

(f) Finally, when properly conducted an interview may yield much insight into behavioral processes which result in safe escape during a building fire. Since those who do not survive can never be interviewed, our knowledge of processes leading to failure can only be based on indirect inference.

SUMMARY, AND ORGANIZATION OF THE DISSERTATION

This investigation considers the practical problem of emergency egress behavior by building occupants. In addition, it deals with the theoretical problems of conceptualizing and modeling this unique and complex phenomenon, and with the methodological issues of computer simulation. The research was guided by the following objectives: (1) to provide a basis from which to develop useful tools for building design, regulation, and evaluation, (2) to demonstrate an approach to the organization and analysis of substantive theory in environmental psychology, and (3) to illustrate the notion that the general understanding of individual research areas can be furthered through the study of their interaction within a given milieu.

Concerning the special problem of human behavior in fires, important arguments advanced by this thesis involve the notions that: (1) A critical knowledge gap exists between what is currently known about the emergency egress behavior of building occupants, and assumptions regarding such behavior which are routinely built into current architectural design and building regulatory practices. (2) This gap can be reduced most effectively through the introduction of a theoretical framework. (3) Deficiencies in the existing literature make empirical model development inappropriate, and suggest the necessity for a deductive approach.

An elementary, or "skeletal" model of emergency egress behavior is presented in Chapter II. The modeling exercise provided an opportunity to combine applicable elements from psychological theory with available empirical knowledge about emergency egress during building fires. Variables and relationships comprising the model were operationalized in the form of a computer simulation program. This program, BFIRES, is introduced in Chapter II. Links between BFIRES and the underlying model of emergency egress behavior are presented in Appendix B, and the program is fully described in Appendix C.

Tests of the internal and external validity of BFIRES are presented in Chapter III. In this dissertation, internal validity refers to the fit between the computer program and the behavioral model from which it was derived. External validity refers to the extent to which simulated fire outcomes correspond to those of actual fire events.

Finally, conclusions and directions for future research are explored in Chapter IV. In particular, findings from the current research will be used to support the utility of computer simulation methodology in modeling specific environment-behavior phenomena, in aiding the development of theory in environmental psychology, and in furthering our understanding of particular substantive areas.

Chapter II

MODEL DEVELOPMENT AND ANALYSIS

BOUNDING THE PROCESS

Context

The tentative model postulated here is grounded with respect to a specific environmental context (occupancy classification): housing. This limits the investigation primarily to examples of multi- and single-family dwellings, in which occupants can be assumed to live independently.

Housing occupancy was selected in order to simplify the study. Clearly, this context differs dramatically from that of, say, a hospital or other health care facility, in which patients and residents are frequently dependent upon staff members for assistance during fire emergencies, and where staff are often trained to respond to emergencies in some particular fashion. It should also be noted that the vast majority of fire deaths and injuries, and of available data on human response patterns, stem from residential fires (NFPCA, 1978). Also residential occupancy types will be found to cluster into various categories, within which many similiarities--relative to safety issues--may be found (i.e., design, density, spatial distribution of occupants, space utilization, levels of emergency preparedness or training, life safety potentials and alternatives). In contrast, the scarce data and anecdotal accounts of fires in health-care facilities and other contexts make it extremely difficult to generalize from one fire incident to another. Even though hospitals or custodial care facilities may cluster into generic design and/or service types, life safety preparations--especially in terms of staff role and training--may be found to vary quite widely.

Behavior Patterns

Building regulations concerned with life safety from fire emphasize *egress* behavior, i.e., the movement of persons from threatened to safe zones. Various assumptions noted earlier about such movement are implied in these regulations. Although many other kinds of behavior are indeed present (e.g., fire-fighting, calling for help, crying), considerations of egress movement have had the most direct influence on the *design of buildings* for life safety purposes. To allow the user to entertain immediate comparison with current regulatory provisions and design practices, the model postulated here emphasizes spatial movement behavior. For example, how does floor plan layout or occupant density influence egress movement during a fire? Are present requirements for the provision of exits justified, or do occupants' emergency egress patterns suggest other alternatives? How do factors *other than building design* influence emergency egress success?

Life Safety Systems

Emphasis on egress behavior may also be considered when bounding the study in terms of an overall "life safety system". Caravaty and

Haviland (1967) were among the first to identify a "chain" of safety-related events, emphasizing the time-dependent nature of the fire system. According to these investigators, segments of the fire incident could be identified such that specific reference to event categories might be useful in life safety planning and building design. These segments, in their proper sequence of occurrence, were identified to be (1) detection of the life threat, (2) alerting building occupants to the threat, (3) escape and refuge-seeking actions by occupants, (4) control and extinction of the fire.

Focusing primarily on human behavioral aspects of fire situations, Nelson (1977) structured a similar sequence of events: (1) discovery, (2) alarm, (3) reaction, and (4) evacuation. Other investigators, most notably Wood (1972), Bryan (1976) and Breaux (1977) have, by interviewing fire victims, attempted to elaborate such structures. "Reaction", for example, has often been found to include such seemingly diverse activities as investigation, helping others, and saving possessions, and not merely exit-seeking.

To the extent that empirical research has actually indicated the existence of such time-dependent categories, various structures suggested by several investigators might usefully be summarized as follows: (1) discovery, or the first indication of human awareness of the life threat; (2) alerting, or communication of information about the threat among occupants; (3) decision-making and concomitant action in or on the environment, by alerted occupants (which may or may not be adaptive, and which may or may not result in the safe exiting of particular occupants).

Assuming this time-based framework, this investigation focused upon phase (3): *decision-making and concommitant action*. Accordingly, the analysis proceeded under the assumption that a fire has already been discovered, and that varying amounts of information about its existence (e.g., its location and severity) are already know to at least one of the potentially affected occupants. The model, therefore, is limited to the conceptualization of emergency egress behavior over time, *in response to some given information baseline*.

A MODEL OF EMREGENCY EGRESS BEHAVIOR

Foundations

The preceding discussion introduced the belief that building fires present dynamic environmental settings which, in severe cases particularly, may be characterized by dramatic and rapid changes in the stimuli presented to participating occupants. It also indicated that different forms of behavior become appropriate as the event progresses over time. These factors suggest that fire events may be conceptualized as "information intensive" systems, in which human participants must continually respond to changing information patterns or content.

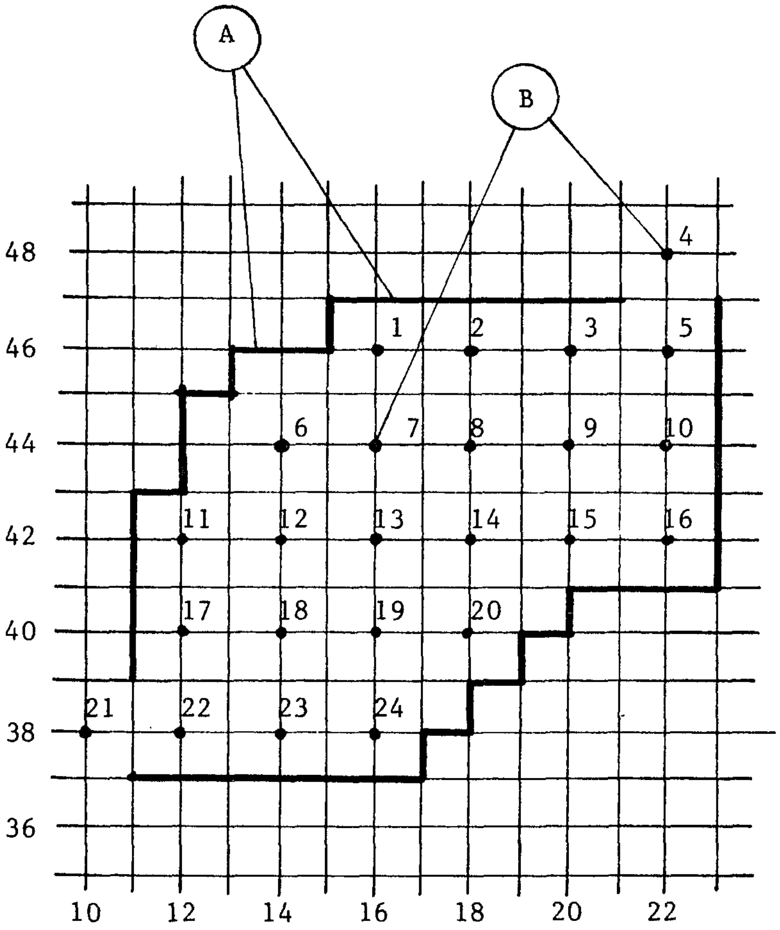
Accordingly, the model of emergency egress behavior posulated here--in its most basic form--was deduced from an information-processing theory of human behavior. It suggests that egress success is ultimately dependent upon: (1) the availability of necessary information about the current state of the system; (2) the quality of available information; (3) the ability of occupants to gather relevant information efficiently; and (4) the ability of occupants to interpret information and to apply it in an effective decision-making strategy.

Expectations About Emergency Egress Behavior

A building occupant moves through an architectural environment as a result of decisions he makes during some period of time. A particular path of travel results from a chain of such decisions. Each incremental decision is derived through a process in which the individual interprets information he has gathered from the environment, in light of his unique movement objectives.

The environmental information field consists of elements external to the individual occupant. These include physical building elements (e.g., walls and doorways), other occupants, and fire products. These elements are not static, and the content of the information field may change continually over time. For example, the spatial location and other aspects of neighboring occupants are constantly changing; the location and severity of life threatening stimuli may change; and the physical features of the architectural setting may change (as a result of human manipulation or pyrological destruction). The current model is concerned with those internal processes by which an individual transacts with this environment.

A simple illustration of these processes involves a planar surface which has been overlaid with an orthogonal grid. Spatial boundaries (i.e., walls) are laid out on this grid, and persons in this field are permitted only to occupy grid points (i.e., the intersection of two orthogonal grid lines; see Figure 2.1). As time advances incrementally,



(A) Walls defining the floor plan

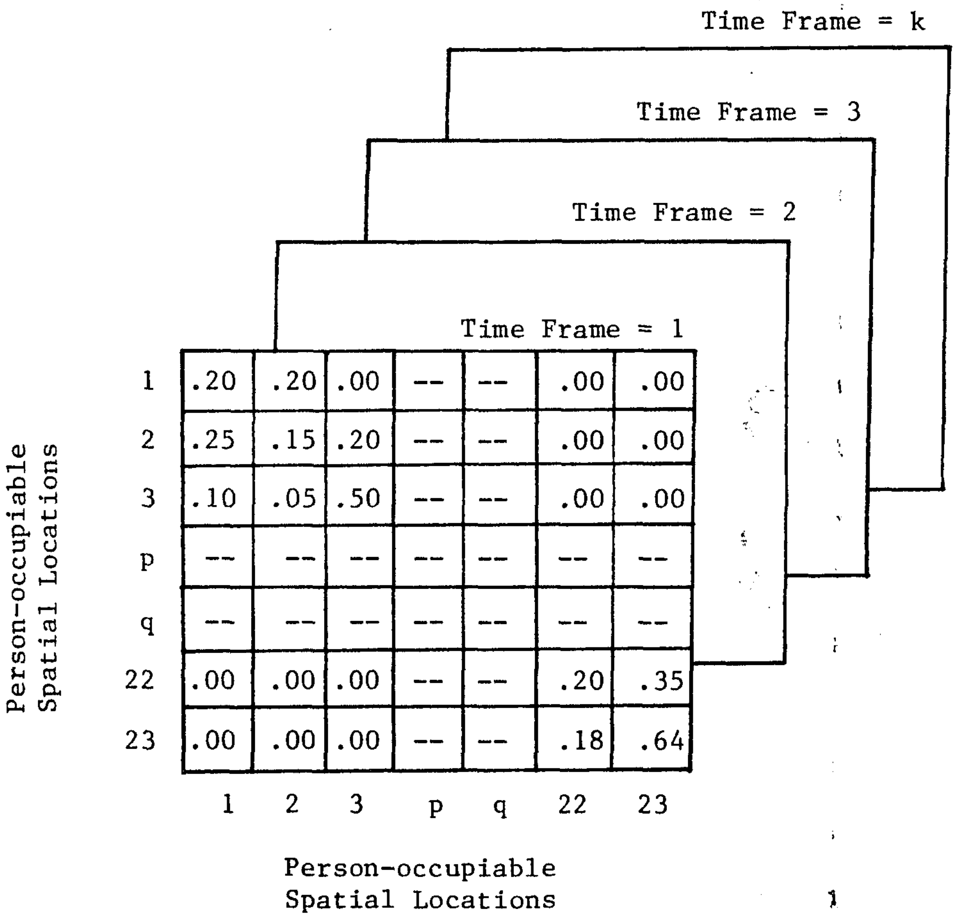
(B) Person-occupiable spatial locations

Figure 2.1 <u>Orthogonal Grid Laid Over a Floor Plan</u>

persons move from one grid point to another. Their decisions to move to specific points are based on interpretations of information they have obtained concerning the degree to which a given move alternative will help achieve some predetermined spatial objective.

The argument thus far does not require the assumption that movement decisions are determined entirely by the state of the external environment. Rather, the process leading to a "decision" is construed as one in which various alternatives are weighed, and by which the probability that each alternative will be selected is derived. Thus, decisions are seen to be biased by environmental information. The biasing of occupants' decision-making behavior, based on their perceptions of current events, is analogous to Brunswik's (1956) "best bet": in a given situation, a person will probably (but not certainly) respond with a particular action. Indeed, in a certain proportion of cases, an occupant will make a "bad" decision, even in the presence of "good" information.

Figure 2.2 illustrates the movement probability concept by means of a matrix of spatial locations. The cells contain values of P_{ij}, the probability that an individual occupying spatial location i will, during a particular time increment, relocate to point j. For any given time increment, each occupant generates "his own unique" P_{ij} matrix, M. Since factors which influence values of P_{ij} vary over time, occupants are thought to "regenerate" their individual matrices at the onset of every succeeding time increment. The process described above may, for analytical purposes, be considered a discrete time, nonstationary Markov process.



	1	2	3	p	q	22	23
1	.20	.20	.00	--	--	.00	.00
2	.25	.15	.20	--	--	.00	.00
3	.10	.05	.50	--	--	.00	.00
p	--	--	--	--	--	--	--
q	--	--	--	--	--	--	--
22	.00	.00	.00	--	--	.20	.35
23	.00	.00	.00	--	--	.18	.64

Probability values in cells are generated by BFIRES, and are updated each time frame to reflect changing conditions.

Figure 2.2 Time Dependent Relocation Probability Matrices

In summary, then, the model postulates that:

(a) Actions in the emergency environment result directly from one's current assessment of available action alternatives.

(b) This assessement is contingent upon such factors as:

(1) perceptions about the availability of action alternatives at time t;

(2) specific perceptions about the possible outcomes of each alternative;

(3) perceptions of information defining the current state of the emergency environment (i.e., the context for action at time t);

(4) attitudes toward the emergency event; and

(5) familiarity with the physical environment, and/or with formal instructions regarding effective behavior during building fires.

In addition, assessment requires the individual to consider the relative advantages and disadvantages of each move alternative, a process which results in the "weighting" of action possibilities at each point in time.

(c) Actions in the emergency environment, at any point in time, have the potential of effecting changes to both its physical and social attributes.

(d) The emergency environment, as altered by a person's actions, provides the cues, stimuli, and information necessary to formulate his action decision during time increment t+1.

Obviously, the process of decisionmaking in a changing environment comprises the keystone of the model. The major components are readily summarized: As the fire event progresses over time building fire participants perceive their environment, alternative movement actions within it, and possible consequences of such alternatives. The use of these perceptions may be modeled as a process in which alternative movement actions are evaluated and weighted, and in which decisions about what to do (specifically, where to go) next are made. As the emergency environment undergoes change, perceptions of it are altered, and as a result, action strategies and behaviors are expected to change.

Finally, this decision process does not determine action outcomes entirely. Rather, the weighting procedure has the effect only of biasing (i.e., increasing the likelihood of) behavior in some particular direction. Depending upon the array of information available to an occupant at time t, his movement decisionmaking behavior may be biased, for example: (1) to evade the threat, (2) to seek-out or approach the exit objective; (3) to respond to some real-time interruption in goal-seeking behavior.

THEORIES, MODELS, AND SIMULATIONS

Until this point, the terms "model" and "theory" were used somewhat interchangeably. However, the distinction between them is important, and bears directly on the method of analysis explored here. A theory, comprises any set of interrelated constructs, definitions, and propositions that present a systematic view of a phenomenon, by specifying relations among variables (Kerlinger, 1973). The purpose of a theory is either to explain or predict the phenomenon. Key attributes are propositions which define constructs, specifications of relationships, explanation, and prediction. In this sense, the conceptualization presented in Chapter II should be viewed as a theory about the emergency egress behavior of occupants during fires in residential buildings.

Taken in the broadest sense, a model is any entity which represents something else. If a theory is written as an interrelated network of English-language statements, or as a set of mathematical statements, then a model would present the most salient aspects of these in some analogic form. Moreover, where concern is with a theory about a dynamic, time-dependent system operating in the real-world, a model of this system is expected to translate constructs and relationships into a form capable of expressing the system's dynamic characteristics. The "gas" analog of human pedestrian behavior, and the "hydraulic" model of free-market economic theory are examples of such models.

In traditional forms of experimentation, theoretical systems usually find analogies in the form of laboratory settings and manipulations. These are designed to simulate real-world conditions under which the theory is expected to hold. Such simulations often raise questions concerning the generalizability of observed behaviors beyond the laboratory exercise. Often, this problem can be mitigated through experimentation in field settings, in which both the analog and the actual conditions under which the theory is expected to hold are one and the same.

However, human behavior in building fires does not lend itself to study through either laboratory simulation or field investigations involving human participants. It is neither practical nor ethical to expose subjects to actual or perceived life threats and dangers, and it is unlikely that events recreated in the laboratory will exhibit the richness necessary for meaningful generalizations. In addition, the task of conducting field experiments during actual building fires would be extremely difficult and costly, and open to serious ethical and legal questions. Because of these factors, this analysis makes use of an alternative means of system simulation: computer simulation methodology.

As with laboratory simulation, computer simulation permits experimentation on a model over time (Kleinjnen, 1974). In both cases, experiments are conducted to test models of real-world systems (which are designed in accordance with specifications derived from an *a priori* theory about a phenomenon), and not the real system iteself. The model under test in computer simulation is, of course, a computer program designed to "imitate" system dynamics postulated by the theory. To the extent that the computer simulation produces outcomes predicted by the theory, the model (computer program) can be thought of as an accurate analog (the problem of "internal validity", examined in Chapter III). To the degree that an internally valid simulation program is capable of producing outcomes similar to those of real-world events, both the program and the underlying theory may be thought of as useful mechanisms for understanding the actual phenomenon (the issue of "external validity", treated in Chapter III). Before presenting a computer simulation program designed for the current problem, the salient literature on simulation modeling is briefly reviewed.

A REVIEW OF RELEVANT LITERATURE ON SIMULATION MODELING

During the last fifteen years, there has been considerable interest in the application of computer simulation techniques to the study of human cognitive behavior (Feldman, 1962; Luce and Raiffa, 1964; Simon, 1967, 1969; Apter, 1970; Schultz, 1974). Arguments have frequently concerned the simulability of human thinking and decision-making (e.g., Neisser, 1963 vs. Simon, 1967), issues of validity, and questions about what to simulate (e.g., processes or outcomes?). Amidst an often confused philosophical climate, computer programs were written, and many simulation-based experiments on human cognitive, motor, and social behavior were conducted (Newell, et al., 1965; see the review by Dutton and Starbuck, 1971).

Moreover, interest in the application of computer simulations of the study of micro-scale person-environment relations has also been evident. Several programs have been written attempting to simulate pedestrian movement behavior within bounded environments, and there have also been attempts to consider human behavior in fires through simulation technqiues. Several examples which are relevant to the problem of simulating behavior under stressful conditions are reviewed below.

Computer Simulations of Pedestrian Movement Behavior

The chief objective of Krystiniak (1972) was to provide pictorial computer output demonstrating the effect of floor-plan arrangement on pedestrian circulation patterns in buildings. His "pedestrians" were endowed with the physical characteristics of body dimensions (the so-called "body ellipse"), with individuality of walking speed, and with the ability to sense obstacles and barriers (e.g., walls). Each pedestrian was presumed to have one and only one objective in the building: to get to his randomly selected exit door in the least amount of time. Door selections were made prior to the actual simulation, and once initial and terminal points were established, a deterministic distance-minimization routine took over. Pedestrians then negotiated the floor plan, approaching their objectives, while avoiding collisions with walls or other obstacles.

In another example, Studer and Hobson (1973) constructed a model of spatial movement behavior predicated on an operant discrimination learning base. In moving from point to point in a spatial field, individuals were seen to continuously select particular routes from among various available alternatives. When movement along a particular route resulted in some short-term goal attainment, the probability that the reinforced individual would make a similar selection decision in the future was increased.

Baer (1974) investigated the simulation of free-flow pedestrian movement behavior within bounded spaces. In response to difficulties imposed by models which primarily considered input and output conditions, ignoring the nature of the behavioral system itself, Baer's simulation focused on the behavior of the individual pedestrian during his trip. The model permitted the simultaneous movement of any number of such individuals, at any level of traffic density, to be simulated. Within the spatial system, persons were guided with respect to the physical and behavioral environments by a deterministic procedure which enabled them to alter their speed and direction within any increment of the journey. The model endowed individual pedestrians with goals, motives, and the ability to evaluate obstacles. However, it is not entirely clear how so-called "free flow" behavior is usefully modeled by a non-stochastic process. Were Baer to expand the scope of his model to include patterns of response to distractions from long-range goals, interpersonal relations, emergency situations, or the psychological effects of crowding, deterministic predictors may not be found to adequately reflect the spontaneity or uncertainty of actual human experience.

Along somewhat different lines, Lozar (1974) discussed a method for simulating spatial behavior in an attempt to determine whether design influences an individual's attitudes toward the environment. In his program, the likelihood that a simulated person would proceed along a particular path was determined by observing movement behavior in the real world (a dining hall).

Computer Simulations of Human Behavior in Building Fires

Perhaps the earliest attempt to simulate by computer the actions of building occupants during a fire was conducted by Wolpert and Zillmann (1969). These investigators constructed a computer model of decision-making in a spatial context. Using the theater fire problem as a case for study, the program largely described individuals' selection of, and then movement toward, alternative goals made conspicuous by new information produced by a fire threat that expanded, contracted, or remained stationary. Forced to continuously reassess their location within a spatial context of uncertainty, actors erected barriers, advanced or retreated, working independently or in groups. Selection from among alternative courses of action depended upon one's location within the space, in relation to the position of the threat and the various safety zones. This selection process was simulated in a non-stochastic fashion. The Wolpert and Zillmann program operated under the assumption that, during a highly stressful period, occupants were capable of objectively assessing time and distance values which separate themselves from both the threat and from available refuge areas, at any given moment. Moreover, in considering the theater fire problem in which all relevant events are occuring within the same spatial field, it was presumed that occupants were always in full visual command of the situation. Accordingly, calculated decisionmaking could be considered possible. The model was capable of generating so-called "panic" within any individual, which allegedly resulted when the person realized that attainment of a desired safety goal had become impossible. Individuals in such a state were then presumed to act maladaptively, clogging impassible exits rather than seeking other egress possibilities.

Concerned with a somewhat different problem context, the simulation model developed by Edmondo, Hahin and Sinay (1969), and the computer program written by Sinay (1971), featured both stochastic and deterministic characteristics. Conducting research for the U.S. Navy, these investigators dealt with the problem of ship-board emergencies, such as fire, bombardments, collisions, etc. The probabilistic components of their program included establishment of both the time and location of the onset of the emergency, the initial locations of ship crewmen, elapsed time until detection of the emergency, and the selection of a response model (i.e., aiding others, securing a space, panicking, escaping). The essential deterministic feature was the selection of an escape route, given certain environmental conditions, from a small array of pre-determined possibilities. Accordingly, once an individual understood the situation, his entire escape route (including possible detours, as necessary) became known in advance. Prediction of escape time could then be simply calculated from a knowledge of the route's length, and a simulated crewman's walking speed.

Most recently, the computer simulation of human behavior in building fires has been considered by Korkemas (1977). For simulated fire events, his chief objectives were to plot fire spread over time, plot occupants' movement patterns over time, record the history of occupants' fates, and to record the history of congestion at building exits. As with the exercise by Edmondo, et al. (1969), Korkemaz's simulation program utilized both stochastic and deterministic variables. The chief probabilistic features included initial fire location, detection time by occupants, and occupant movement velocities. Deterministic variables included fire migration, rates of increase of toxic substances in the atmosphere, and occupant movement (i.e., spatial displacement) along <u>pre-defined</u> paths. As time advanced, the fire covered ever-wider territory, and the density of toxic substances in the air increased. These were assumed to have the major effect of slowing the occupant down, as he moved along his pre-set path to a refuge zone or exit. The rate of decrease in movement speed was governed by deterministic equations. If occupants failed to reach their goals before the level of toxicants surpassed their tolerance levels (adjustable by the experimenter), then they were assumed to have been consumed by the fire. In commenting upon his work, Korkemas recommended that future simulation programs would have to account for a "familiarity factor" (i.e., the notion that some people are more familiar than others with circulation paths within the building, and that such familiarity might influence emergency response), selection from among alternative routes, and the possibility that mid-course route-switching might occur. This factor is critical since in any given building, occupants may be expected to vary in their familiarity with the physical layout. Accordingly, occupants may not share similar perceptions regarding appropriate egress strategies.

Critique

On the basis of earlier discussion of human behavior in fires (Chapter I) and of the development of conceptual schemes and models of such behavior (Chapter II), important limitations of the utility of the simulation programs reviewed above become apparent. First, each of the simulation models and programs reviewed presumes an environmental deterministic basis for behavior. Earlier discussion, however, suggests that for the fire context there is an apparent need to view the environment in terms of both physical *and* social components, and to emphasize the importance of the environment *as mediated* through perceptual and cognitive processes. The importance of viewing building occupants as active participants, who continually modify their environment, and are thereby affected by its changing structure over time has also been noted earlier.

Moreover, most of the simulations discussed avoided the question of how particular paths were created, or why they were followed. In fact, these routes were pre-set, or inserted by the experimenters, who made certain assumptions about emergency egress very similar to those which underlie current safety design codes: when the alarm sounds, people will immediately and purposefully seek exits in the most direct manner. Finally, none of the investigators discussed above reported tests of the validity of their simulations.

"BFIRES": A COMPUTER PROGRAM WHICH SIMULATES EMERGENCY EGRESS BEHAVIOR

A computer program was designed and written specifically to simulate the theoretical framework presented earlier. This work was carried out at the National Bureau of Standards (NBS), a research facility of the United States Department of Commerce. The program is designated "BFIRES", and was written in FORTRAN V for the UNIVAC 1108 computer at NBS.

The central features of BFIRES is the "individual occupant loop". This cycle enables all occupants on a building floor to individually exercise their decision-making procedures, during each time increment. The occupant loop consists of three main components: (a) an information gathering component which scans the information field; (2) an information interpretation and processing component which compares available information with predetermined objectives, biases spatial behavior, and establishes values of P_{ij} (the probability of moving from location i to location j); and (3) an action component which probabilistically selects the actual move to be undertaken, and relocates the occupant.

The occupant loop functions within the next higher level of BFIRES: the "time loop". The time loop enables the iteration of individual occupant decision procedures over the span of a fire event, on the assumption that the event may be subdivided into a finite number of discrete units of equal duration. All occupants in the simulation are "processed" during each successive iteration of the time loop. Each time loop iteration is referred to as a "time frame". Appendix A treats the conversion of time frame units to real time units (i.e., seconds).

Finally, the time loop is nested within the "replication loop". This facility enables the experimenter to run any number of replications of a simulated fire event, under a single set of input conditions. As the highest level of the program, the replication loop also serves as the BFIRES executive routine.

The composition of BFIRES and the location of principal subroutine calls are illustrated in Figure 2.1. The functions of essential subroutines are outlined in Table 2.1, and the rationale and theoretical issues underlying BFIRES subroutines are detailed in Appendix B. Program flow diagrams, computational formulas, and FORTRAN listings are provided in Appendix C.

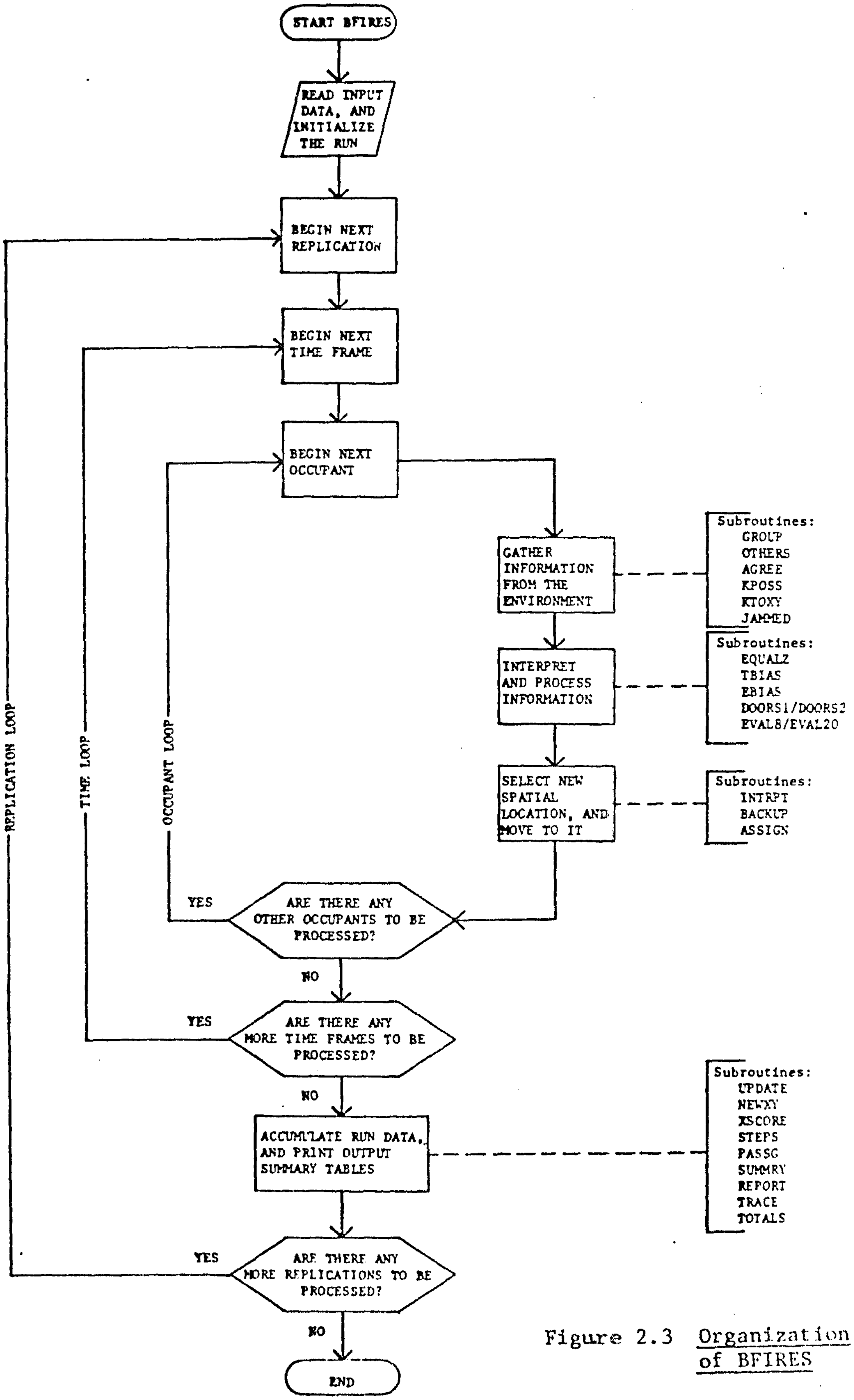


Figure 2.3 Organization of BFIRES

Table 2.1 Essential Subroutine Descriptions[1]

Behavioral Category	BFIRES Subroutine Name	Outline of Purpose
Perception	GROUP	Establishes and updates the the social environment of occupants as they progress through the simulated fire event.
	OTHERS	Records the number of other occupants in a spatial subdivision occupied by a given person. Records the numbers of others who are mobility impaired (if any), and the states of egress knowledged possed by other occupants.
	AGREE	Determines whether a "consensus exit" has been decided upon by occupants in a given spatial subdivision.
	KPOSS	Scans the occupant's immediate spatial environment, and determines whether a move along any directional vector would be rendered impossible because of either a physical constraint (i.e., a wall), or because of overcrowding by other occupants.
	JAMMED	Enables the occupant to gather information about the degree of physical crowding of locations he may wish to enter.

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[1] Refer also to Appendices B and C for theoretical foundations and functional details.

Table 2.1 Essential Subroutine Descriptions, continued

Behavioral Category	BFIRES Subroutine Name	Outline of Purpose
Decision-making	EVAL8	Enables the occupant to process distance information, and to thereby determine his current safety status. A positive status evaluation results whenever the occupant's perceived status at time t is better than it was at time t-1. Otherwise, the evaluation is negative.
	EVAL20	An alternative approach to status evaluation, in which the occupant compares his egress progress at any point in time with his belief about what his progress "should" be. A positive status evaluation results whenever the occupant thinks he is still within the perceived safe time limit. The selection of evaluation processing via EVAL8 or EVAL20 is made by the program user, at execution time.
	EQUALZ	Creates the condition of "indecision" which results when the criteria for decision biasing have not been satisfied. Under this condition, the probability values associated with all move alternatives available to an occupant are equalized.
	TBIAS	Effectuates threat evasion choice behavior. When TBIAS is assigned, move probability values are established in such a way as to favor the selection of moves which maximize the occupant's distance from the life threat.

Table 2.1 Essential Subroutine Descriptions, continued

Behavioral Category	BFIRES Subroutine Name	Outline of Purpose
Decision-making, (cont.)	EBIAS	Effectuates egress goal seeking movement behavior. EBIAS weights move selection probabilities to favor moves that minimize the occupant's distance to an exit goal.
	DOORS1	Determines whether the occupant will open a closed door which is along an available alternative movement path.
	DOORS2	Determines whether the occupant will close a door behind him, once he has in fact passed through.
Action	INTRPT	Probabilistically determines whether the occupant's goal-directed behavior will be interrupted during time t. INTRPT determines both the occurrence and mode of interruption behavior.
	BACKUP	Processes occupants in the "back-tracking" interruption mode, by retracing their steps back toward their initial starting locations. Once this location has been reached by a back-tracking occupant, normal goal seeking is resumed.
	ASSIGN	Considers all factors comprising the occupant's current perception of his situation, and then switches control to the appropriate biasing routine. Once probability values have been established for available move alternatives, ASSIGN selects the next move for the occupant, and relocates him to the new location.

SUMMARY

First, the specific boundaries of the modeling effort were discussed. In particular, the focus of the study was defined as the analysis of occupants' egress movement behavior during fires in residential buildings, at and beyond the temporal point at which occupants actually become aware of the existence of the fire emergency.

Second, a model of emergency egress was advanced, as a tentative postulate for analytical purposes. The model was shown to derive from an information-processing explanation of human behavior, and to consider emergency egress as a discrete time, nonstationary Markov process.

The utility of analyzing the proposed model through computer simulation methodology was considered. The primary argument concerned the notion that laboratory simulations and field experiments with human participants were neither practical nor desirable from social, ethical, and legal viewpoints. A number of recent investigations were reviewed, in which general pedestrian and emergency egress situations were simulated by digital computers. Several shortcomings of the earlier research were noted, and the "BFIRES" computer program for simulating occupants' emergency egress behavior was presented. Chapter III considers results from tests of the validity of BFIRES.

Chapter III

TESTS OF INTERNAL AND EXTERNAL VALIDITY

TESTS OF THE INTERNAL VALIDITY OF THE MODELING PROCESS

Introduction

Rationale

Sensitivity analysis is an important step in the overall validation of computer simulation programs such as "BFIRES". Generally, sensitivity analysis helps the simulation designer to determine whether the "cause-and-effect" relationships which comprise the underlying process model are demonstrated when the computer simulation is run. Another way of expressing this problem is by asking how variation in simulation parameter values affects the results of computer runs, and whether these results conform with hypotheses derived from the underlying theoretical framework.

Sensitivity analysis yields no information about whether the framework correctly describes the actual phenomenon under study. Similarly, it does not tell whether the most important or useful parameters (from an applied point of view) have been selected for study. However, the procedure does provide a considerable amount of information about the internal consistency of the modeling and simulation design processes. This is accomplished through the examination of specific hypotheses about anticipated causal relationships, employing data from computer simulation exercises.

Overview of the Approach

BFIRES enables the user to simulate any number of situations. This is accomplished by adjusting computer input parameters to reflect a particular set of initial occupant and environmental conditions. The complete set of parameters defines the initial state of a given event, which may be altered by changing values assigned to the parameters.

Computer simulations are useful because they help to make causal predictions (of the "if...then..." type), and to evaluate differences among outcomes from initially dissimilar events. Accordingly, one would expect differences in initial occupant and environmental conditions to yield variations in simulated emergency egress outcomes. For example, occupants initially located near a safe exit (and at the same time located far from the threatened zone) would be exptected to leave the building or floor well before those located a greater distance from the exit. Similarly, one would anticipate occupants who are familiar with the building, and who know the location of exits, to escape faster than those who have no such familiarity. Moreover, mobility-impaired occupants would be exptected to require more time to leave the building or floor than will their unimpaired counterparts. These expectations assume that the model accounts for the most salient variables.

The primary question for sensitivity analysis is, then, whether variations in event-defining input parameters produce the expected variations in computer-generated behavior? This question was studied by establishing base fire scenarios, manipulating input parameters, and then measuring differences between simulated egress outcomes (e.g., numbers of occupants escaping, egress time, and path length). According to this rationale, one may conclude that BFIRES is sensitive to variation in a particular parameter if, while holding all other parameter values constant, a significant difference between outcomes obtained from simulations run under two or more different values of the test parameter is found.

For example, if occupants of a floor with deadend corridors require significantly more time to escape than do individuals on a floor without deadends, and all other parameters are held constant, then one may conclude that the computer program is sensitive to variation in an aspect of "floor plan configuration". Similarly, if occupants with no familiarity with exit locations are found to traverse significantly longer paths than do individuals possessing exit knowledge, then, under the given conditions, BFIRES would appear sensitive to variation in "exit knowledge" or "building familiarity".

The following list contains input parameters manipulable by the BFIRES user. To reiterate, the user presents the initial state of a fire events by assigning values to these variables, and differentiates between events by varying the values of one or more parameters. Items marked with an asterisk (*) were the subjects of specific sensitivity analyses reported later in this chapter:

* (1) initial threat location;

* (2) placement of interior doors and exits from the floor or building;

* (3) spatial configuration (involving: layout, corridor arrangement, access to exits, shape of spaces);

* (4) number of spatial subdivisions contained within a floor plan;

(5) number and location of occupants on the floor;

(6) occupants' knowledge of the initial threat location;

* (7) occupants' familiarity with the floor or building (i.e., their knowledge of a "best exit");

* (8) occupants' mobility status;

* (9) permissible occupant density (or degree of crowding);

(10) door type (i.e., whether manually or automatically closing);

(11) initial door position (i.e., open versus closed);

(12) the probability that occupants will open a closed door they encounter;

(13) the probability that occupants will close a door they have passed through;

(14) the probability that an occupant will encounter or experience an interruption to goal-seeking behavior.

These parameters were selected for user manipulation because of their practical appeal and meaning to building designers, regulators and managers, and to professionals interested in evaluating the effects of training programs. The following two experiments are sensitivity tests for BFIRES, drawing on the above input parameters.

Experiment 1

Description and Objectives

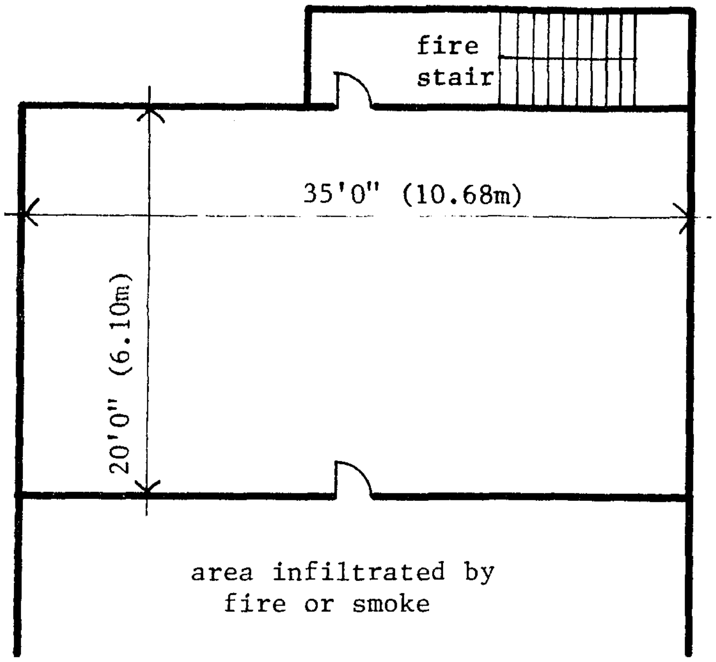
Fire events were run within a simulated rectangular spatial zone measuring 20 feet by 35 feet (6.10 m by 10.68 m). Two exits from the zone were provided, one at the center of each long wall. One exit provided direct egress to a place of refuge; the other connected the zone under study with another section of the building. During all simulation runs in Experiment 1, this latter exit was assumed to lead directly to life-threatening agents (i.e., fire and smoke). Accordingly, although two exits were physically provided from the zone under investigation, one was assumed to have been rendered impassible prior to the onset of the simulation.

Simulations were conducted under various values of the spatial configuration and interior door placement parameters (see Figures 3.1 through 3.4). These conditions simulated different ways of subdividing the original zone into a larger number of smaller functional units (i.e., rooms). These may be viewed as representing variations in the layout of a wing of a house or small apartment building.

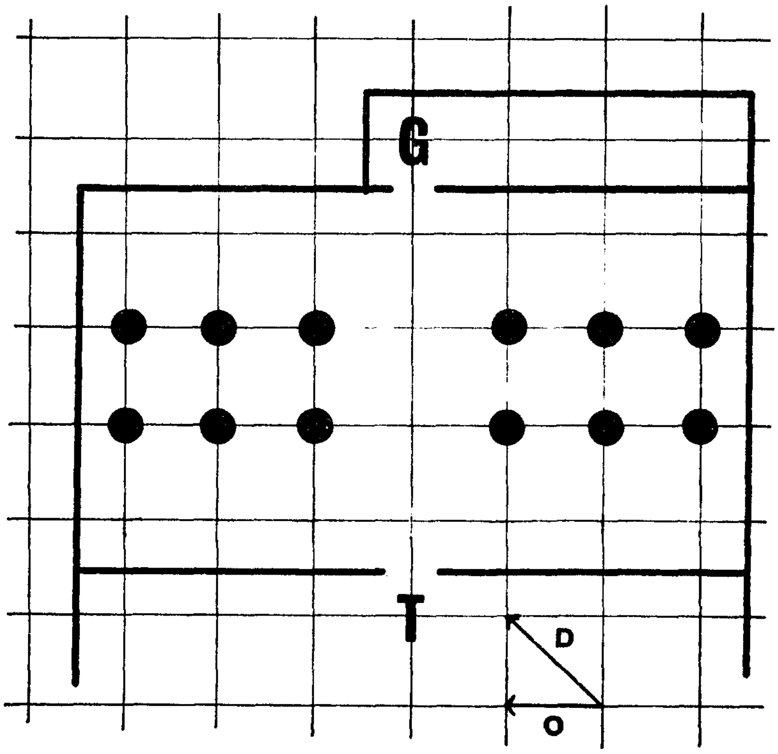
Each simulation run involved 12 occupants. These were initially located at points shown in Figures 3.1 through 3.4. At the start of each run, all occupants were assumed to have been alerted to the existence of the fire emergency, and to the fact that a particular exit was already blocked and should therefore not be used. In all cases, occupants were assumed to be ordinary residents: they were fully mobile without any form of assistance, and they possessed no specialized emergency training.

The principal objective of this analysis was to determine whether BFIRES is sensitive to differences in floor plan configuration (more specifically, the degree of spatial subdivision). Secondary objectives were to determine whether the program is sensitive to variations in permissible occupant density, and whether it produces an interaction effect between spatial organization and permissible density.

(A) Floor Plan



(B) Floor Plan in BFIRES Grid Form

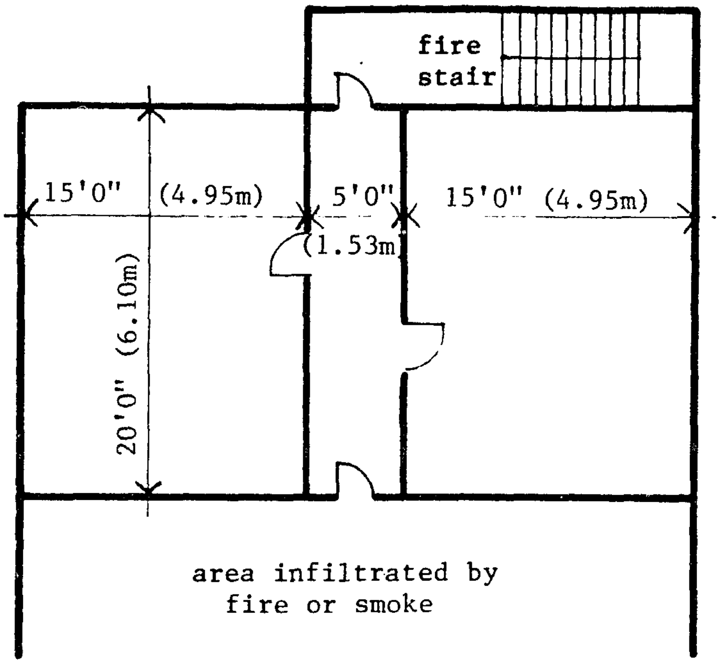


LEGEND:

G	Egress Goal Location
T	Threatened Exit Location
+	Person-occupiable Spatial location
●	Location containing one occupant at t_1
D	Diagonal "step" 7'1" (2.16m)
O	Orthogonal "step" 5'0" (1.53m)

Figure 3.1 Unsubdivided Spatial Zone

(A) Floor Plan



LEGEND:

G Egress Goal Location

T Threatened Exit Location

┼ Person-occupiable Spatial location

● Location containing one occupant at t_1

D Diagonal "step" 7'1" (2.16m)

O Orthogonal "step" 5'0" (1.53m)

(B) Floor Plan in BFIRES Grid Form

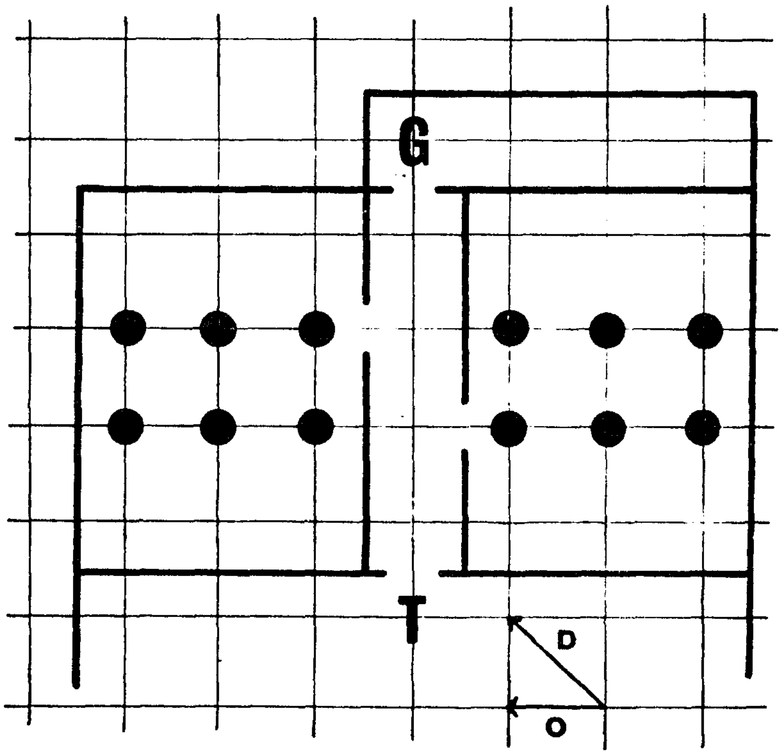
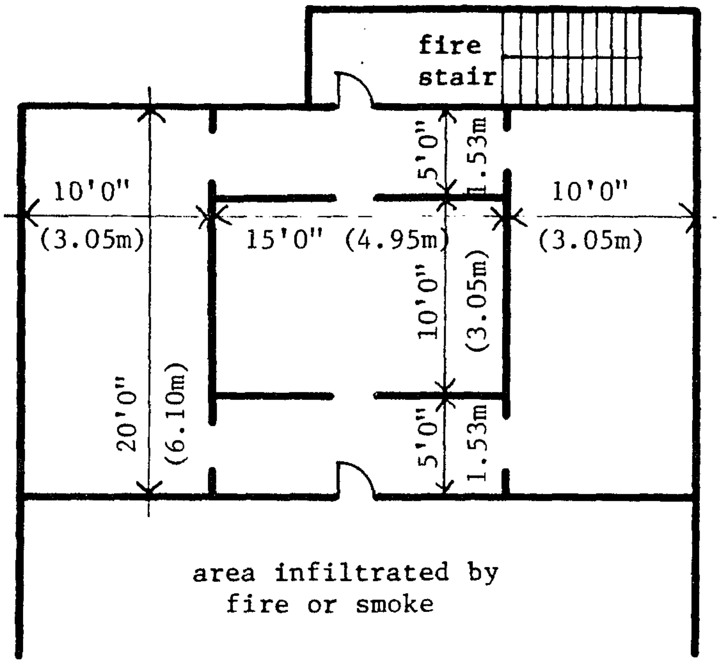
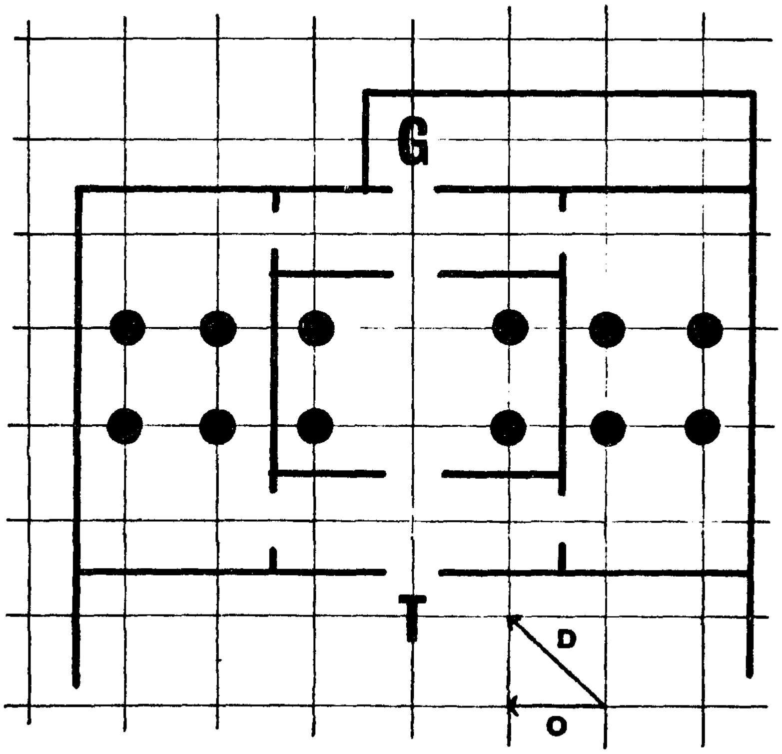


Figure 3.2 Spatial Zone Subdivided into Three Units

(A) Floor Plan



(B) Floor Plan in BFIRES Grid Form

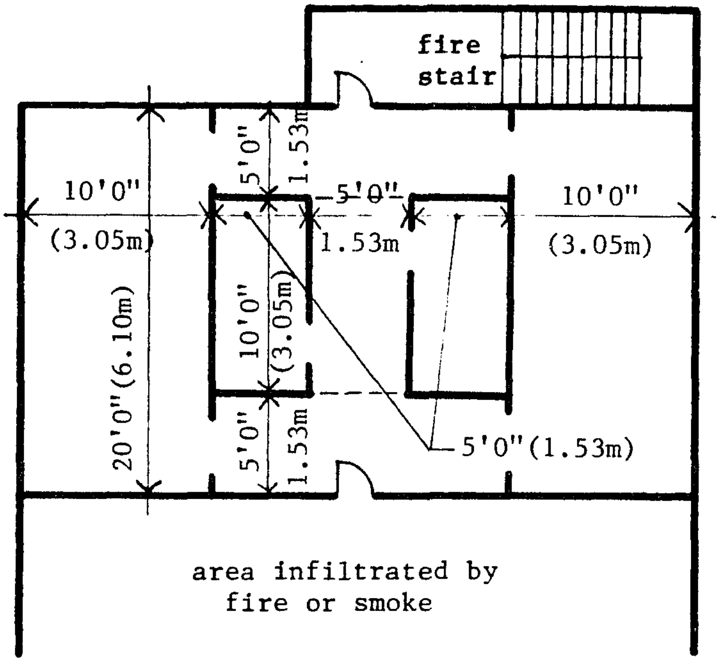


LEGEND:

G	Egress Goal Location
T	Threatened Exit Location
+	Person-occupiable Spatial location
●	Location containing one occupant at t_1
D	Diagonal "step" 7'1" (2.16m)
O	Orthogonal "step" 5'0" (1.53m)

Figure 3.3 Spatial Zone Subdivided into Five Units

(A) Floor Plan



LEGEND:

G	Egress Goal Location
T	Threatened Exit Location
+	Person-occupiable Spatial location
●	Location containing one occupant at t_1
D	Diagonal "step" 7'1" (2.16m)
O	Orthogonal "step" 5'0" (1.53m)

(B) Floor Plan in BFIRES Grid Form

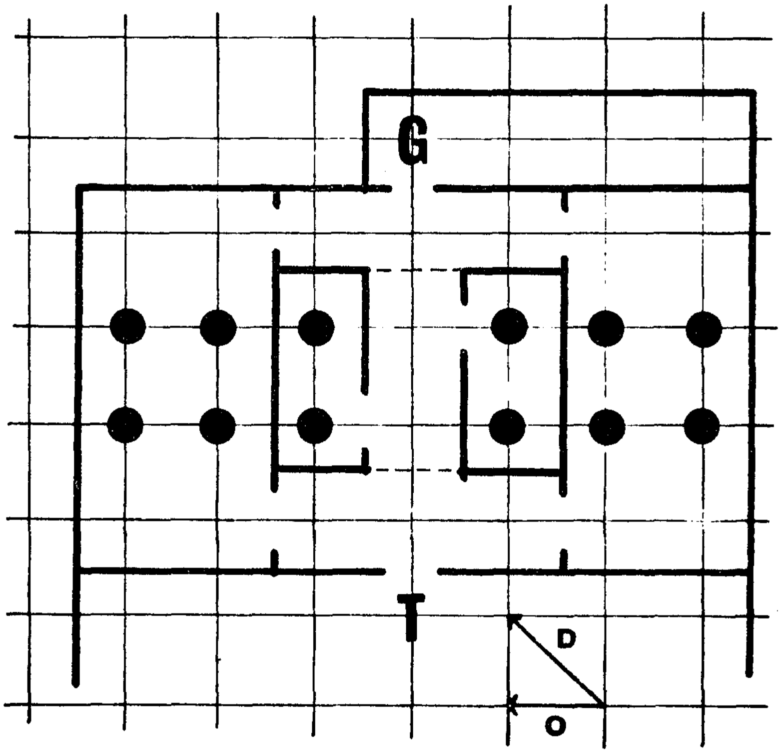


Figure 3.4 Spatial Zone Subdivided into Seven Units

Experimental Design

A two-way factorial design was employed to test the effects of spatial subdivision (the actual number and size of spaces constructed within the basic rectangular zone) and permissible occupant density (the maximum number of occupants permitted to inhabit a single person-occupiable location at any point in time). The 4x3 design is shown in Figure 3.5.

The study of these variables was warranted for certain practical reasons. For example, fire safety regulations address the design of access to exitways, and the "directness" of egress paths, without actually evaluating the costs and benefits of alternative designs. A simulation program sensitive to various aspects of spatial configuration could help address this issue.

The two dependent variables measured were occupants' escape scores and their total numbers of spatial displacements ("steps"). Escape score is the ratio of time required for escape versus the total length of the simulated event, and is computed as follows:

$$E = \frac{t - f}{t} \qquad (2)$$

where: E = occupant's escape score,

t = total length of the simulated event in time frames,

f = total number of frames the occupant actually spent in the floor of study, prior to his escape.

Accordingly, if a simulation was run for a total of 100 time frames, and an occupant escaped during the 50th frame, then his escape score is

SPATIAL CONFIGURATION

(subdivision of a basic spatial zone)

	density thresh. = 1 0.04 persons/ft^2 0.43 persons/m^2	density thresh. = 3 0.12 persons/ft^2 1.29 persoms/m^2	density thresh. = 5 0.20 persons/ft^2 2.15 persons/m^2	
1 space area = 700 ft^2 (65.15 m^2)				
3 spaces mean area = 233.33 ft^2 (21.70 m^2)				
5 spaces mean area = 140 ft^2 (13.02 m^2)				
7 spaces mean area = 100 ft^2 (9.30 m^2)				

PERMISSIBLE OCCUPANT DENSITY

(density threshold)

Figure 3.5 4x3 Factorial Design for Experiment 1 computed to be 0.50. If the individual never escapes during the run, his score will be 0.00. The higher the escape score, the earlier during the simulated event escape occurred.

A spatial displacement, or "step", is a single movement from one person-occupiable location to another, in either the orthogonal or diagonal directions of the grid. Depending upon the manner in which the particular simulation has been calibrated, such a displacement may or may not approximate the average stride length of a person. The total number of displacements made by an occupant during a simulation run, and the extent of deviation from the minimum number of steps actually required, may be used as indicators of egress path directness and complexity.

In addition to the magnitude of differences between event outcomes, the structure of the BFIRES program also suggests particular directions. Accordingly, five hypotheses are examined during Experiment 1.

(1) Escape score varies as a function of the extent of spatial subdivision; as a zone of fixed gross area is subdivided into more (and smaller) spaces, escape score will--on the average--increase (i.e., occupants will escape faster).

(2) Total spatial displacement varies as a function of the extent of spatial subdivision; as a zone of fixed gross area is subdivided into more (and smaller) spaces, occupants will --on the average--traverse shorter routes to the exit goal.

These expectations derive from the structure underlying BFIRES, which requires that before selecting a particular move, occupants first scan the available alternatives weighing the relative costs and benefits of each. This structure implies that as the number of alternatives available to an occupant at time t increases, the likelihood that he will in fact select the biased move decreases. As a result, it was expected that more frequent goal-directed movement decisions, and hence a more direct egress route (i.e., higher escape score and fewer displacements) would result in cases providing the fewest movement alternatives over the course of the event.

(3) Escape score varies as a function of permissible occupant density (i.e., the maximum number of persons permitted to inhabit any person-occupiable location, at any point in time); the more occupants permitted to occupy person-occupiable locations, the more quickly will the floor be evacuated (as evidenced by higher overall escape scores for occupants of the floor).

(4) Total spatial displacement varies as a function of permissible occupant density; the more occupants are permitted to inhabit person-occupiable locations, the shorter will be routes traversed by occupants as they seek the exit goal.

The notion that occupant density (the physical aspect of crowding) impacts egress time and escape route is also expressed in BFIRES, as is the idea that the effects of density vary as a function of spatial configuration. While scanning alternative target locations, simulated occupants assess the viability of each with respect to certain criteria. The first criterion an alternative target must pass is its possibility of being reached. Accordingly, "imaginary" targets which are in fact blocked by walls cannot be reached in a single step, and are thus deleted from the occupant's array of alternatives during time t. Similarly, targets perceived by the occupant as "crowded" will also be ruled out.

Although the reduction of alternatives has the effect of increasing the likelihood of selecting a goal-directed alternative, it also has the effect of reducing the actual number of alternatives leading toward a specified goal. This may influence simulated egress behavior. For example, when occupying a large open space, a simulated individual will often have nine movement alternatives available to him (the maximum possible) at a given point in time. Where the individual perceives three of these alternatives as adaptive (i.e., as being highly goal-directed), and notes that one of these will lead to a crowded location, this choice will be dropped it from the list of alternatives. However, there is still a high probability that one of the remaining two goal-directed moves will be selected.

On the other hand, the individual may occupy a much more confined space, where, at time t, there are only four movement alternatives available. In this case, the occupant may perceive that only one of these will satisfy express objectives. If the target location of this move is perceived to be crowded, then less adaptive movement behavior will result (e.g., remaining in place, or meandering), and valuable time will be wasted.

(5) The effect of occupant density is dependent upon the extent of spatial subdivision; density has the greatest impact where spatial zones are more highly subdivided into smaller units.

The interaction of spatial subdivision with occupant density can now be discussed. In larger spaces, an occupant will often have large numbers of move alternatives available (up to nine) to chose from. More than one of these will usually be perceived as goal-directed, and so the overcrowding of any single key location need not result in nonadaptive movement behavior. Therefore, the likelihood of successful escape from larger spaces should depend very little upon the crowding threshold (permissible number of occupants) for individual spatial locations.

In floor plans subdivided into many smaller spaces, however, the simulated occupant will usually have relatively few move alternatives to choose from any a given point in time. Often, only one of these will be perceived as goal-directed, and hence the crowding of key locations should lead to nonadaptive movement behavior. Therefore, the likelihood of successful escape from highly subdivided zones should depend upon the crowding threshold. In such cases, higher thresolds should "forestall" the perception of crowding, by simply endowing occupants with a greater tolerance for being "packed together". The five hypotheses discussed above are summarized in Figure 3.6.

Data Collection and Analysis

The spatial subdivision and occupant density parameters were examined at levels indicated in Figure 3.5. Variation in spatial subdivision was defined as the extent to which the original 700 square foot zone was subdivided into smaller spaces, as follows:

Level 1: one space; area equals 700 square feet (65.15 m^2);

Level 2: three spaces, mean spatial area equals 233.33 square feet (21.70 m^2);

Level 3: five spaces; mean spatial area equals 140 square feet (13.02 m^2);

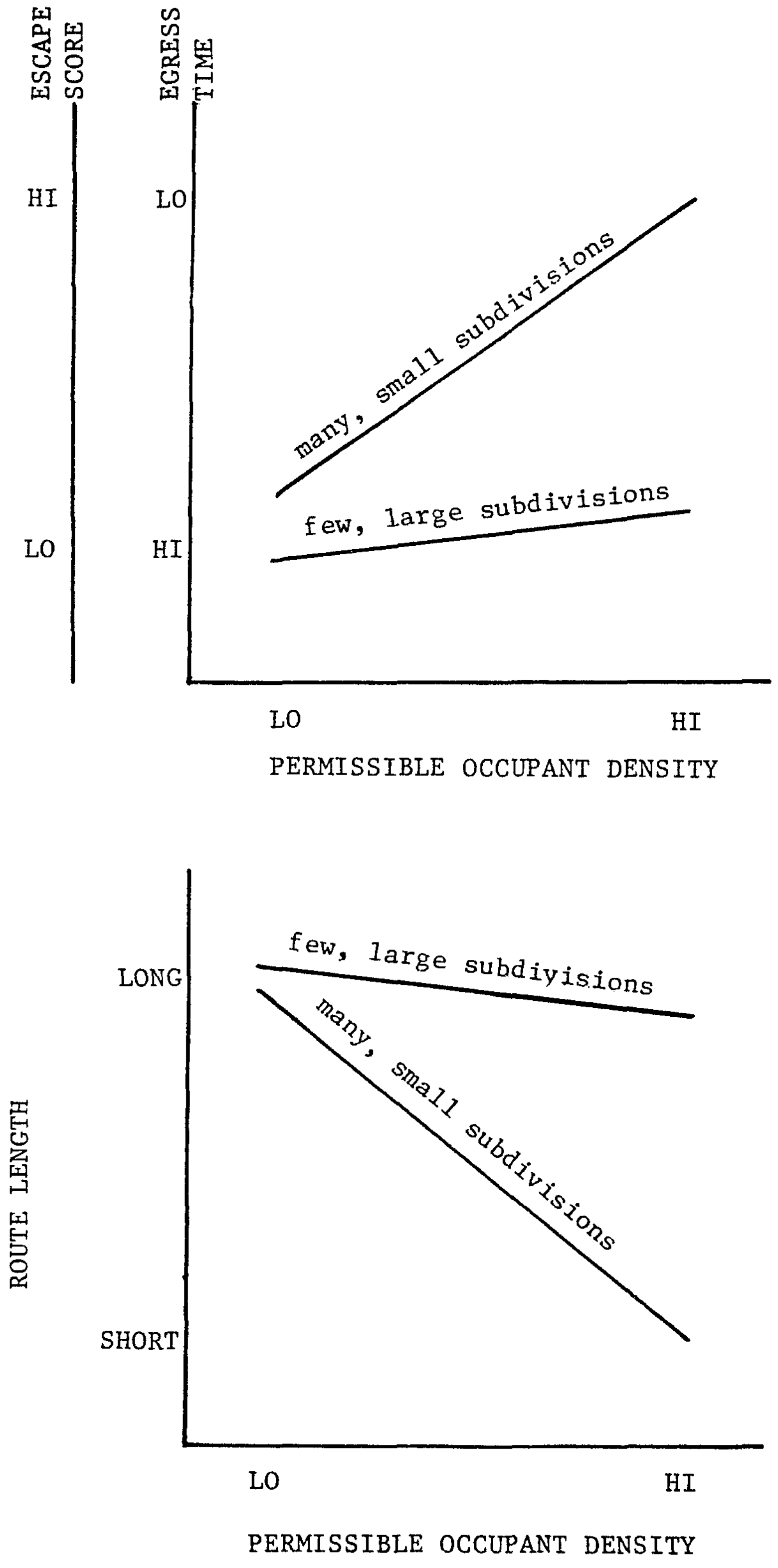


Figure 3.6 Graphic Summary of Hypotheses (1) Through (5)

Level 4: seven spaces; mean spatial area equals 100 square feet (9.30 m^2).

Variation in occupant density was defined in terms of the maximum number of persons permitted to occupy any spatial location at a given point in time. In Experiment 1, a person-occupiable spatial location represented an imaginary envelope of 25 square feet (2.25 m^2). Therefore:

Level 1: density threshold equals 1; maximum allowable density equals 0.04 persons per square foot (0.43 person per m^2);

Level 2: density threshold equals 3; maximum allowable density equals 0.12 persons per square foot (1.29 persons per m^2);

Level 3: density thresold equals 5; maximum allowable density equals 0.20 persons per square foot (2.15 persons per m^2).

The 4x3 design was replicated 10 times. For each cell, values of both mean escape score and mean spatial displacement (across the replications) were recorded. Separate analyses of variance were conducted for each of the two dependent variables (even though they were very highly correlated: $r = -.93$).

The random effects analysis of variance model was employed, in which the interaction mean square is used to compute values of F for the main effects. This model was employed since the levels of the independent variables could, at least in theory, have been selected randomly from some larger range (Edwards, 1972). Use of the random effects model permits inferences to be drawn from the particular findings to all levels of the variables, within such a range.

Results

Mean outcomes from simulation runs assuming density thresholds of one, three, and five are shown in Tables 3.1, 3.2, and 3.3, respectively. Each table indicates mean escape scores and route lengths (in numbers of steps) aggregated across all 12 occupants within each replication. Hence, the grand means were computed by aggregating across occupants and replications, for each level of the spatial subdivision variable. These data are shown graphically in Figures 3.7 and 3.8. Analyses of variance for escape score and step total are summarized in Tables 3.4 and 3.5.

Hypotheses (1), (3), and (5) above were supported by simulated escape score data. In particular, the computer program was found sensitive to variation in both spatial subdivision and occupant density, in the predicted directions. Moreover, the predicted interaction effect between these variables was also found to be statistically significant.

Hypotheses (2) and (4) were supported by simulated data on route length. In particular, the program was found to be sensitive to variation in both spatial configuration and occupant density, in the predicted directions. However, no statistically significant interaction effect between these variables was found.

Table 3.1 Mean Outcomes From Simulations Based on a Density Threshold of 1

Rep	1-Space Plan		3-Space Plan		5-Space Plan		7-Space Plan	
	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps
1	.27	16.50	.18	16.92	.19	17.17	.38	12.58
2	.31	14.50	.28	14.58	.36	12.42	.35	11.42
3	.26	17.08	.33	13.83	.26	14.83	.31	12.50
4	.33	14.58	.22	16.25	.28	14.33	.30	13.25
5	.32	14.67	.20	16.50	.26	15.00	.36	10.58
6	.22	16.50	.26	14.25	.42	10.25	.36	12.92
7	.41	13.58	.27	16.42	.29	14.50	.27	13.67
8	.34	14.17	.24	15.58	.32	13.67	.29	13.00
9	.35	13.58	.17	17.17	.27	14.92	.36	11.83
10	.42	12.75	.22	15.42	.27	15.08	.27	14.58
Means	.32	14.79	.24	15.69	.29	14.22	.33	12.63

Table 3.2 Mean Outcomes From Simulations Based on a Density Threshold of 3

Rep	1-Space Plan		3-Space Plan		5-Space Plan		7-Space Plan	
	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps
1	.18	19.58	.34	13.75	.56	10.25	.49	10.75
2	.39	13.83	.39	14.75	.53	10.67	.55	9.17
3	.49	11.25	.34	13.58	.45	12.33	.51	9.83
4	.38	14.17	.34	15.17	.35	15.33	.46	10.50
5	.43	13.33	.31	13.67	.47	11.17	.49	11.00
6	.32	14.17	.26	16.58	.38	13.25	.29	15.08
7	.42	13.25	.24	16.33	.47	11.83	.58	8.75
8	.33	15.67	.27	16.58	.39	13.83	.56	8.67
9	.39	13.58	.41	13.67	.56	9.08	.45	12.17
10	.39	13.58	.32	15.75	.55	9.33	.54	10.25
Means	.37	14.24	.32	14.98	.47	11.71	.49	10.62

Table 3.3 Mean Outcomes From Simulations Based on a Density Threshold of 5

Rep	1-Space Plan		3-Space Plan		5-Space Plan		7-Space Plan	
	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps	Mean Escape Score	Mean Steps
1	.46	12.17	.32	14.92	.34	14.33	.44	12.92
2	.46	13.17	.20	17.58	.50	10.17	.52	9.50
3	.45	13.00	.38	12.92	.59	8.50	.51	10.33
4	.26	17.08	.40	13.08	.52	10.50	.50	10.33
5	.47	12.00	.21	17.33	.53	10.00	.66	6.25
6	.36	14.83	.27	16.33	.56	9.00	.40	13.58
7	.26	16.83	.35	14.00	.41	12.33	.44	11.58
8	.34	15.08	.42	11.83	.49	10.50	.56	9.58
9	.34	14.67	.26	16.92	.64	7.67	.62	8.67
10	.41	13.75	.29	15.50	.37	13.33	.42	12.92
Means	.38	14.26	.31	15.04	.49	10.63	.46	10.57

Table 3.4 Analysis of Variance for Escape Score

N=120

SOURCE	d.f.	S.S.	M.S.	F
Density (D)	2	.415	.207	12.936**
Number of Spaces (S)	3	.417	.139	8.688*
D x S	6	.097	.016***	3.027**
Within	108	.577	.005	
Total	119	1.506		

Table 3.5 Analysis of Variance for the Total Number of Steps Taken

N=120

SOURCE	d.f.	S.S	M.S.	F
Density (D)	2	69.874	34.937	6.660*
Number of Spaces (S)	3	314.167	104.722	19.962**
D x S	6	31.478	5.246***	1.619
Within	108	349.912	3.240	
Total	119	765.431		

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* $p < .05$

** $p < .01$

*** in the random effects model, the D x S interaction mean square is used to compute values of F for the main effects.

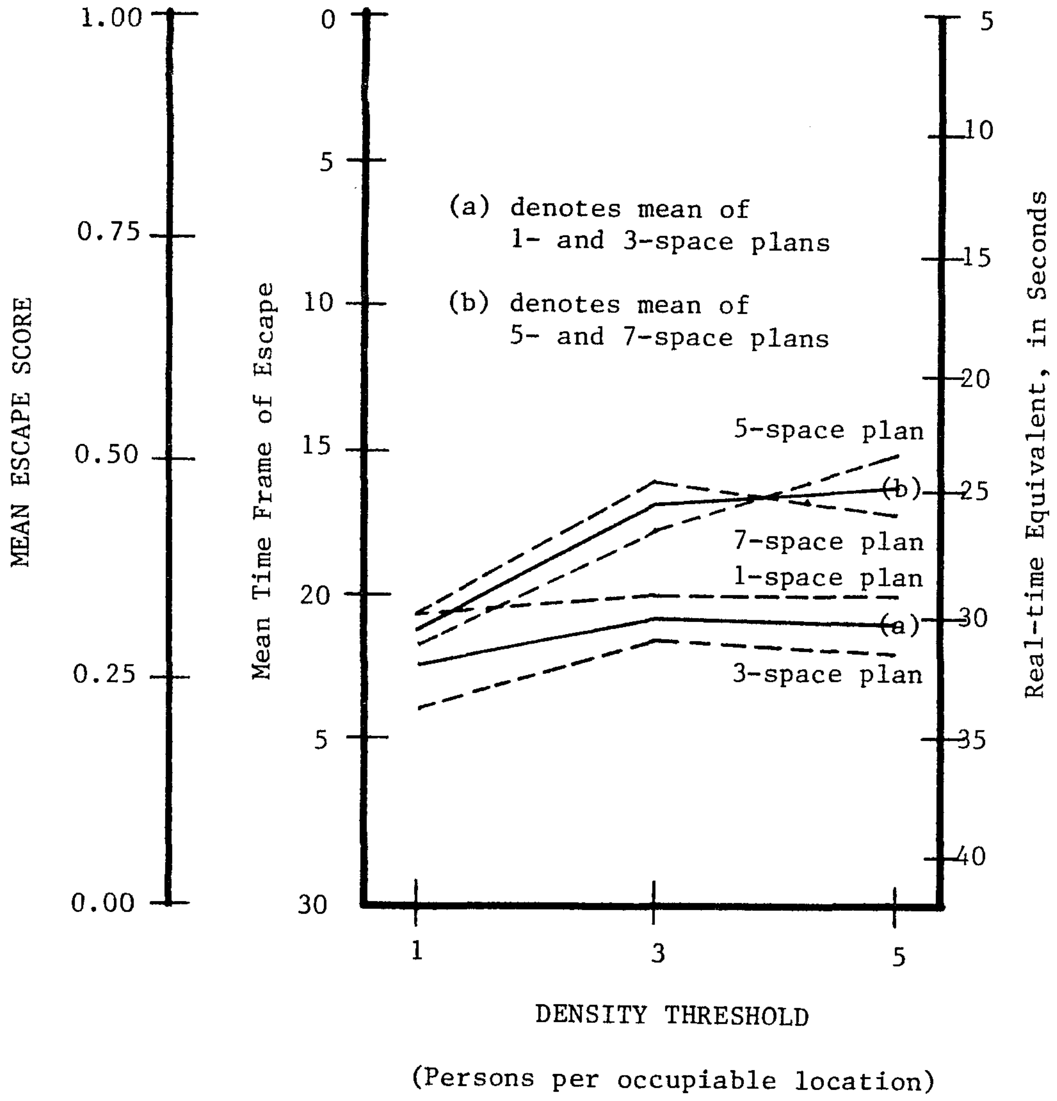


Figure 3.7 Effects of Spatial Subdivision and Occupant Density on Escape Score

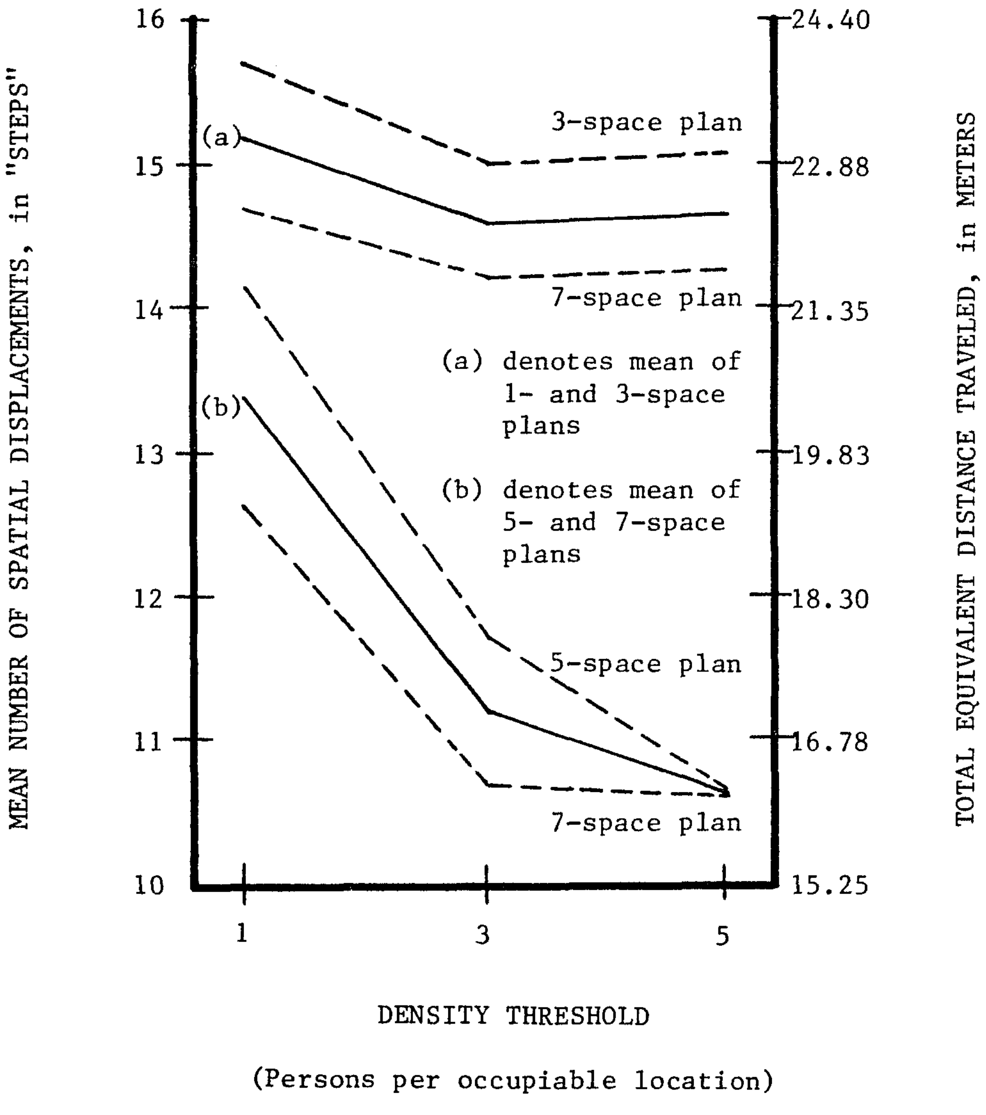


Figure 3.8 Effects of Spatial Subdivision and Occupant Density on Route Length

Experiment 2

Description and Objectives

Findings from Experiment 1 suggest that BFIRES outcomes are sensitive to variations in room size and spatial subdivision. The principal objective of Experiment 2 was to determine whether simulated outcomes are sensitive to variations in other aspects of floor plan configuration (such as the presence or absence of deadend corridors), while holding room size constant. Under these conditions, the effects of variation in occupant density were also studied, as in Experiment 1.

Fire events were simulated in a single story of a multiple floor building. The floor under study consisted of a double-loaded corridor with four rooms on each side (as in a dormitory facility). The corridor was divided into two segments by a wall, and the segments were connected by a doorway provided in this wall. Two egress stairs were provided. One stairway led to a place of refuge; the other was assumed to be smoke-filled, due to a fire already burning on another floor of the building.

Simulations were conducted under two different floor plan configuration conditions. In the first condition, stairways were located at the extreme ends of the corridor (Figure 3.9). In the second, the stairways were located closer toward the center of the building, leaving deadends of 15 feet (4.58 m) at each end of the corridor (Figure 3.11).

Each simulation run involved 20 occupants. These were initially located at points shown in Figures 3.10 and 3.12. At the start of each run, all occupants were assumed to have been alerted to the existence of

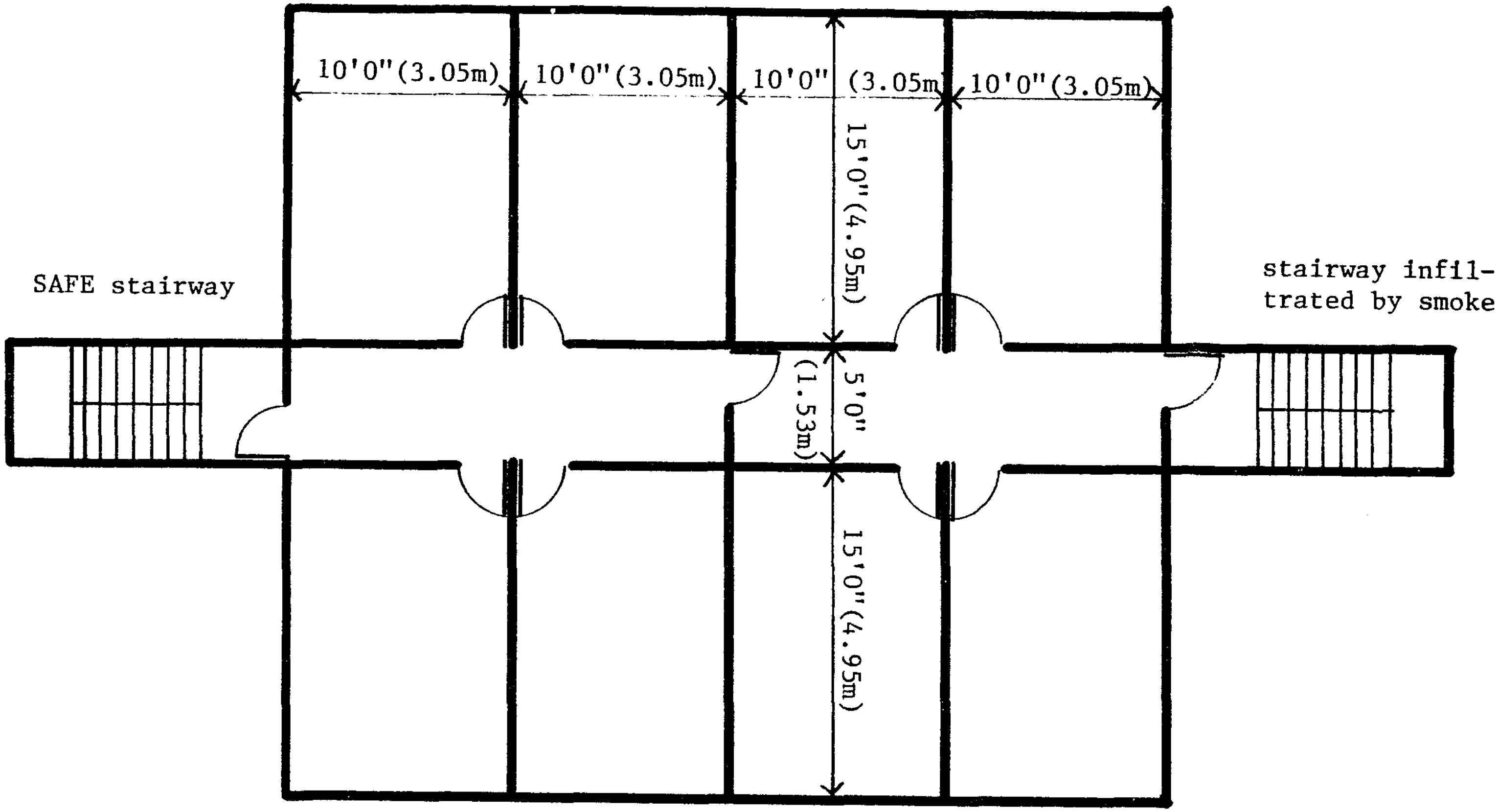


Figure 3.9 Non Dead-end Floor Plan

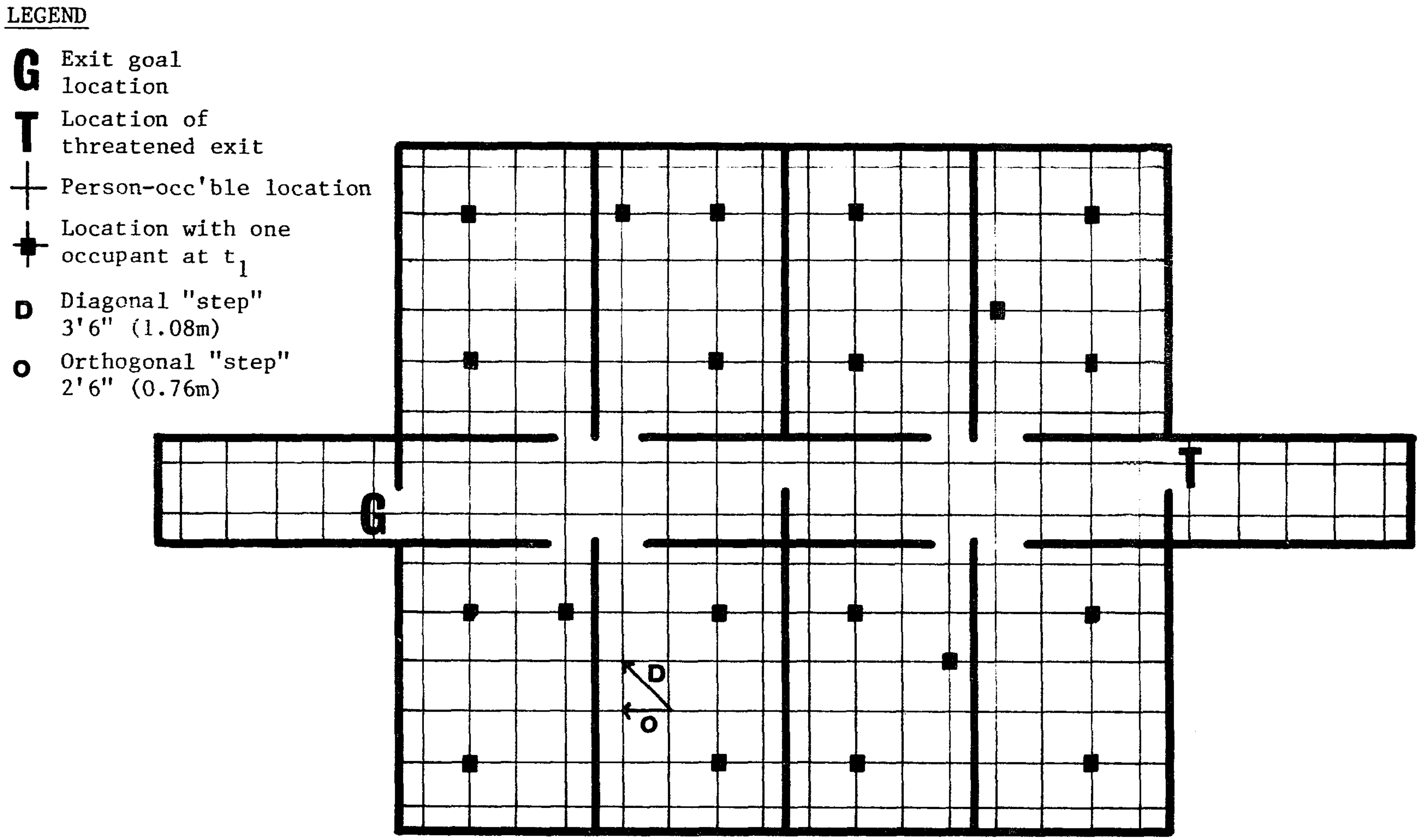


Figure 3.10 Non Dead-end Floor Plan in BFIRES Grid Form

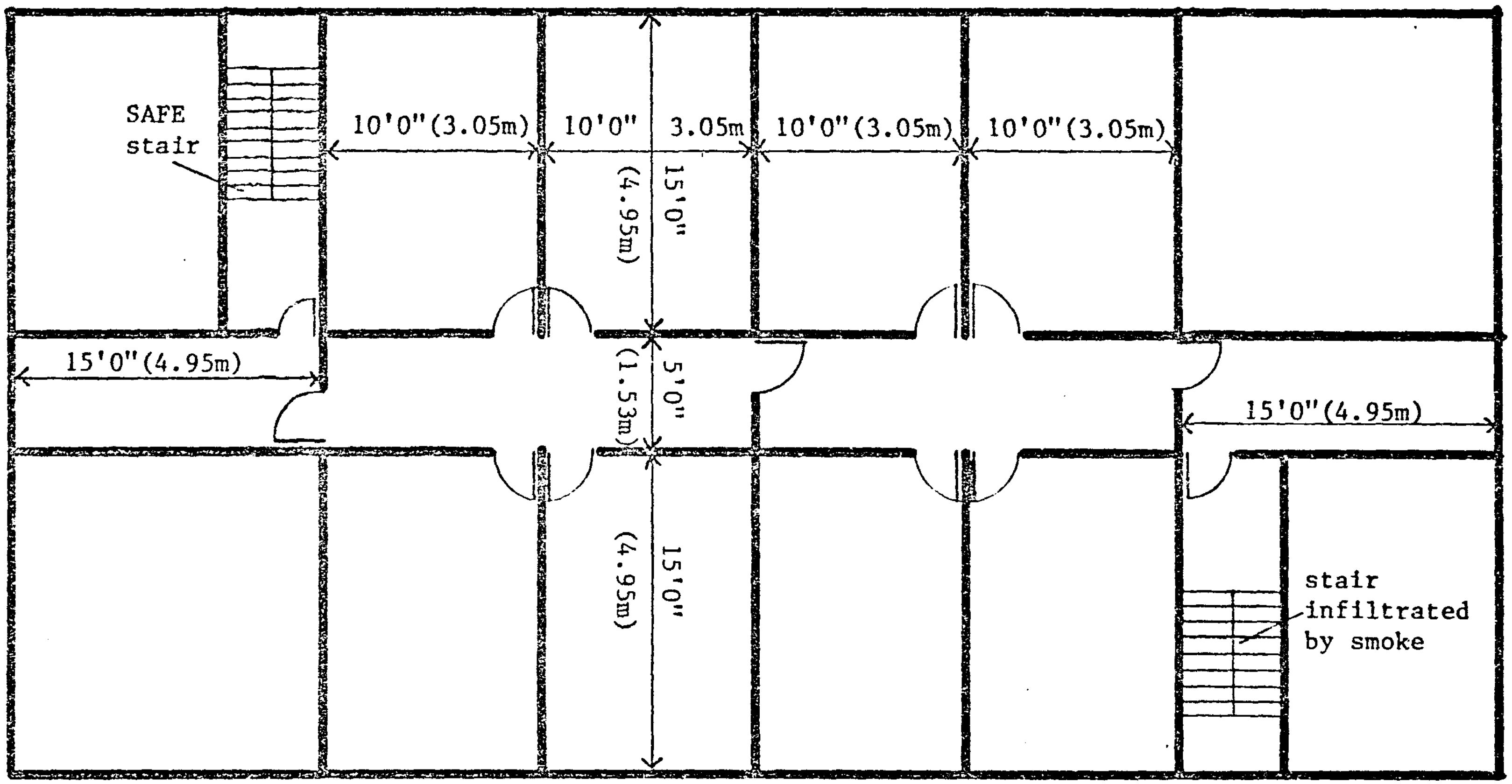


Figure 3.11 Dead-end Spatial Configuration

For LEGEND, see Figure 3.10

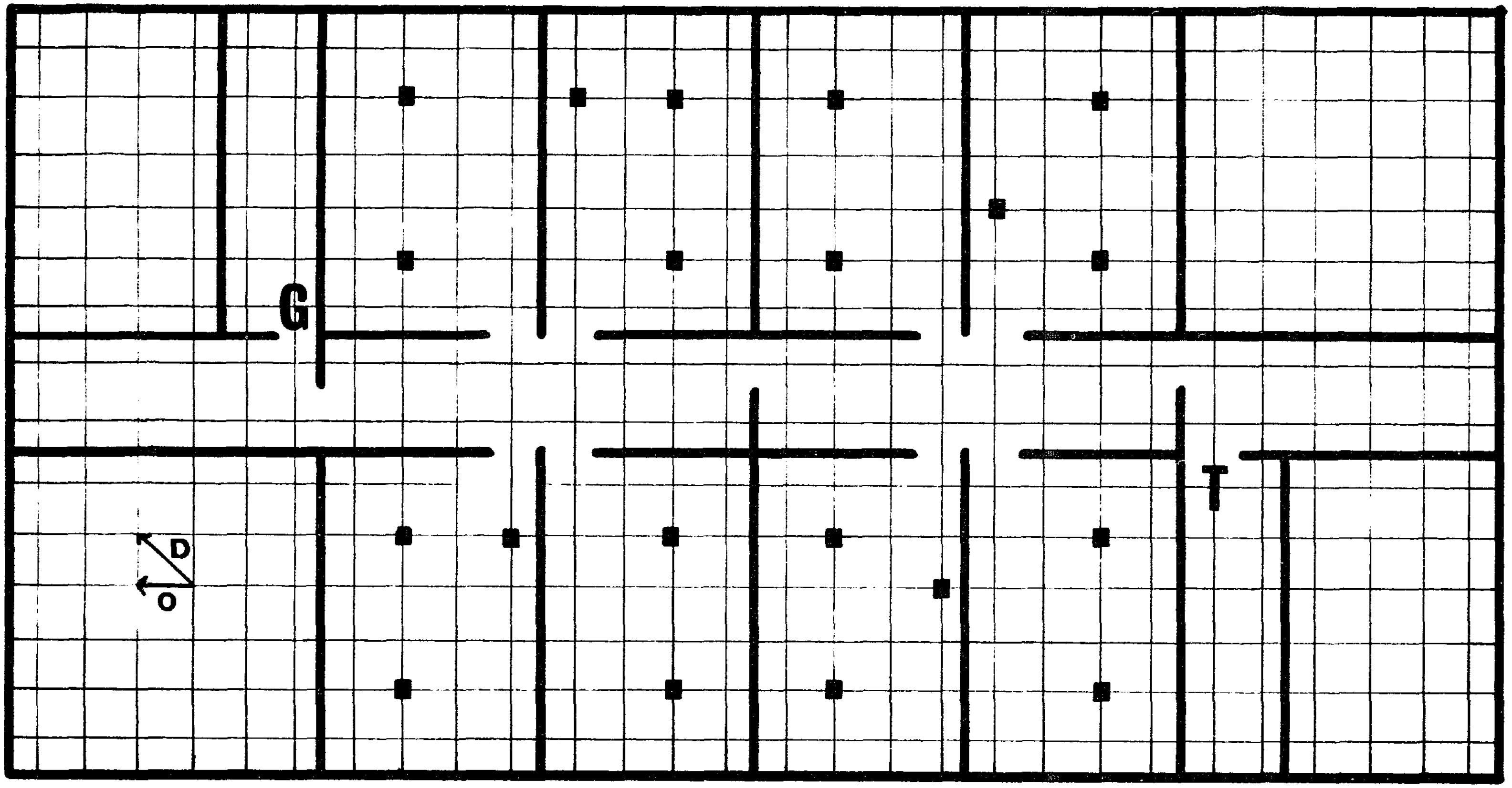


Figure 3.12 Dead-end Floor Plan in BFIRES Grid Form

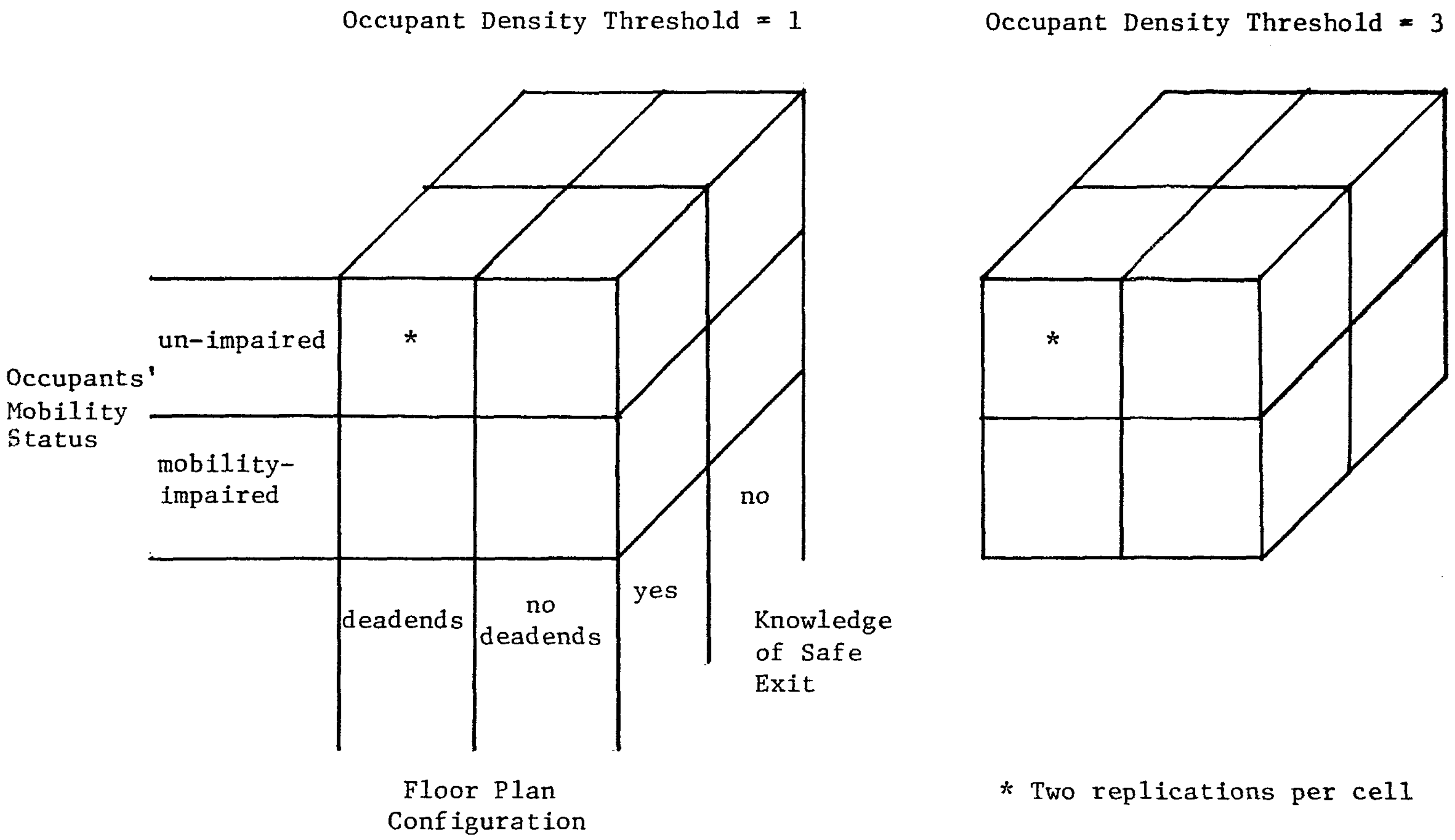
a fire elsewhere within the building. In addition, all occupants were assumed to be "ordinary residents", as in Experiment 1 above.

Simulations were conducted under several different occupant conditions. Comparisons were made between simulations in which occupants knew which stair was blocked and which was safe, and those in which occupants had no such direct knowledge. In addition, comparisons were made between simulations in which occupants were fully mobile, and those in which they were mobility-impaired.

Experimental Design

A four-dimensional factorial design was employed to test the effects of floor plan configuration, occupant mobility, occupants' knowledge of the safe exit location, and occupant density. The 2x2x2x2 design is shown in Figure 3.13. These variables are important for a number of reasons. For example, Experiment 1 suggested the sensitivity of BFIRES to variation in a particular aspect of building design: spatial subdivision. Floor plan configuration and exit arrangement are other aspects of design which are under the immediate control of the architect, and which are treated by design regulations. If BFIRES can assist architects and regulators in evaluating differences between alternative floor plan arrangement, it will be deemed a valuable design tool. Similarly, the ability of the computer program to distinguish among types of occupants will strengthen its value as a facility management and occupant training tool.

Measures of four dependent variables were recorded: (a) the total number of occupants who escaped the floor by the end of an event of arbitrarily defined length; (b) the difference between occupant's



* Two replications per cell

Figure 3.13 Four-Dimensional Factorial Design For Experiment 2

initial distances from the safe exit and their final distances; (occupants' "difference" scores);
(c) occupants' escape scores; and (d) occupants' total numbers of spatial displacements. Variables (c) and (d) have already been described in detail under Experiment 1.

Variable (a), the total number of occupants escaping is self explanatory. This provides a somewhat gross measure of the overall outcome of a fire event: at the end of a given period of time, how many people escaped the floor under study? Variable (b), the difference score, on the other hand, provides a finer measure of occupant performance during a particular event. When a simulated fire is curtailed at some arbitrarily chosen point, it is quite likely that many occupants <u>who would have eventually escaped</u> will still be found on the floor. It is therefore useful to have some measure of the <u>progress</u> of the remaining occupants, without having to actually trace the complete movement paths of each individual (although BFIRES does permit the user to conduct such tracing exercises). The difference scores accommodates this need. The output is computed for each occupant, and is defined as the difference in straight-line distance separating the individual and the safe exit location between the initial and terminal time frames.

If the difference value output for occupant$_i$ is zero, for example, then this individual was neither nearer to, nor farther from, the safe exit at the terminal time frame as compared with the initial frame. This does not necessarily mean that occupant$_i$ remained in place through out the entire event. It simply means that all the occupant's activity resulted in no net improvement in distance from the safe exit location. Indeed, an occupant with a zero difference value may also have experienced a large number of spatial displacements during the event. This combination would suggest that movement decision making occurred in an environment almost devoid of information (particularly regarding the location of the safe exit). It would also suggest that decision-making occurred in a confused context, in which multiple sources of conflicting information were present.

Alternatively, non-zero difference values may be either positive or negative. Positive values indicate that the occupant is nearer to the safe exit at the terminal time frame; negative values show that the individual finished farther away. Consider two examples: An occupant with a high positive difference value and a relatively small displacement output was probably making movement decisions on the basis of "good" information, and is obviously enroute toward reaching the safe exit. Had the simulation been run for another few time frames, and the fire continued to be confined to another floor, this occupant may very well have attained the exit goal. On the other hand, an individual with a high negative difference value is likely to be operating under an erroneous idea of the safe exit's location. A high negative difference may also result when both the safe and threatened exits are very close to each other.

As in Experiment 1, the structure of BFIRES suggests that event outcomes should vary in direction as well as magnitude. Nine additional hypotheses were examined during Experiment 2.

(6) Occupant density will have no significant effect on the dependent variables, nor will it interact with knowledge of the safe exit location, the presence of deadend corridors, or occupant mobility.

Experiment 1 suggested that variation in occupant density produced changes in event outcomes, depending upon the extent to which a spatial zone was subdivided into incrasingly smaller units. In Experiment 2, occupant density was varied while spatial subdivision and size were held constant. Under these conditions, no variation in event outcomes is expected. Moreover, the model suggests neither theoretical nor logical links between occupant density and safe exit knowledge, the presence of deadend corridors, or occupant mobility.

(7) In general, a larger number of occupants possessing knowledge of the safe exit location will escape the floor than will individuals without exit knowledge.

Exit-seeking is the most important objective processed within BFIRES. In order to work toward the exit objective, an occupant must, by definition, possess knowledge of its location. Given a knowledge of the safe exit's location, the occupant is enabled to traverse a route through any network of spatial subdivisions. Without such knowledge, the occupant must resort to satisfying the second-order objective: increasing the distance from the threat. In BFIRES, however, this may result in "meandering", during which the safe exit location may be found only by chance. On the average, then, most occupants with safe exit location knowledge are expected to escape the floor within the time allowed. Likewise, very few individuals possessing no exit knowledge are expected escape.

(8) Regardless of floor plan configuration, more occupants with unimpaired mobility will escape the floor than will mobility-impaired individuals.

BFIRES defines mobility-impairment in terms of a reduction in movement velocity. This is accomplished by forcing "impaired occupants" (modeling the elderly or arthritic) to remain in place during every other time frame. The overall effect is an average velocity reduction of 50% (the user may wish to adjust the program to produce other levels of velocity reduction). Because of this reduction effect, fewer mobility-impaired occupants are expected to reach the exit objective by the terminal time frame.

(9) By the terminal time frame, occupants with a knowledge of the safe exit location will have moved closer to that objective than will individuals with no safe exit knowledge; this will occur irrespective of floor plan configuration.

As in the discussion of hypothesis (7), it is assumed that many fully able and knowledgable occupants will have escaped the floor by the terminal time frame, had a curtailed simulation been run for a longer period (say, 150 instead of 100 time frames). Accordingly, it is expected that such individuals increase the difference considerably between their initial and final positions, and that their movement behavior will be directed toward the exit objective. Moreover, hypothesis (8) suggests:

(10) The effect predicted by hypothesis (9) will be greater for unimpaired occupants than for those with mobility impairments.

Hypotheses (7) and (9) also suggest the following:

(11) Occupants with knowledge of the safe exit location will achieve higher escape scores than will those with no exit knowledge.

Escape score is an index which indicates not only whether an occupant has escaped by the terminal time frame (any non-zero score), but also how quickly (the higher the score, the earlier the escape). Exit knoweldge equips the occupant with the highest priority goal, and individuals working toward this goal are expected to escape earliest.

(12) Occupants with unimpaired mobility will achieve higher escape scores than will mobility-impaired individuals.

According to BFIRES, mobility-impaired occupants will require about twice as much escape time than will unimpaired ones. Since escape score is a measure of escape time[1], scores for impaired individuals will--by definition--be significantly lower than those achieved by fully able occupants.

(13) Occupants with knowledge of the safe exit will traverse a shorter egress route (i.e., will take fewer "steps") than will their counterparts possessing no exit knowledge.

Occupants with the exit objective clearly in mind should have relatively little difficulty in planning their escape routes. These routes will be as direct and as linear as possible, with deviations resulting only from random variation and either cognitive or environmental interruptions.

(14) Unimpaired occupants will traverse longer paths during the simulated event than will those with mobility-impairments.

---

[1] $ET = FL(T(1-ES))$, where: (3)

ET = escape time, in seconds
FL = length of a single frame, in seconds
T = total number of frames run
ES = occupant's escape score

By definition, unimpaired occupants will take about twice as many "steps" as impaired individuals. Deviations may result from either random variation or from interruptions, as in the case of hypothesis (13).

Data Collection and Analysis

The floor plan configuration, occupant mobility, exit knowledge, and density parameters were examined at the levels indicated in Figure 3.13, as discussed above. Variation in occupant density was defined in terms of the maximum number of persons permitted to occupy any spatial location at a given point in time. In Experiment 2, a person-occupiable location represented an imaginary envelope of 6.25 square feet ($0.56\ m^2$). Therefore:

Level 1: density threshold equals 1; maximum allowable density equals 0.16 persons per square foot (1.79 persons per m^2);

Level 2: density threshold equals 3; maximum allowable density equals 0.48 persons per square foot (5.36 person per m^2).

The 2x2x2x2 design was replicated twice. For each cell, values of total numbers of escapees, locational difference, escape score, and spatial displacement were recorded. Separate fixed-effects analyses of variance were conducted for each dependent variable. The fixed-effects model was selected because all possible levels of the independent variables were included in the analysis (Edwards, 1972).[1]

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[1] Mobility, floorplan, and exit knowledge are treated as dichotomous. Density thresold was treated as dichotomous in Experiment 2 to simplify the analysis.

Results

Mean outcomes from simulation runs are shown in Table 3.6. The values recorded are aggregations of the original data from the 20 occupants in each replication. The data were further aggregated across the two replications. These data are graphically presented in Figures 3.14 through 3.21. Analyses of variance for the four dependent variables studied are shown in Tables 3.7 through 3.10.

For all dependent variables studied, variation in floor plan configuration (i.e., the presence or absence of deadend corridors) produced no significant change in simulation outcomes.

Variation in occupant density (i.e., whether the density threshold was _1_ or _3_) had no significant effect upon simulation outcomes for total numbers of occupants escaping, total spatial displacement, and escape score. Variation in this parameter did, however, significantly effect occupants' final positions relative to their initial ones, as follows: On the average, occupants in the case permitting a higher density were one step closer to the exit goal than were individuals in the low density case. This distance translates to 3.5 feet (1.08 m).

Variation in occupant mobility, i.e., whether occupants could move during every (versus every-other) time frame had a significant effect upon simulation outcomes for all dependent measures recorded. In all cases, the effect was in the predicted direction.

Variation in safe exit knowledge (i.e., whether or not an occupant knew the location of the safe exit at the onset of the simulated event) significantly affected event outcomes for all dependent measures. In each case, the effect was in the predicted direction.

Table 3.6 Mean Data from Simulated Fire Events

CASE	PLAN[a]	DT[b]	MOB[c]	KNOW[d]	# ES[e]	DIFF[f]	SCOR[g]	STEP[h]
1	1	1	0	0	0	1.45	.00	81.38
2	0	1	0	0	0	1.00	.00	80.63
3	0	1	0	1	14.5	15.30	.30	55.68
4	1	3	0	0	0	0.70	.00	82.75
5	0	1	1	0	0	0.10	.00	40.13
6	1	1	1	1	4.0	5.60	.06	37.33
7	0	3	0	0	0	0.60	.00	82.43
8	0	3	0	1	14.5	15.35	.31	55.90
9	0	3	1	1	5.5	11.75	.05	40.63
10	0	3	1	0	0	-0.20	.00	40.98
11	1	3	1	1	5.5	9.85	.07	38.85
12	0	1	1	1	4.0	7.60	.05	40.18
13	1	3	0	1	13.0	15.65	.30	59.93
14	1	3	1	0	0	0.20	.00	42.18
15	1	1	0	1	10.5	13.50	.19	63.95
16	1	1	1	0	0	1.05	.00	40.70

Notes: (a) floor plan configuration:
1 = dead-end plan
0 = non-dead-end plan
(b) occupant density threshold:
value indicates actual number of occupants permitted per person-occupiable spatial location
(c) occupants' mobility status:
0 = all occupants were unimpaired
1 = all occupants were impaired
(d) occupants' knowledge of the safe exit location:
0 = no occupants possessed knowledge of the safe exit location
1 = all occupants possessed knowledge of the safe exit location
(e) number of occupants who escaped the floor by the 100th time frame
(f) occupants' final locations relative to their initial locations, in grid steps*
(g) occupants' escape scores
(h) total number of actual spatial displacements, in grid steps*

* mean grid step = 3.5 feet (1.08 m)

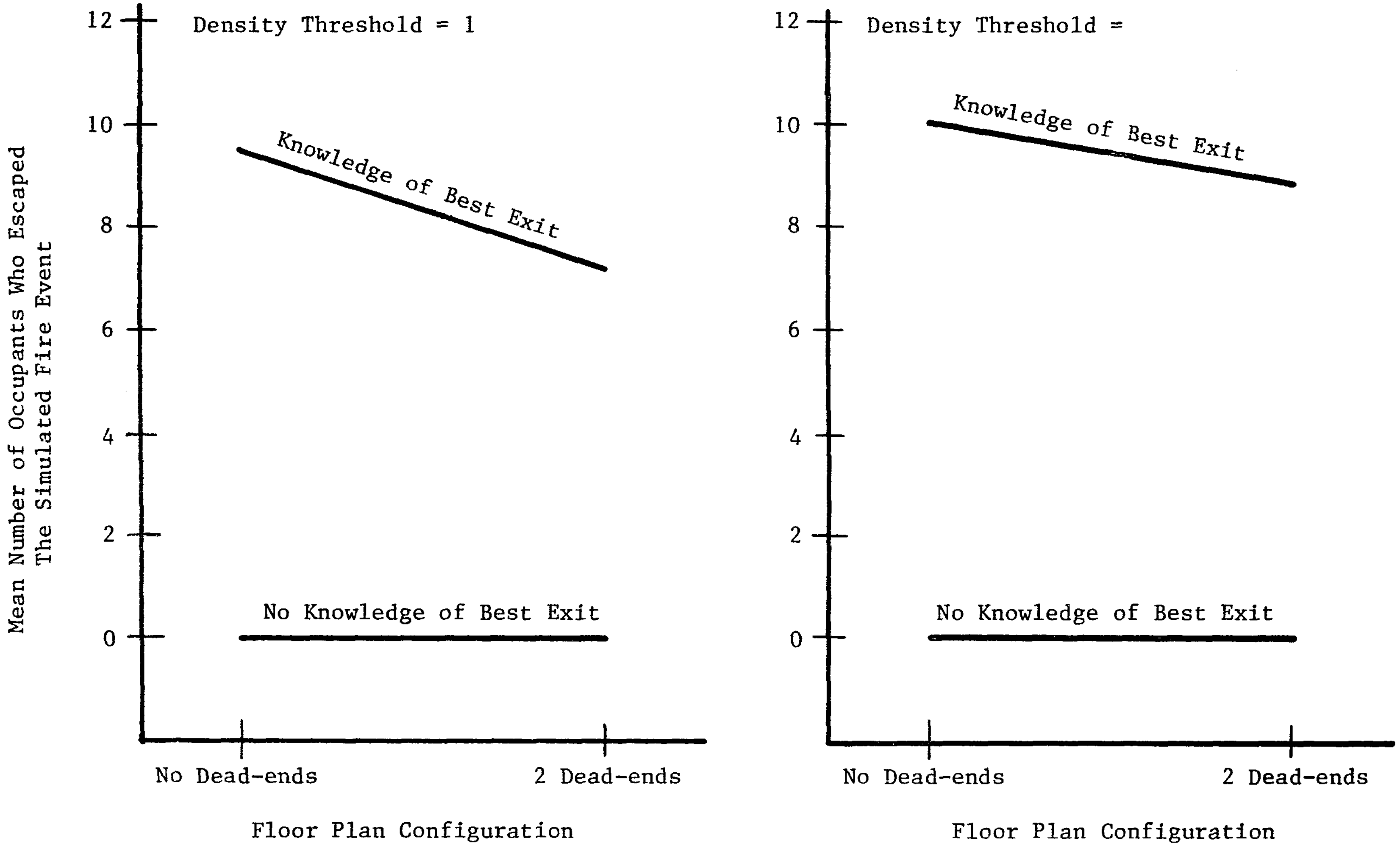

Figure 3.14 Effects of Knowledge of Best Exit Location, Floor Plan Configuration, and Occupant Density on the Mean Number of Occupants Escaping the Floor

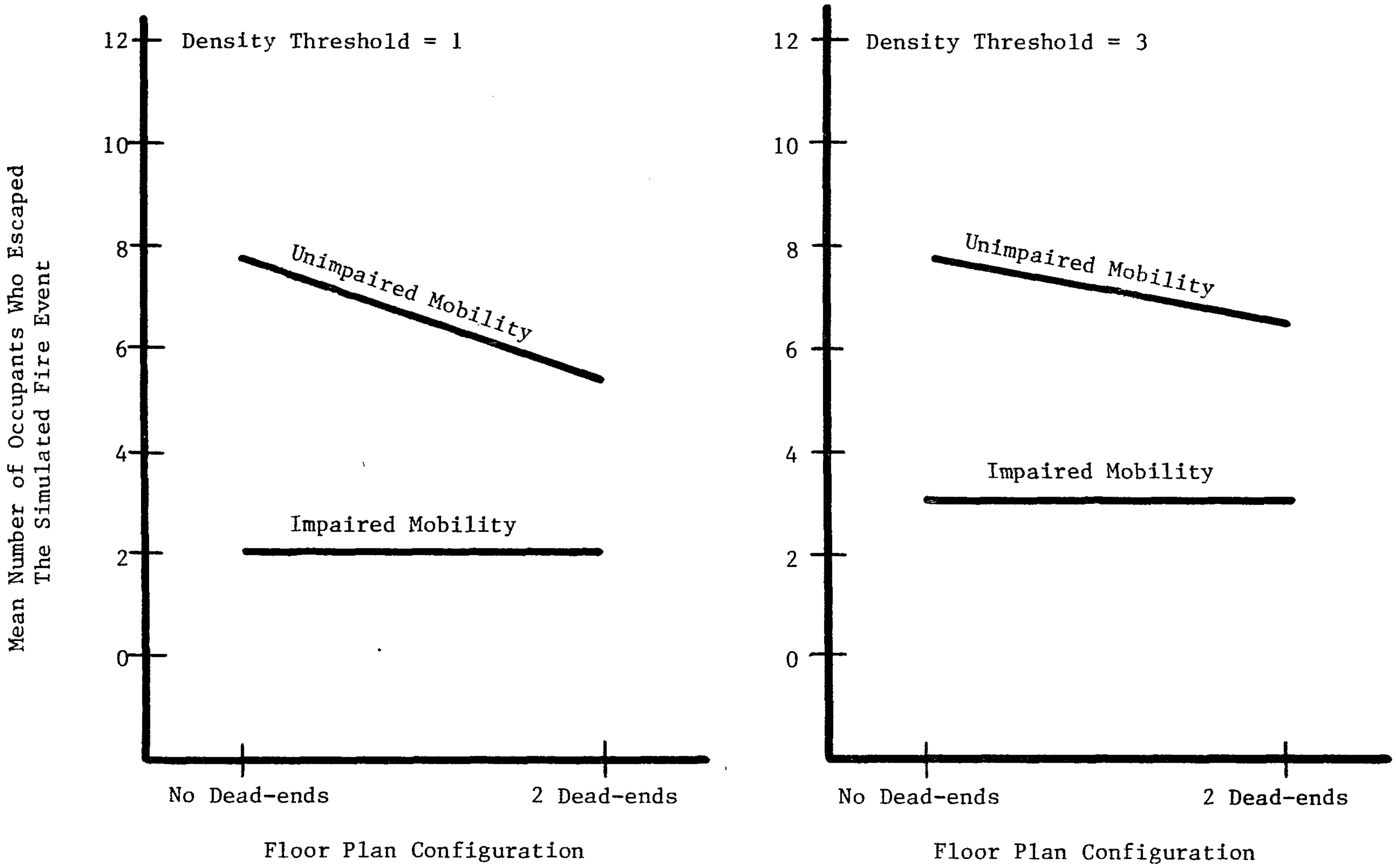

Figure 3.15 <u>Effects of Occupant Mobility, Floor Plan configuration, and Occupant Density on the Mean Number of Occupants Escaping the Floor</u>

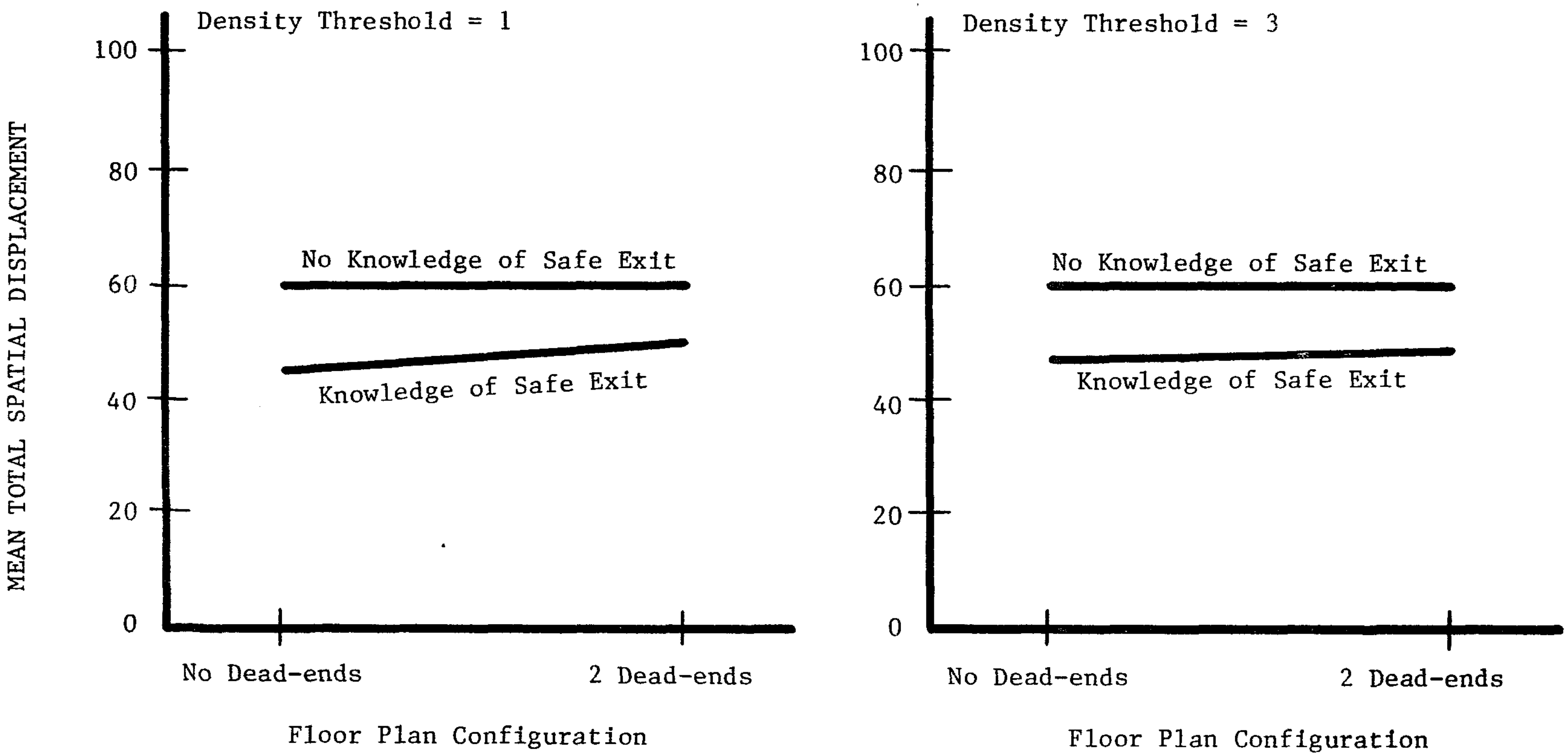

Figure 3.16 Effects of Knowledge of Safe Exit, Floor Plan Configuration, and Occupant Density on Mean Spatial Displacement

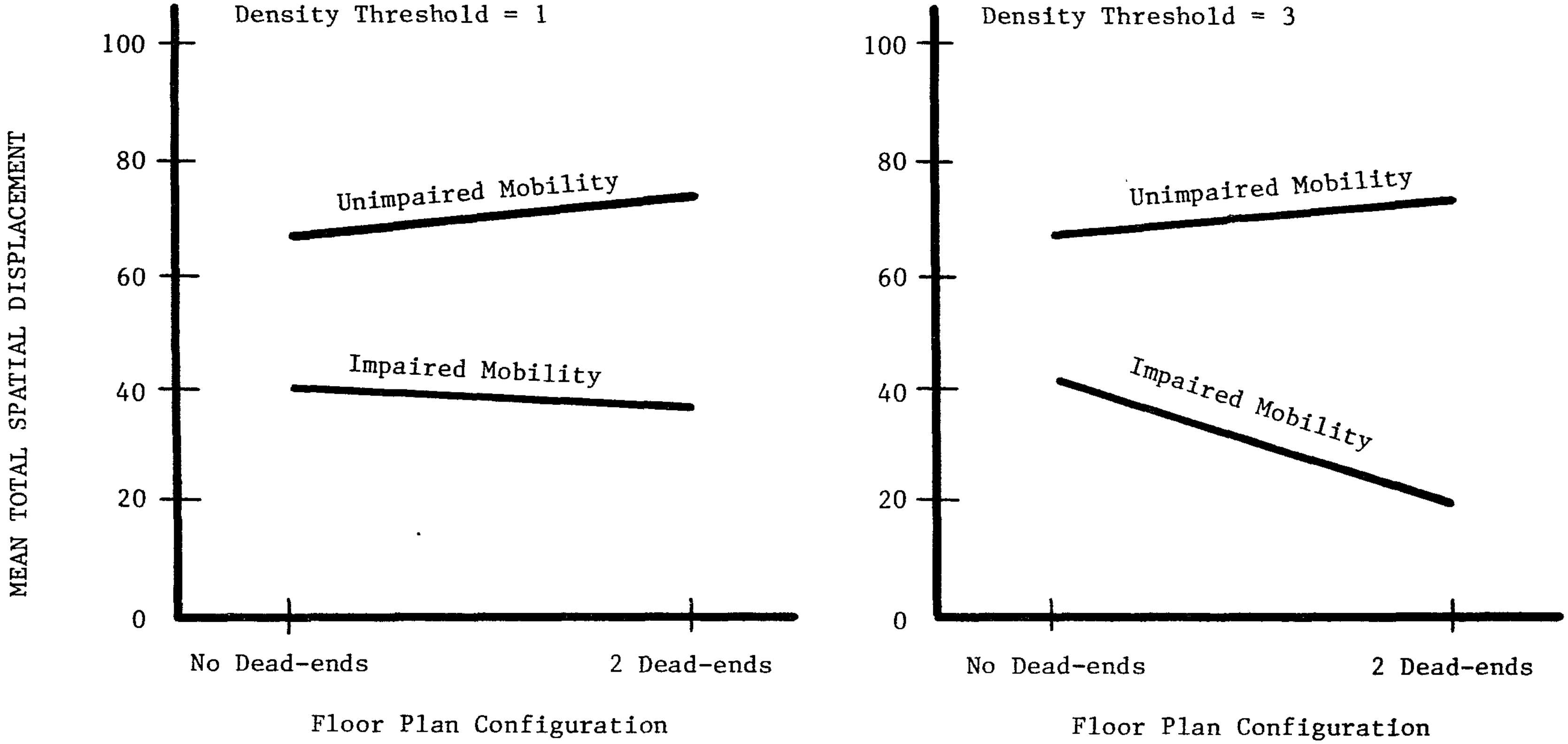

Figure 3.17 Effects of Occupant Mobility, Floor Plan Configuration, and Occupant Density on Mean Spatial Displacement

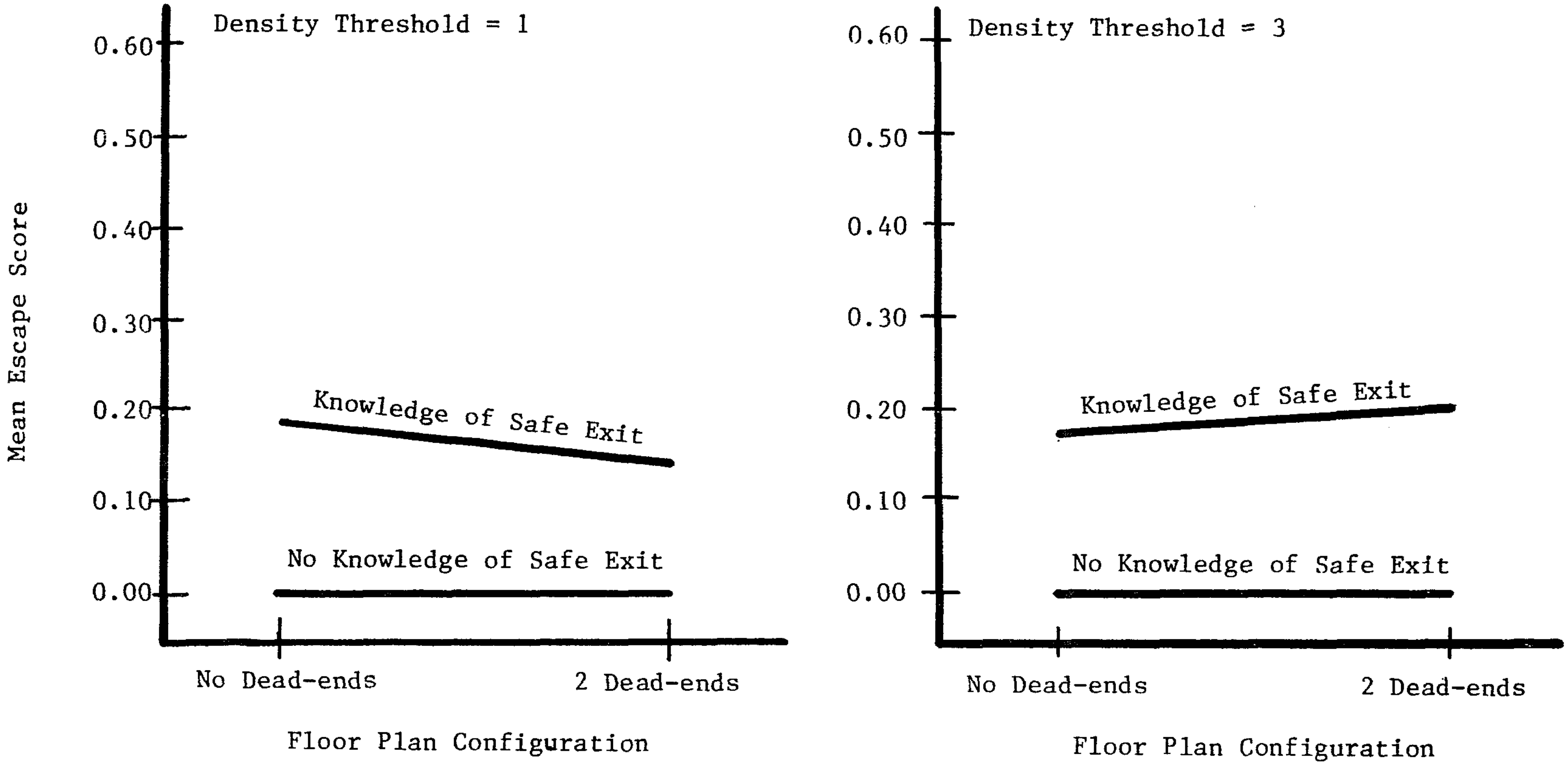

Figure 3.18 Effects of Knowledge of Safe Exit, Floor Plan Configuration and Occupant Density on Mean Escape Score

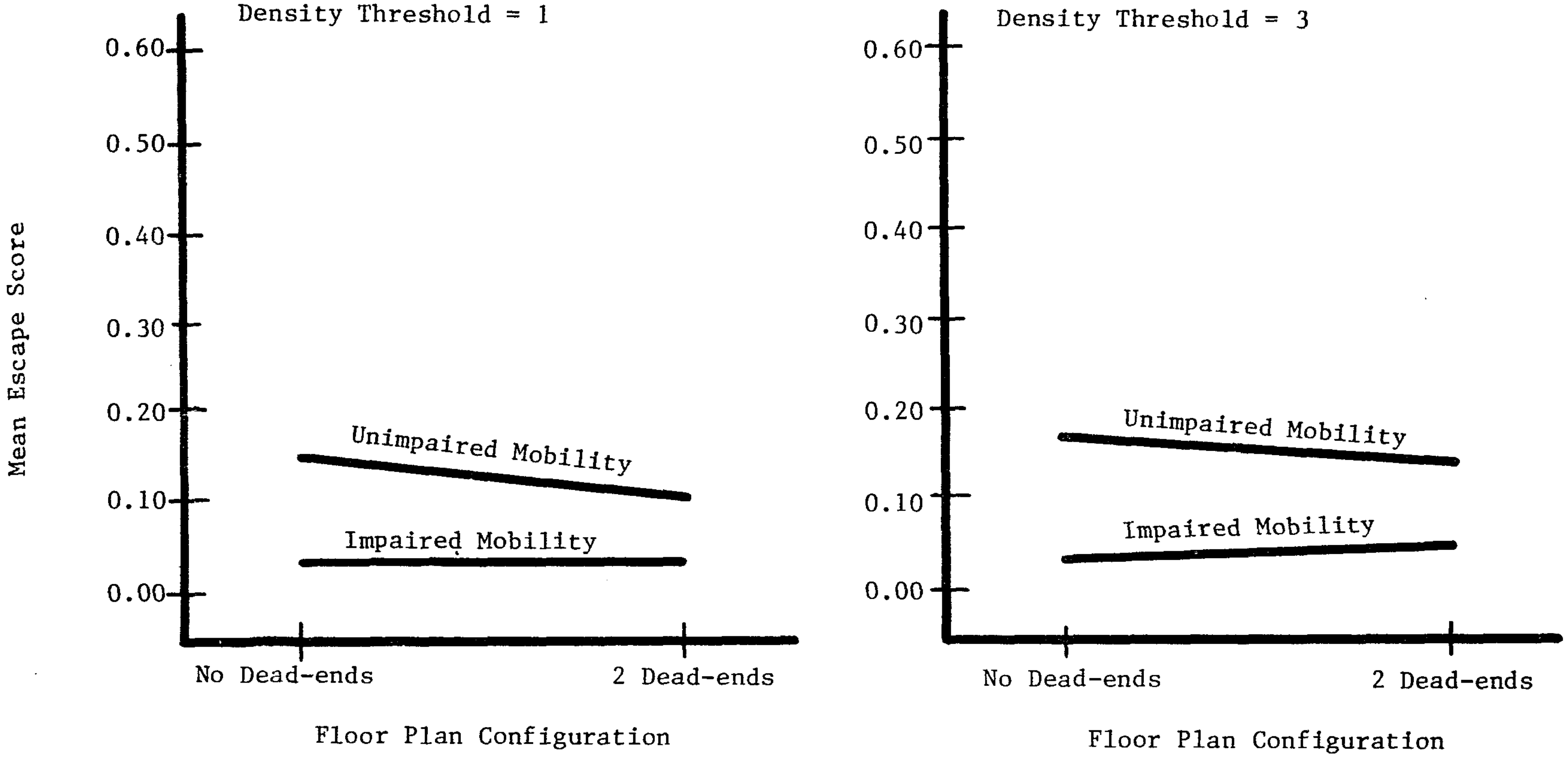

Figure 3.19 Effects of Occupant Mobility, Floor Plan Configuration and Occupant Density on Mean Escape Score

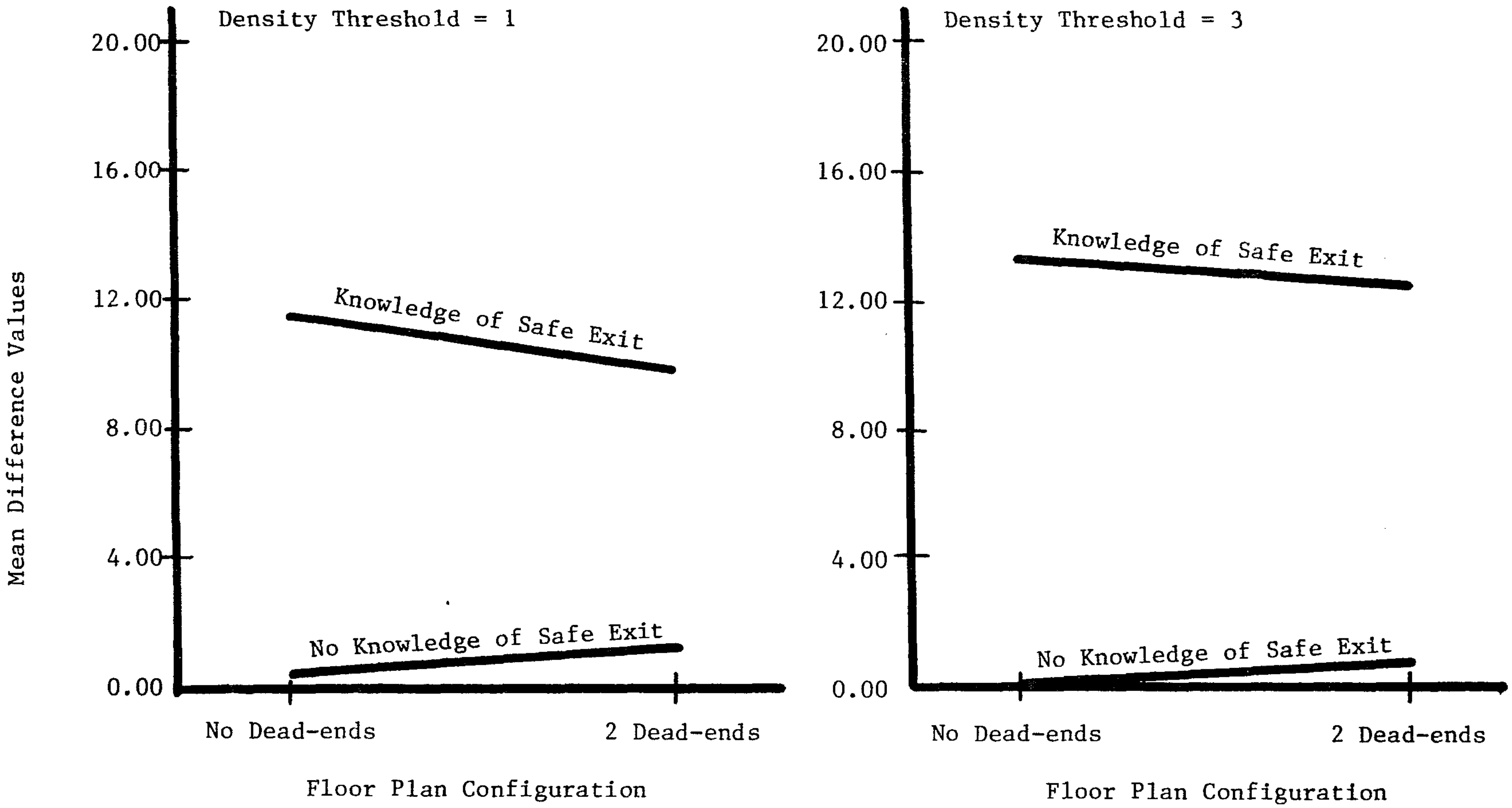

Figure 3.20 Effects of Knowledge of Safe Exit, Floor Plan Configuration and Occupant Density on Mean Difference Values

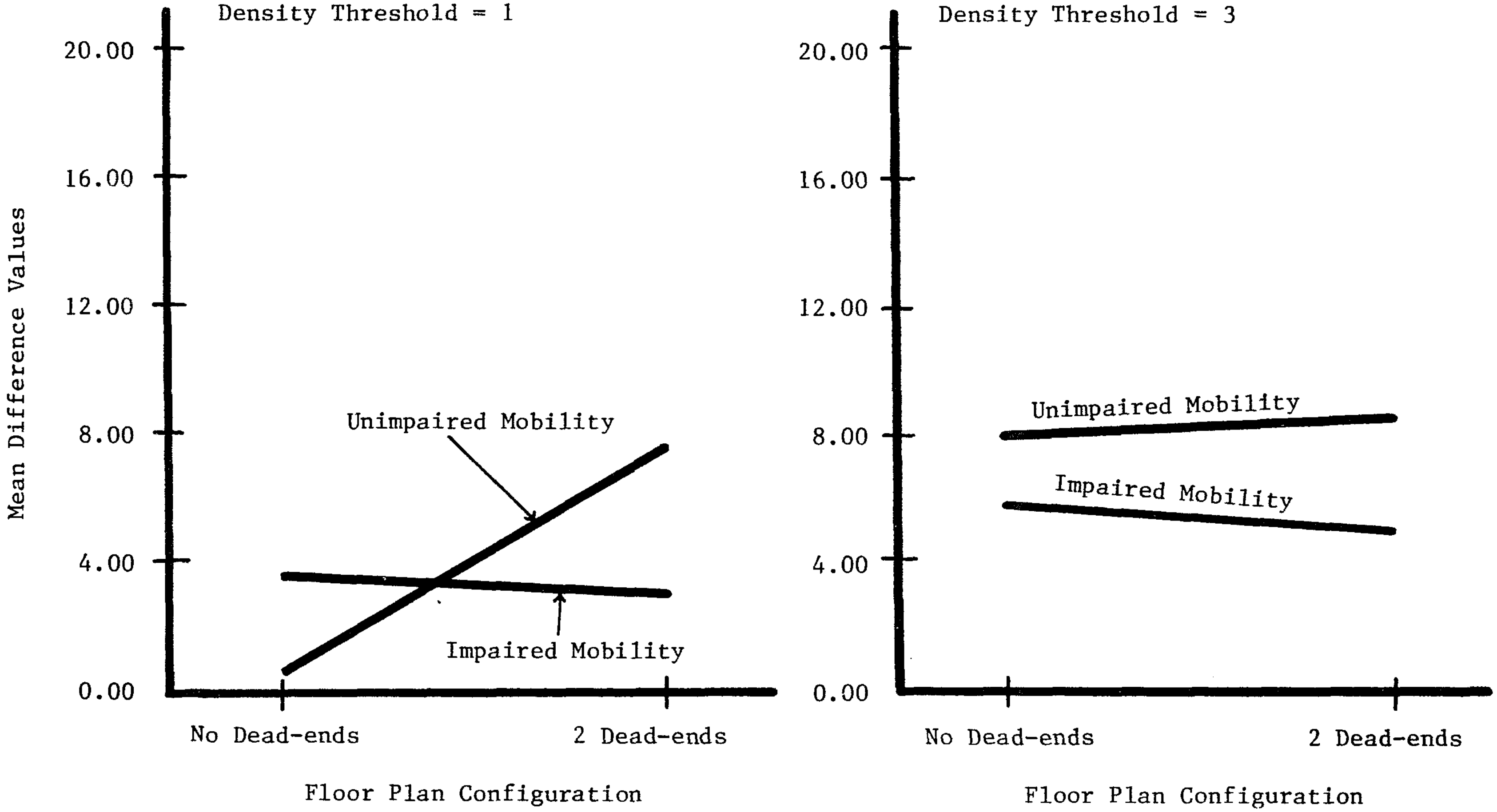

Figure 3.21 Effects of Occupant Mobility, Floor Plan Configuration and Occupant Density on Mean Difference Values

Table 3.7 Analysis of Variance for Total Number of Occupants Escaping the Floor

N = 32

SOURCE	d.f.	S.S.	M.S.	F
Floor Plan Config. (F)	1	3.781	3.781	3.270
Density Threshold (D)	1	3.781	3.781	3.270
Occupant Mobility (M)	1	140.281	140.281	121.325*
Exit Knowledge (K)	1	639.031	639.031	522.677*
F x D	1	.781	.781	less than 1
F x M	1	3.781	3.781	3.270
F x K	1	3.781	3.781	3.270
D x M	1	.031	.031	less than 1
D x K	1	3.781	3.781	3.270
M x K	1	140.281	140.281	121.325*
F x D x M	1	.781	.781	less than 1
F x D x K	1	.781	.781	less than 1
D x M x K	1	.031	.031	less than 1
F x M x K	1	3.781	3.781	3.270
F x D x M x K	1	.781	.781	less than 1
Within Groups	16	18.500	1.156	
Total	31	963.969		

* $p < .001$

Table 3.8 Analysis of Variance for Route Length

N = 32

SOURCE	d.f.	S.S.	M.S.	F
Floor Plan Config. (F)	1	7.078	7.078	less than 1
Density Threshold (D)	1	.057	.057	less than 1
Occupant Mobility (M)	1	7120.717	7120.717	685.441*
Exit Knowledge (K)	1	1293.496	1293.496	124.512*
F x D	1	4.463	4.463	less than 1
F x M	1	21.863	21.863	2.105
F x K	1	.416	.416	less than 1
D x M	1	7.851	7.851	less than 1
D x K	1	13.326	13.326	1.283
M x K	1	961.959	961.959	92.598*
F x D x M	1	10.986	10.986	1.058
F x D x K	1	5.080	5.080	less than 1
D x M x K	1	11.580	11.580	1.115
F x M x K	1	26.736	26.736	2.574
F x D x M x K	1	6.616	6.616	less than 1
Within Groups	16	166.216	10.389	
Total	31	9658.441		

* $p < .001$

Table 3.9 Analysis of Variance for Escape Score

N = 32

SOURCE	d.f.	S.S.	M.S.	F
Floor Plan Config. (F)	1	.001	.001	less than 1
Density Threshold (D)	1	.002	.002	1.000
Occupant Mobility (M)	1	.092	.092	55.819*
Exit Knowledge (K)	1	.218	.218	131.502*
F x D	1	.001	.001	less than 1
F x M	1	.003	.003	1.932
F x K	1	.001	.001	less than 1
D x M	1	.001	.001	less than 1
D x K	1	.001	.001	less than 1
M x K	1	.092	.092	55.819*
F x D x M	1	.001	.001	less than 1
F x D x K	1	.001	.001	less than 1
D x M x K	1	.001	.001	less than 1
F x M x K	1	.003	.003	1.932
F x D x M x K	1	.001	.001	less than 1
Within Groups	16	.026	.002	
Total	31	.450		

* $P < .001$

Table 3.10 <u>Analysis of Variance for Difference Values</u>

N = 32

SOURCE	d.f.	S.S.	M.S.	F
Floor Plan Config. (F)	1	2.205	2.205	4.308
Density Threshold (D)	1	10.125	10.125	19.780**
Occupant Mobility (M)	1	93.161	93.161	182.002**
Exit Knowledge (K)	1	1019.261	1019.261	1991.249**
F x D	1	.361	.361	less than 1
F x M	1	.125	.125	less than 1
F x K	1	6.125	6.125	11.966*
D x M	1	3.920	3.920	7.658*
D x K	1	19.845	19.845	38.770**
M x K	1	66.701	66.701	130.309**
F x D x M	1	.781	.781	1.526
F x D x K	1	.781	.781	1.526
D x M x K	1	5.445	5.445	10.637*
F x M x K	1	1.620	1.620	3.165
F x D x M x K	1	.151	.151	less than 1
Within Groups	16	8.190	.512	
Total	31	1238.799		

* $p < .01$
** $p < .001$

For each of the four dependent variables studied, the occupant mobility by exit knowledge interaction was significantly large. The analysis of variance for final location relative to initial location yielded a number of other significant interaction effects. These included the first order interactions between occupant density and mobility, density and exit knowledge, and floor plan and exit knowledge. Moreover, the second order effect between density, mobility, and exit knowledge was significantly large.

Discussion

Experiment 1

Two important conclusions are suggested by findings from Experiment 1. First, under the experimental conditions established, the BFIRES computer program faithfully replicated theoretical relationships postulated with regard to spatial subdivision and occupant density. Thus, confidence in the internal validity and consistency of BFIRES is strengthened. Second, when simulating certain kinds of fire events, users should expect to find BFIRES capable of distinguishing among variations in such important environmental and occupancy factors as spatial subdivision and occupant density.

Experiment 2

The analyses for numbers escaping, escape score, and spatial displacement appear to establish a consistent pattern of results. The analysis for final versus initial location (difference scores) produced results falling outside this pattern, and will be considered separately.

The mobility and knowledge main effects, and the mobility-by-knowledge interactions, were all statistically significant. The main effects by themselves lend support for the sensitivity hypotheses enumerated for Experiment 2, above: occupants' escape behavior, under the experimental conditions established, are affected by variation in levels of occupant mobility and knowledge of safe exit location. Moreover, in comparison to these "occupant" variables, variation in both allowable density and floor plan configuration have negligible effects.

However, the interaction of occupant mobility with safe exit knowledge is important for assessing the sensitivity of BFIRES to variation in these two parameters. That BFIRES produces interactions among certain variables is of critical importance, and permits more specific statements about the program's sensitivity. In particular, sensitivity to exit knowledge appears contingent upon the level of occupant mobility considered. Although occupants require a knowledge of the safe exit location in order to escape the floor: (a) those who are knowledgeable are more likely to escape if they are not mobility-impaired; and (b) those who are knowledgeable will escape more quickly if they are not mobility-impaired. Moreover: (c) mobility-impaired occupants traverse the fewest steps, but for non-impaired individuals, full exit knowledge results in fewer steps than does a lack of knowledge. These effects are consistent with the structure underlying BFIRES, as discussed in connection with hypotheses (6) through (14), above.

The analysis of variance for the difference between initial and final occupant locations (difference scores) produced results falling far outside the pattern discussed above. Recall that the "difference score" was defined as the difference between an occupants' initial linear distance from the exit goal, and their final distance measured at the terminal time frame. This variable was expected to indicate whether those occupants whose attainment of the exit goal was terminated prematurely (by the arbitrary selection of the simulation end point) had otherwise made substantial progress toward the escape objective. Accordingly, a pattern of results similar to that produced by the analysis for numbers escaping was anticipated. Portions of this pattern were, indeed, found in the analysis of difference values: occupant mobility and exit knowledge main effects, and the first order interaction between these parameters. However, the occupant density main effect was also found to be significantly large, as were a number of other first and second order interactions. These complicate the analysis.

It may be that these effects are predictable from the framework underlying the computer program, but involve relationships so complex as to require additional analyses. Such studies would involve observing the variables studied here at other levels, as well as considering additional variables.

But perhaps these effects cannot be traced to the model. In that case, the program may not have been consistently deduced from the framework, or alternatively, the inconsistent findings may be artifacts of the particular sample of cases studied. Again, the solution of these problems will be tasks for future research. For example, it may be desirable to prepare a number of programs, each deriving generally from the theoretical framework, while varying in the composition or structure of particular algorithms. Simulation outcomes generated by each program could then be compared to determine which outcomes most closely correspond to the theoretical expectations. Simulations of a wide variety of fire cases would help guard against artifacts.

Sensitivity to Environmental versus Occupant Parameters

In Experiment 1, all replications involved occupants who were fully knowledgeable of the safe exit location, and who were not mobility-impaired. Under these conditions, event outcomes for various levels of two environmental parameters (occupant density and spatial subdivision) were examined. The analysis concluded that, under the conditions established for study, BFIRES may be considered sensitive to variation in both environmental parameters.

In Experiment 2, however, two occupant-based parameters (mobility) impairment and knowledge of safe exit location) were investigated in conjunction with the environmental variables studied in the former case. Occupants in Experiment 2 varied in level of mobility impairment and exit knowledge, as well as on the basis of which environmental system they inhabited. This analysis concluded that, when simulated individuals vary on the basis of occupant parameters, BFIRES is sensitive only to these parameters. That is, under these conditions, the effects of variation in environmental parameters disappear.

This finding is critical for two important reasons. First, it helps define the ranges of conditions under which we should expect the program to be sensitive to the various parameters. Second, it raises an important theoretical question worthy of future investigation: Is the likelihood of safe escape dependent upon the extent of occupants' mobility, emergency preparedness, and emergency alert, while virtually independent of the physical design of the building?

AN EXAMINATION OF THE EXTERNAL VALIDITY OF SIMULATION OUTCOMES

Introduction

Purpose

The internal validation procedure dealt with the question of whether experimental manipulations in the simulated environment actually made significant differences in event outcomes. This problem was addressed through the sensitivity analysis discussed in the previous section. In general, it was shown that not only did manipulations significantly influence the outcomes of simulated fire events, but that these differences occurred in the directions predicted by the program's underlying theoretical structure. These findings bolster confidence in the belief that the computer program was, in fact, deduced from the antecedent framework first postulated.

The broader, and more difficult criterion to satisfy is that of external validity, the representativeness or generalizability of simulation results (see Kerlinger, 1973). Two questions arise here: (1) To what populations (of persons, environments, and levels of variables) can inferences from simulations be properly drawn? (2) Is the computer simulation program a useful device for predicting real-world events? The first question has already been considered in the context of individual research designs employed in the sensitivity analyses. This section, is concerned with the second question.

Levels of External Validity

In addition to sampling, ecological, and variable representativeness (Kerlinger, 1973), two additional 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 reasonably likely (i.e., "face-valid")?

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.

Experiment 3

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

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[1] National Fire Protection Association-Fire Incident Data Organization

media, 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 categories are explained below.

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.

Experimental Design

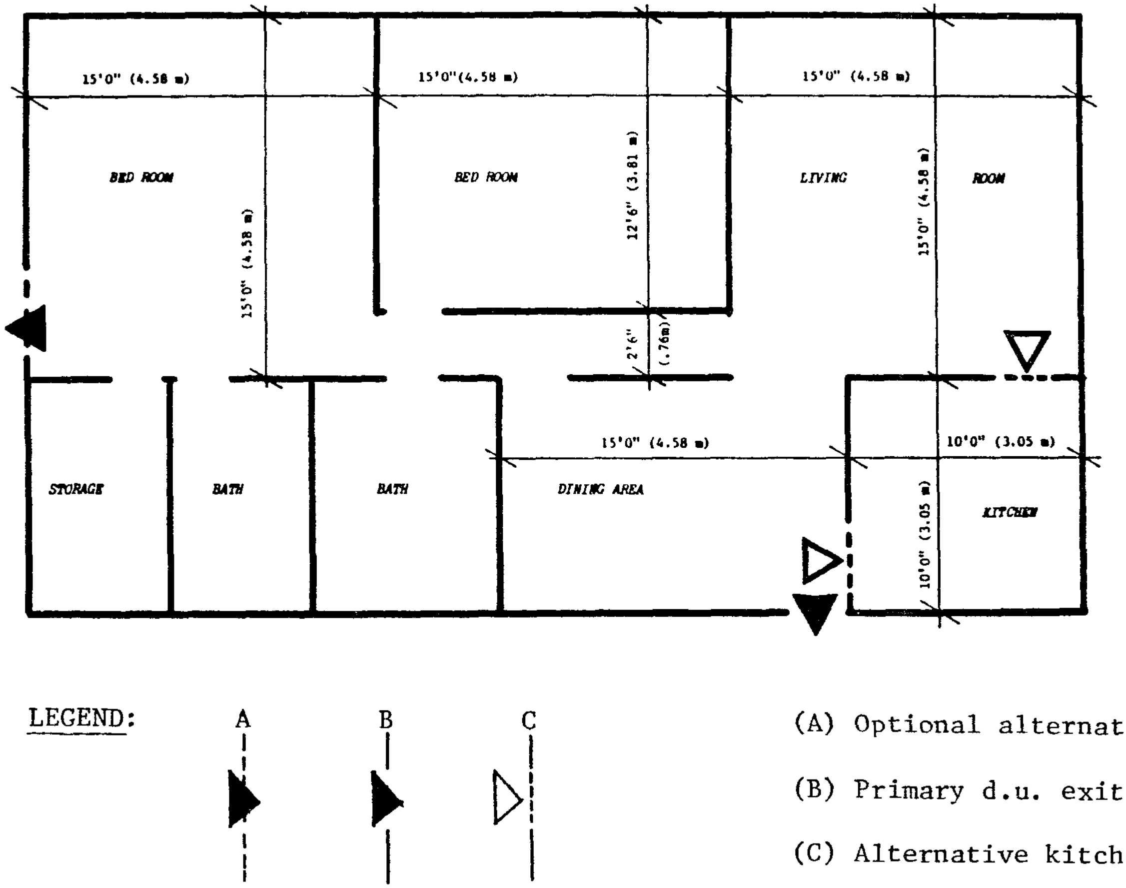
All simulated fire events were run for several variations of a basic floor plan. These variations were constructed to simulate those found in the FIDO files. In all cases, four occupants were assumed to inhabit the dwelling units. It was also assumed that the events occurred during the night hours, and 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. Plans and occupant locations are exhibited in Figure 3.22.

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) 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 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 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:

$$\mathrm{LOL} = \frac{n_f}{n_b + 1} \qquad (4)$$



(A) Optional alternatuve d.u. exit

(B) Primary d.u. exit

(C) Alternative kitchen entry locations

Figure 3.22 Schematic Plan of Dwelling Unit Showing Variations in D.U. Exit and Kitchen Entry Locations where: LOL = dwelling unit loss-of-life (D.U. LOL) index,

n_f = number of fatalities in the dwelling unit, and

n_b = number of bedrooms in the dwelling unit.

Simulated events were run for 200 time frames, or about four minutes (refer to Appendix A for time transformation procedures). Most fire professionals agree that, in general, a person who has not been removed from a fire in a small area (such as a apartment) within four minutes has a very low chance of survival at all. Thus, the simulated LOL index was computed as:

$$LOL' = \frac{n_f'}{n_b + 1} \tag{5}$$

where: LOL' = simulated dwelling unit loss-of-life index, and

n_f' = number of occupants remaining in the dwelling unit at the 200th time frame.

Comparisons between simulated events, and those reported in the NFPA-FIDO files were studied through the examination of three main 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 LOL' data do not differ significantly from actual fire data reported in the NFPA-FIDO files.

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 experimental condition, and then by replicating each condition ten times. Because the FIDO sample was quite small, comparisons were made using only five of the original ten computer replications. Zero values of LOL' were selectively omitted. The hypotheses enumerated above were examined by means of one-tailed t-tests (for independent groups) between appropriate samples.

Results

Simulated data are reported in Table 3.11. Comparisons between simulated and FIDO data are shown in Table 3.12. When comparing differences between simulated fire conditions, it was found that: (a) the dwelling unit loss-of-life index (LOL') was significantly greater for the plan exhibiting kitchen/d.u. exit adjacency, then for the plan in which no such adjacency was present ($t_{18}=16.00$, $p<.01$); and (b) LOL' was significantly lower for the 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 ($t_{18}=10.00$, $p<.01$).

When simulated data were compared with those obtained from the FIDO files, the following results were found: (a) no significant difference in LOL versus LOL' was noted for the one exit/adjacency condition ($t_6=1.29$, $p>.05$); (b) LOL' was significantly higher than LOL, for the

Table 3.11 Loss-of-Life Indices for Simulated Residential Fires (LOL')

Replication	Condition A[1]	Condition B[2]	Condition C[3]
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

[1] Condition A: kitchen entry--d.u. exit adjacency

[2] Condition B: no adjacency

[3] Condition C: two d.u. exits

Table 3.12 Comparisons of Loss-of-Life Indices Between Real (LOL) and Simulated (LOL') Residential Fires

Replication	Condition A[1]		Condition B[2]		Condition C[3]	
	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

[1] Condition A: Kitchen entry--d.u. exit adjacency

[2] Condition B: no adjacency

[3] Condition C: two d.u. exits

one exit/non-adjacent condition (t_6=13.00, p<.01); and (c) no significant difference in LOL versus LOL' was noted for the two exit condition (t_7=1.40, p>.05).

Experiment 4

Description and Objective

During the winter of 1977-78, a fire occurred in a small movie theater in Washington, D.C., claiming 11 lives. Of the 20 occupants present at the time of the fire, two escaped the building before conditions became intolerable, and the seven remaining survivors were removed by firefighters. Among the 11 who died, about three died in hospitals as a result of burns and smoke inhalation. The others died during the fire.

The theater was located in a second story loft space. A single stair at the rear was used both for access and egress. An emergency exit leading to the first floor roof was provided at the front, but this was locked shut to prevent entry by vandals, and was effectively unavailable. The theater space is shown in Figure 3.23.

The fire originated in the ground floor lobby, and resulted from the careless storage of highly flammable cleaning fluids. Dense acrid smoke quickly migrated up the stairway into the theater area, and flames blocked this (only) egress path.

Several investigations of this fire were conducted, including those by the Washington, D.C. fire and police departments, the National Fire Protection Association and the National Bureau of Standards. Various arguments regarding the fire resistiveness of the structure and means for

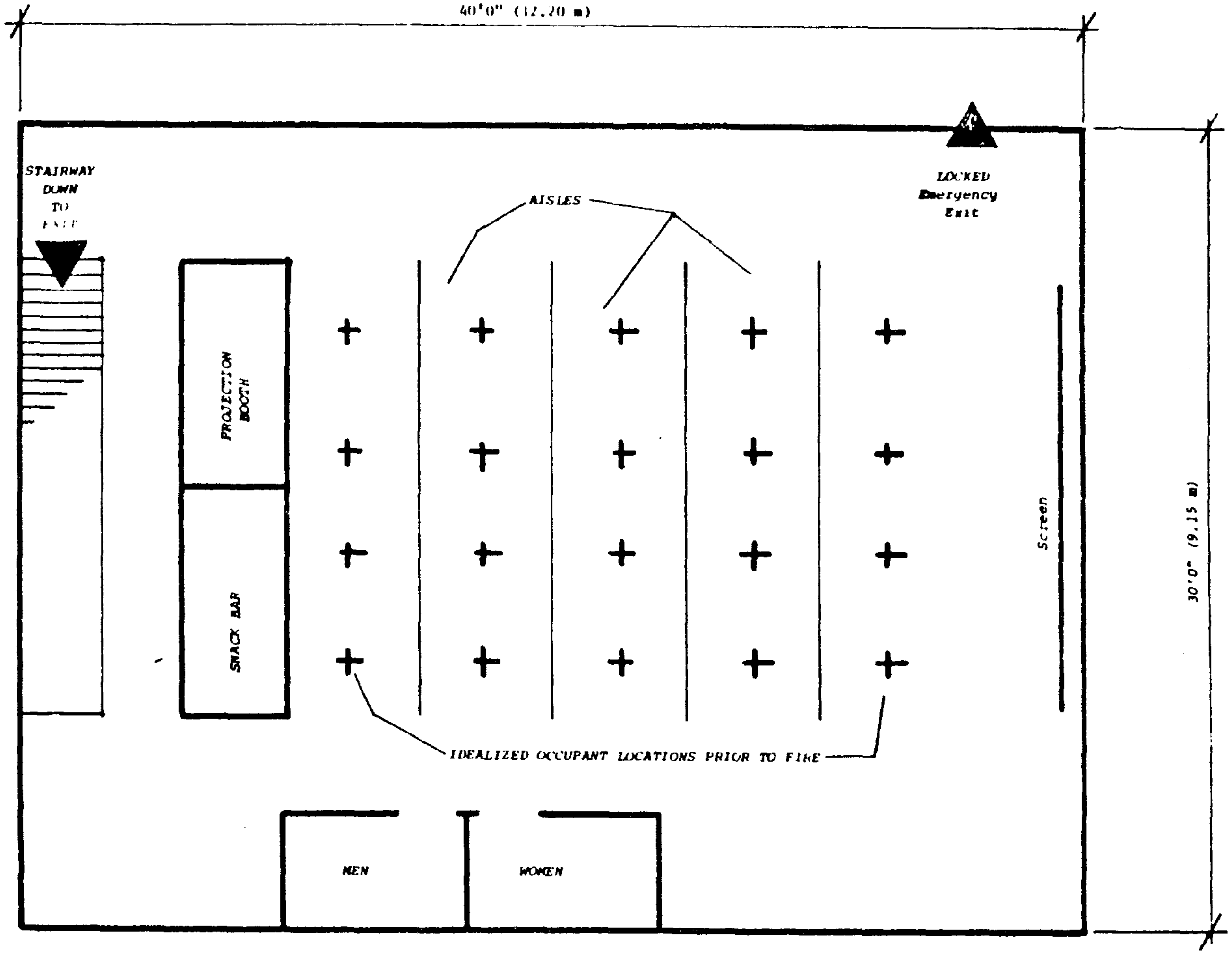


Figure 3.23 Schematic Diagram of Theater Plan

blocking smoke flow need not concern us here. However, all professionals agreed that the high loss of life was caused by the blockage of the only means of escape, and that had an alternative exit been available, there might have been no fatalities at all.

The objective of this experiment, then, was to determine whether BFIRES was capable of (a) reproducing the casualty statistics of the actual historical event, and (b) agreeing with professional experts concerning possible outcomes had an alternative exit been available.

Experimental Design

Actual fires are unique events, and for any single building or facility, it is difficult to think in terms of a distribution of events which may be described by certain parameters. In may be possible, however, to consider distributions of events having occurred in a single class of buildings, such as theaters. But even when this approach is taken, the objective of recreating a single event in a particular facility is not approached directly. One could argue, however, that if simulated outcomes generally conformed to those found among numerous events from a given real-world class, then the simulation program is useful for predicting outcomes of fires in any member of that class.

Because data were available only for a fire in a single theater of a particular design and occupancy, a modified version of the above approach was followed. Specifically, five replications of the simulated event were run, and the mean of the replication outcomes was compared (qualitatively) against results from the actual fire. In addition, replications of events under each of the two exit conditions were run, and the means for each compared.

In all simulation runs, occupants were assumed to be fully mobile. However, the various exit conditions were treated in terms of differences in knowledge of the safe exit location. That is, occupants in the one exit case, seeing that the only available exit was totally blocked, had no knowledge of any alternative. Occupants in the two exit case, however, were assumed to be knowledgeable of the location of the alternative exit.

Simulated fires were run for 100 time frames, corresponding to approximately 2.25 minutes. Fire professionals suggested that, under the conditions present in the theater, persons who did not escape on their own by this time would likely be unconscious. The number of occupants escaping by the 100th frame were recorded at the conclusion of each of five replications, for each of the exit conditions. It was assumed that those remaining within the theater by the end of each replication had either been removed later by firefighters, or else had perished.

Results

Simulated data are reported in Table 3.13. In the one exit case, no occupants escaped the theater during any replication. In the two exit condition, an average of 19.80 occupants escaped, across the five runs. These preliminary findings conform to the fact that only two persons actually escaped on their own before conditions became intolerable, and suggest that the presence of a viable alternative exit would have dramatically reduced the number of casualties.

Table 3.13 Numbers of Occupants Escaping From Two Simulated Theater Fires

Replication	Condition A[1]	Condition B[2]
1	0	20
2	0	19
3	0	20
4	0	20
5	0	20
Means	0.00	19.80
Std. Devs.	0.00	0.45

[1] Condition A: one exit available, but blocked

[2] Condition B: one exit blocked, alternate exit clear

Discussion of Experiments 3 and 4

Experiment 3

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.

These comparisons with the NFPA-FIDO data reinforce our confidence that BFIRES is sensitive to certain important parameters, as discussed earlier. In particular, we note that variation in factors under the direct control of building designers and regulators (floor plan and exit arrangement, and numbers of exits) seem to have a substantial impact upon the likelihood of escape.

The discussion on sensitivity also suggested that this effect should be especially pronounced in cases where occupants could be assumed not to vary along such factors as exit knowledge (familiarity with the building's layout) and mobility. In Experiment 3, 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 (e.g., that under certain conditions variation in occupant factors minimize 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 behavior under a very wide spectrum of cases, and to similarly examine alternative models and explanations of the same phenomena.

Experiment 4

This experiment points to certain shortcomings inherent in BFIRES which make interpretation of the data less than straightforward, and which help define the domain of problems to which the program is best suited. Consider, for example, the fact that occupants never escaped the simulated one-exit space. In general terms, the theoretical structure underlying BFIRES in no way precludes escape under such conditions. Thus, either the translation from theory to the computer model, or else the deployment of the model to the particular case, resulted in the inability of occupants to escape.

One explanation for this result is perhaps that the particular fire under study lay outside the boundaries delineated by BFIRES, and was thus inappropriate for study by means of this computer simulation program. It must be noted that in the real fire, the development of flame and smoke required a certain period of time (albeit less than one minute). During the early stages of this developmental process, it is not surprising that some occupants (perhaps already near the stairway) recognized the potentially dangerous situation, and proceded down the stair before conditions became untenable. BFIRES, however, does not model physical fire development over time, nor does it simulate human responses under direct contact with fire biproducts (recall that BFIRES users must usually assume that the fire is occurring in some other part of the building, while evacuation is taking place in the zone under study). Thus, at the onset of the simulated event, we must assume that conditions had already become intolerable, and that the stairway was already impassible. Under this assumption, it seems quite logical--and predictable--that no simulated occupants would escape the theater space. We might conclude, then, that BFIRES is in fact an appropriate simulator for fires in this building class, provided we accept the idea of simulating an event after it has already reached a certain critical stage.

Another shortcoming is illuminated by the facts that victims of the real fire were reported to have attempted escape via the locked exit, and that a number of persons were found in the immediate vicinity of that door by firefighters. Familiarity with the second exit was supported by police interviews with survivors, which indicated that the door was marked with an exit sign, and that some persons even saw the door used on previous occasions. However, in the absence of a specified exit goal, BFIRES produced behavior characterized as "meandoring", and simulated occupants were not found to cluster in the vicinity of the blocked exit by the 100th time frame. In fact, those simulated occupants who did respond adaptively sought the corner of the theater farthest from the stair, in an effort to maximize their distance from the threat source. But this corner was across the room from the blocked exit. The fact that BFIRES does not account for previous experiences in a building, or for such cues as "exit" signs is clearly a shortcoming which limits the range of its application.

An Examination of Face Validity

Experiments such as those discussed above provide primary evidence for or against the predictive and replicative 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 we also try to reconcile simulations with conventional and professional wisdom.

Comparisons With the Literature

In Chapter I, various impediments to empirical model building using data reported in the literature were noted. In light of those problems, comparisons between BFIRES outcomes and phenomena reported *independently* 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 (LTB) 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. Recall that all other early research on the carrying capacity of pedestrian ways involved the study of flow rates on isolated paths (e.g., a single stair flight, or a measured segment of a particular corridor). Data reported in this chapter for Experimentl appear to support the opinions of the LTB investigators. The data suggest that varying degrees of route "constriction" produce differences in movement behavior and 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 simulated evacuation on an actual hospital ward. Although rescue activities are not accommodated by BFIRES, the experiments reported earlier in this chapter 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, but that this mode of behavior 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 simulated events frequently deviates from an optimal path toward a safe exit, even when individuals are familiar with the building, are mobile, and are making decisions on the basis of unambiguous and correct information. Although BFIRES occupants do 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 data all agree that unidirected 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 conclusions do not concur with BFIRES data which suggest that, despite the deviations and detours described above, familiarity is a necessary component of rapid and direct evacuation. As discussed earlier, however, BFIRES greatly simplifies the egress problem by ignoring non-movement related behaviors which contribute to egress success.

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).

Design professionals have long agreed that no building occupant should ever be trapped in the situation where the only available 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 from Experiments 3 and 4.

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 the BFIRES data, 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.

Design and regulatory professionals generally expect few problems to derive from dead-end corridors of relatively short length (about 15 feet or less). However, where dead-ends lead to maze-like networks of spaces (as in older office buildings, factories, or hospitals), people not familiar with emergency egress routes are expected to become confused, get lost, and not escape the floor within a reasonable period of time. Data from Experiment 2 suggests that, for occupants knowledgeable of exit locations, dead-ends of short length are of virtually no consequence. However, longer dead-ends, or corridors leading to additional rooms, may result in unnecessary meandoring, and the concommitant loss of valuable time. This hypotheses was not specifically tested during the current investigation.

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 simulated data from Experiments 1 and 2.

Correspondence with Anecdotal Accounts

Fire reports published by the National Fire Protection Association during the last five years were reviewed. 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 these appear to conform with BFIRES-produced behaviors:

(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.

SUMMARY

Sensitivity and Internal Validity

In cases where all occupants knew the safe exit location, and where no occupants were mobility-impaired, experiments using the BFIRES computer simulation program yielded results suggesting that:

(1) Escape score varies as a function of the extent to which a spatial zone is subdivided into smaller segments. For a zone of given gross area, the mean escape score for all occupants should increase as the number of spatial subdivision is increased.

(2) Total spatial displacement by occupants varies inversely as a function of the extent of spatial subdivision. As a zone is subdivided into more spaces, the number of steps taken by occupants should decrease.

(3) Escape score varies as a function of permissible occupant density in a simulated environment. With a higher permissible density, a higher mean escape score should be found for all simulated occupants on the floor.

(4) Total spatial displacement varies inversely as a function of permissible occupant density. At higher densities, fewer spatial displacement should be found.

(5) The effect of occupant density is dependent upon the extent of spatial subdivision. Density appears to have the greatest impact where spatial zones are subdivided into a larger number of smaller areas.

Under conditions where occupants varied in their knowledge of safe exit location, and their levels of mobility impairment, BFIRES experiments yielded results suggesting that:

(6) Floor plan configuration (specifically, the presence or absence of dead-end corridors) has no effect on emergency egress outcomes.

(7) In general, egress outcomes will not be influenced by variations in permissible occupant density.

(8) Egress outcomes vary as a function of occupant mobility. Unimpaired occupants are more likely to escape the floor within a given period of time, will escape more quickly, and will traverse shorter routes than will their mobility-impaired counterparts.

(9) Egress outcomes vary as a function of occupants' knowledge of the safe exit location. Knowledgeable occupants are more likely to escape the floor, will escape more quickly, and will traverse shorter routes than will uninformed individuals.

(10) The effect of exit knowledge is dependent upon occupants' mobility. In general, occupants may never escape within the time allowed if they are not informed as to the location of the safe exit. However, occupants who do know the safe exit's location will escape faster and along more direct routes if they are not mobility-impaired.

External Validity

The external validity of simulation results was evaluated. Two experimental tests were discussed, in which an attempt was made to compare outcomes from BFIRES simulation runs against (a) data selected from an archival file and (b) outcomes reported for a single historical fire. Results of these tests suggest that, within the boundaries established by the experiments, BFIRES is capable of reproducing certain important fire outcomes (e.g., numbers of persons ultimately escaping; loss-of-life indices).

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. With few exceptions, these comparisons illustrate agreement between simulation results and various independent sources, and suggest that (at least on certain superficial levels) convergence is possible.

Chapter IV

DISCUSSION

GENERAL CONCLUSIONS

Conclusions from the Experimental Results

This study demonstrated the feasibility of systematically conceptualizing the emergency egress behavior of building occupants under certain specified conditions, and illustrated the utility of simulating this behavior by computer. Specifically, results from experiments designed to examine the validity of BFIRES suggest that:

(1) A variety of general egress situations could be simulated by means of BFIRES.

(2) Every such situation is unique, and is defined by the set of user-supplied input parameter values which describe the building, the threat, and the occupants.

(3) BFIRES output is readily interpretable in terms of familiar units of space and time. Thus, the program is capable of simulating environments of known (or desired) spatial dimensions, and events of known (or desired) temporal duration.

(4) BFIRES is sensitive to variations in parameters of immediate interest to building designers and regulators. These include: (a) several aspects of floor plan configuration; (b) the existence of impairments to occupants' mobility, (c) occupants' familiarity with the building layout, (d) levels of occupant density, and (e) exit blocking.

(5) Under certain conditions, BFIRES is capable of independently reproducing important behavioral patterns known to have occurred during real fires. These generally concern: (a) speed and directness of egress movement; (b) responses to blocked exits; (c) effects of familarity with exit locations; and (d) effects of mobility impairments.

Comparisons with Other Simulations

Three important applications of computer simulation methodology to the study of emergency egress behavior were reviewed in Chapter II. These included the models by Wolpert and Zillmann (1969), Edmondo, et al., (1969), and Korkemaz (1977). Clearly, work on the development of BFIRES drew most directly from Wolpert and Zillmann's approach. In particular, BFIRES and the earlier simulation are the only two exercises in which an attempt to model the movement decisionmaking behavior of occupants was specifically made. Both programs require individual occupants to "work their way" out of the life-threatening environment, on the basis of given initial conditions, as well as environmental changes which occur over time.

The essential difference between BFIRES and the Wolpert and Zillmann program, however, is the fact that BFIRES treats decisionmaking and concommitant action as a stochastic process. Thus, under a particular set of conditions at any point in time, move decisions are made probabilistically, and tend only to be biased in the direction suggested by available information. By contrast, a given set of environmental conditions will produce a unique movement decision in Wolpert and Zillmann's simulation.

Other simualtions by Edmondo, et al., and by Korkemaz, avoided the question of how occupants respond to information in the emergency environment. In their models, egress paths were predetermined, based on the floor plan configuration of the building under study. Accordingly, once occupants selected a general direction for movement, evacuation proceeded along the preselected paths.

Unlike BFIRES, the other models reviewed _did_ attempt to simulate fire and smoke movement within the immediate environment of escaping occupants. Both Wolpert and Zillmann, and Edmondo, et al., treat these agents as barriers to egress movement, and as potential initiators of route-switching behavior. Korkemaz, on the other hand, emphasized the physiological effects of inhabiting a space infiltrated by smoke (e.g., the reduction of occupants' movement speeds).

Limitations on the Application of BFIRES

As suggested in Chapters II and III above (and also in Appendix A), the use of BFIRES is subject to a number of important limitations. In particular, the program user is forced to make a variety of assumptions about (a) the fire, (b) the building enclosure, (c) modes of information transmission and reception, (d) the content of information, (e) possible patterns of egress movement, and (f) modes of emergency behavior other than egress movement.

Assumptions Regarding the Fire

When using BFIRES to analyze a particular fire event, the user must generally assume that the fire begins and remains in a portion of the building distinctly separated from the evacuation zone under study. In the simplest cases, the fire is assumed to occur either on an entirely different floor of the building, or else in a zone sufficiently separated from--while on the same floor as--the area being observed.

When this assumption is violated, simulated fire event outcomes may not necessarily be useful. Consider for example Experiment 3, in which the fire originated in the kitchen of an apartment. Clearly, the separation assumption was violated in that case. However, results from Experiment 3 seem to suggest that under some conditions, BFIRES is robust with respect to the fire location. Results from Experiment 4, however, do not necessarily support this notion, since calibrating the simulation to produce real-world outcomes may have required establishing initial conditions which differed unacceptably from those preceding the real fire.

Assumptions About the Building Enclosure

When applying BFIRES, the user must reduce the building's form to extremely simple elements, namely wall segments and doorways. In connection with doorways, the program allows the user to choose whether a doorway will contain a door panel, and whether such panels are to be automatically- or manually-closing. Walls must be specified in linear segments, and must lie along rectilinear grid lines. Curved or diagonal segments may only be simulated by "stepping" short rectilinear segments (as in Figures 2.1 and A.2).

The simulation of furnishings within rooms is not directly accomodated by BFIRES, although where such elements as book cases, wardrobes and other large units are thought to provide wall-like barriers, they can be simulated indirectly as walls. Similarly, windows cannot be simulated directly, but may in certain cases be treated as doorways.

Stairways, ramps, and other irregular surfaces cannot be simulated directly. They can be treated as level, smooth surfaces, however, by distorting their length and/or widths. A stair enclosure, for example, may be simulated by adjusting its dimensions so that movement rates within such an enclosure in an actual building are approximated.

Assumptions About Information Transmission and Reception

When preparing to simulate a fire under a particular set of conditions, and to observe the behavior of simulated building occupants in response to the fire danger, the BFIRES user must bear in mind that: (1) The "visual" capabilities of simulated occupants extend only to the perception of barriers to their movement (i.e., walls and other occupants). (2) Sign-born information (e.g., "exit", "no exit", etc.) is not accomodated. (3) Auditory communications are limited to the transmission of information about exit locations and the fire location, via either interpersonal contacts or public address. (4) The transmission of visual or auditory information directly from fire, smoke, or building deterioration is not accommodated.

Assumptions About the Content of Information

When provided, fire alerts impart unambiguous information specifically identifying exit and fire locations. Occupants are assumed to "get the message right the first time", and not to misinterpret the information. BFIRES permits the introduction of fire alerts at the onset of simulated events only, and allows any number of occupants to be designated as recipients of the initial alert.

Assumptions About Patterns of Emergency Egress Movement Behavior

BFIRES restricts occupants to movement between person-occupiable grid locations only. Movement between such locations may occur along any of the eight possible vectors (see Figure C.2). The remain-in-place option is, of course, always available. The principal goals of emergency egress behavior considered by BFIRES are exit goal seeking, threat evasion, or some combination of these. Once an occupant has exited the study area, he is removed from the analysis, and reentry to the danger zone is not simulated.

Emergency Behaviors Other than Egress Movement

The following behaviors are chief among those excluded from simulation via BFIRES: (a) helping persons unable to remove themselves from the danger zone (by other escapees), (b) rescuing by nonoccupants (e.g., firefighters), (c) purposefully investigating the fire situation, and (d) seeking assistance (e.g., alerting the fire department).

Interpreting the Limitations

The degree to which violations of assumptions summarized above influence the usefulness of simulated data depends upon the nature of the application itself. Two extreme cases illustrate this point. In a high-rise building, emergency response activities may be studied on the third story, while the fire has been confined some distance away, for example on the tenth story. It may be perfectly reasonable to assume that all occupants of the study floor are ambulatory, have been alerted to the existence of the fire, and have even been informed that one of the two stairways has become blocked by smoke and should not be used. It may also be reasonable to assume, as in the case of a multifamily residential building, that all occupants are sufficiently familiar with the layout of their floor, and that they can locate safe exits--routes to them--without the aid of descriptive signs or schematic diagrams. If the fire occurs during the daytime or early evening in such a building, occupants may be assumed awake, alert, and capable of receiving incoming information. Under such circumstances, BFIRES should be expected to yield useful outcomes, with respect to egress movement patterns, egress times, and numbers of persons escaping the floor (see Experiments 1 and 2). Another somewhat analogous situation would be the simulation of a fire drill, in which we seek to predict movement patterns, times, etc.

The converse situation is one in which a fire begins during the night within a zone occupied by elderly residents, many of whom suffer severe mobility impairments, are nonambulatory, or are heavily sedated. Under these conditions, BFIRES should not be expected to provide data useful in predicting fire outcomes.

Because of limitations such as those discussed above, the application of BFIRES to actual design or regulatory problems is not presently recommended. In the next section, directions for research into the mitigation of these shortcomings are considered.

IMPLICATIONS FOR FUTURE RESEARCH

The model presented and applied in Chapters II and III serves as a network of interrelated hypotheses about relationships and parameters believed to describe building fire events. As the first such model to treat human decisionmaking as the fundamental building block, it is speculative and tentative. Indeed, the computer simulation program based on this model does generate egress movement behavior by simulated humans under certain, rather narrowly defined circumstances. However, Experiments 3 and 4 described above only begin to illuminate the extent to which the aplication of BFIRES provides data applicable to real world fire outcomes.

As a computer simulation of human behavior, BFIRES does more than generate artificial behavior patterns (i.e., event outcomes). The program also makes a precise statement about the ways people are thought to gather and use information from the environment, to identify and evaluate action alternatives, and to otherwise deal with the problem of attaining safety from a fire threat. The user concerned only with the validity of simulation outcomes may have little interest in the verisimilitude between BFIRES' structure and the organization of human cognitive processes. However, given a preliminary statement by BFIRES about the organization of such processes with respect to a given environment (however, crude or simplistic), further research with the program should offer opportunities for attaining a deeper understanding of human behavior during fires, and for enriching our understanding of pertinent substantive areas.

Several specific implications for future research stem from the modeling, programming, and experimental exercises described earlier. These include (a) research toward specifying the range of applicability of BFIRES as a tool for environmental analysis, in its current form; (b) research toward expanding the range of applicability of BFIRES; (c) research into new questions about human behavior during fires; and (d) new perspectives on research in related substantive areas.

Research Toward Specifying the Range of Applicability of BFIRES

In the previous section, a variety of assumptions and limitations governing the application of BFIRES were summarized. The fact that the simulation experiments presented here only begin to specify the range of the program's applicability--as a tool for environmental analysis--was also discussed. Any user of the program will be concerned with two important questions: (1) Can the application of BFIRES to a particular design problem be expected to provide valid and useful data? (2) Does the application of BFIRES to a particular design problem require assumptions about the building, the fire, and other occupants--in the real world--which cannot be supported?

Future research must address these questions, and specify for the user the exact conditions under which satisfactory data from simulation runs may be expected. This will require the conduct of numerous simulation experiments of the type presented in Chapter III. As such data bases as the NFPA-FIDO files expand to include more examples of diverse historical fire events, it will become possible to pattern studies after Experiment 3, and to explore the applicability of BFIRES under an increasingly broad range of environmental and occupancy conditions.

At any time, moreover, it should be possible to attempt simulating specific real-world fires for which sufficient data are obtainable. Such case studies can be modeled after Experiment 4. Unlike historical data bases, over which the BFIRES user has virtually no control, the case study enables the investigator to obtain very specific kinds of data for a fire event. This can benefit the BFIRES user by enabling the investigator to specifically request data in program-usable form, and thus to reduce the risk that assumed simulation input conditions are not sufficiently analogous to those defining the actual event. This latter point underscores the importance of establishing good working relations with appropriate groups such as local fire and police departments. For example, Experiment 4 was facilitated by tape recordings of interviews with fire victims conducted by local police officials, in connection with the actual theater fire. Facts revealed concerning specific occupants' action patterns--as these unfolded over time--were useful as a basis for analyzing the validity of simulated events. In general, data at so fine a level of detail are not included in large-scale data bases.

Research Toward Expanding the Range of Applicability of BFIRES

Future research oriented toward improving BFIRES as a design analysis device might concentrate on narrowing the limitations governing its use, and to bring its underlying assumptions more closely in line with conditions likely to be found when analyzing actual events. In a very real sense, these goals will require retracing all the steps of modeling, program development, and testing presented in Chapters II and III. Several directions may be pursued.

For example one may wish to start with the current version of BFIRES, and add subroutines designed to simulate phenomena not previously included, e.g., (a) the direct exposure of occupants to fire products, (b) rescue activities and helping behavior, and (c) the introduction of sign-born information and other forms of verbal and nonverbal communication. Here, the simulation designer must first design the appropriate routines, coordinate them with the existing program, and then conduct validation experiments for both internal and external tests. Given such expansions to the basic form of BFIRES, one should expect the new version to be capable of replicating a greater variety of historical fire events, and to be applicable under considerably fewer limitations or assumptions.

As an alternative to building upon the current program, investigators may wish to examine models which differ fundamentally from that underlying BFIRES. For example, a variety of models are possible which emphasize socio-environmental dynamics, rather than information processing and decision-making *per se*. Researchers are only now beginning to consider the importance of communications processes and obedience to authority in the building fire context (Canter, et al., 1978; Edelman, et al., in press). In addition, investigators have only recently become interested in the impact of role identification by occupants, and in the effects of implicit social rules, upon behavior during fire emergencies (Canter, in press; Gordon, 1978; Swartz, 1978). Surely each of these components contributes some portion of the total variance found in emergency egress behavior.

Research Into New Questions About Human Behavior During Building Fires

An important advantage of employing computer simulations is that the process of setting up a problem for the computer forces the investigator to define the simulated event in sufficient detail enabling the computer not only to run, but to yield meaningful results as well. As illustrated in the previous sections of this chapter, this is likely to require a variety of assumptions about "what really happened" during some historical event (or, what might be expected to happen during some hypothetical future event), and about the ability of the simulation program to imitate important aspects of the actual process. Valuable biproducts of this process are the new questions for research which arise whenever it is impossible--using available knowledge--to verify such assumptions. The list of such questions is lengthy and a few examples are outlined below.

When setting up input conditions for a BFIRES experiment, the user may determine whether all occupants start out with complete knowledge of exit locations, whether only certain occupants begin with such knowledge, or whether none do at all. When deciding how to initialize this part of the program, the experimenter in effect makes certain assumptions about occupants' initial familiarity with the building's layout. Such familiarity may stem from long-term use of the facility, or from such training devices as evacuation drills or lectures. BFIRES makes no distinction as to the origin of exit familiarity; moreover, it never actually defines exit location knowledge as "familiarity with the building's layout", *per se*. These are assumptions made by the user, in an attempt to match simulated with real-world conditions. However, since experiments using BFIRES suggest that exit location knowledge influences egress behavior, the importance of such knowledge is underscored, and our interest in its origins and nature is increased.

Two investigations have begun to explore the importance of training (Herz, Edelman and Bickman, 1978) and vocal alerting (Keating and Loftus, 1977), as means for imparting knowledge about where to go and what to do during fire emergencies. These are representative of the kinds of field studies which could assist the designers and users of simulations such as BFIRES.

Herz, et al. (1978), conducted a study to determine whether training a nursing home staff effectively augmented knowledge of an emergency egress plan. Staff members were divided into two groups: (1) those who attended a training lecture session, and (2) those who did not. All subjects filled out questionnaires designed to record their pretraining knowledge about emergency egress. Some time after training, subjects who attended the lecture session filled out questionnaires designed to determine the effects of the training program. In general, the investigators found that the training adequately conveyed certain types of useful information to nursing home staff members. In another investigation, Keating and Loftus (1977) reviewed the use of voice emergency alerting in nursing homes, as transmitted via electronic public address systems. These researchers recommended specific guidelines for the development and deployment of instructional messages.

On the basis of findings from such research, the BFIRES user might more accurately match simulated with actual starting conditions. In addition, investigations of the type reported by these researchers enables the simulation designer to more accurately replicate information gathering, transmission, and processing.

Other examples involve the notions of leadership, social roles, and differnetial cognition during fire emergencies. Although BFIRES permits certain kinds of information to "spread" among occupants, and allows each individual to "change his mind" under certain conditions, positions of leadership and the obedience of others to authority are not specifically simulated. Similarly, BFIRES does not simulate differences in emergency cognition among building occupants. But as with the previous examples, the program's user may be forced to operate under certain assumptions regarding these parameters while attempting to prepare a real-world case for computer simulation analysis. Again, as with the previous examples, recognition of the potential influence of these factors upon emergency egress performance may lead the investigator in a number of fruitful research directions. For instance, Canter (in press) has begun to conceptualize the role of social rules and structures during fire situations, while Stahl (1978) has outlined an approach to studying the differential impact of one's position within an organization upon emergency perceptions and behavior.

Similarly, results from experiments presented in Chapter III raise numerous empirical questions about the roles of floor plan configuration, exit location and number, accessibility of exits, occupants' physical capabilities with respect to mobility, and other parameters. However, very little of this work has been undertaken to date.

New Perspectives on Research in Related Substantive Areas

Chapter I advanced the notion that our understanding of numerous discrete substantive areas could be furthered through their study in connection with a single, complex environmental setting. During the course of the investigation, references were made to various psychological concepts and problems, in order to suggest ways in which many of these interact during building fire events. Several such concepts were addressed directly in connection with the formulation of a model of egress behavior, and during the presentation of the BFIRES computer simulation program (e.g., stress and stress agents, decisionmaking, information perception, emotional and motivational controls over behavior). Other concepts were only indirectly treated or implied (e.g., crowding, personal space, anxiety), and some--though potentially quite relevant to the fire problem--were not dealt with at all (sex differences, information overload, short- versus long-term memory, altruism).

Research in such areas will likely contribute some proportion of our overall understanding of building fires. In turn, their study in the fire context should increase knowledge within specific research areas. This is possible because building fires provide a unique and untapped naturalistic setting for psychological research: environmental trauma of extremely short duration (usually on the order of minutes). Thus, the study of occupant behavior during fires offers important opportunities for the investigation of concepts previously studied in connection with long-term or ongoing events, or with regard to long-term human development (e.g., stress in relation to illness, crime, employment; information overload resulting from high density or visually confusing environments; sex differences in connection with personality development, task performance, etc.).

REFLECTIONS ON THE USEFULNESS OF SIMULATION MODELING

The dissertation explored possibilities for developing and using computer simulation models, particularly when studying human responses to narrowly defined environmental conditions of short duration. Tests of BFIRES revealed that, within the limitations detailed earlier in this chapter, simulation exercises may be useful both as tools for building design and regulation, and as aids to constructing and analyzing theory in environmental psychology.

A Tool for Building Design and Regulation

The most obvious opportunities for the practical application of simulations such as BFIRES derive from their use as building design and regulatory tools. The essential aspect of the building design process is the fact that alternative solutions to problems are proposed and evaluated at almost all levels, from large-scale site planning to the minute detailing of building hardware. To as great an extent as possible, the evaluation of design alternatives is based on well-developed ideas about the costs and benefits of each. In many areas concerning building utilization, however, the architect's knowledge base is far from complete. In these areas, design decisions are frequently made on the basis of expediency or economic considerations, or on the basis of knowledge from other--potentially irrelevant--disciplines for which data in quantitative form are readily available. Designing for life safety from fire is an important example of such an area. Here, the architect typically tailors various design decisions to "meet" building regulatory prescriptions (codes). As a result, design for emergency egress is based on the principles of "traffic engineering" (as discussed in Chapter I) which are typically written into the applicable building codes. The designer is rarely challenged to analyze specific life safety needs with regard to the particular facility under development, since to do so might result in solutions which are difficult to interpret in terms of code prescriptions.

In many cases, it is possible for the architect to arrive at a number of alternative solutions to a given life safety problem. The question of which to select (and which should be encouraged by regulatory officials) might usefully be answered through the utilization of computer simulation techniques. For example, designers and officials could conduct simulated fires in buildings designed to exhibit each alternative approach (note that the buildings are evaluated while on paper, before construction begins). Distributions of outcomes could be constructed for each alternative, and the distributions compared statistically. Where a particular design consistently yielded superior egress performance, the design problem may be considered solved.

This scenario presupposes, however, that the computer simulation program has been adequately validated for the building type and occupancy conditions in question, and that it has been accepted for use by designers and local building officials. Clearly, BFIRES--in its current configuration--is not advocated for such applications. Future research of the type discussed earlier in this Chapter is expected to move the program in this important direction.

But even where a program such as BFIRES is not accepted as an "arbiter" in any official sense, its application might still be useful. For example, the Life Safety Code (National Fire Protection Association, 1973) specifies that where two means of egress must be provided from a building floor, these should be as remotely positioned from one another as possible. However, the document provides the architect with extremely little guidance in determining adequate degrees of remoteness. Again, the designer could run simulations for several design schemes, comparing results from each. While such exercises might not be defensible in any legal or regulatory sense, they may contribute informally to the process of selecting an appropriate design alternative.

An Approach to Constructing and Analyzing Substantive Theory in Environmental Psychology

As discussed in Chapter I, computer simulations provide means for (1) concisely describing complex relationships among large numbers of variables, and (2) describing dynamic processes over time. These requirements are highly relevant to environmental psychologists, whose objectives are usually to understand the nature of ongoing, naturalistic person-environment systems. Unfortunately, the complexity of such systems has stifled--rather than marshalled--theoretical growth.

The BFIRES exercise has shown that, for certain kinds of problems, computer simulation methodology yields extremely concise theoretical statements: computer programs (concise for the very reason that only complete, fully closed programs may be executed on a computer). It has also demonstrated that, since computer programs may be executed to simulate ongoing systems which undergo change over time, experiments with the programs are direct tests of the theoretical structures upon which they are based. These tests will ultimately suggest to researchers the importance of certain variables, and of the linkages between them. Moreover, simulation exercises will direct researchers to investigate those variables and relationships which seem to contribute to the overall variance in the data (in the case of BFIRES, occupants' emergency egress behavior). Other problems of interest to environmental psychologists may be amenable to examination via computer simulation methodology. These include--but are not limited to--the study of small-scale urban crime scenarios, interior space usage patterns (and concommitant design), the use of park and other outdoor amenities, and nonemergency pedestrian behavior (e.g., with regard to the design of commercial facilities). The expansion of computer simulation methodology into such domains is expected to greatly increase activity toward the development of grounded substantive theories about particular person-environment systems.

Appendix A

CALIBRATION OF THE COMPUTER SIMULATION PROGRAM

INTRODUCTION

The BFIRES simulation program produces tabular output in various forms. By analyzing this output, the user can draw inferences about building fire events. The actual output itself, of course, possesses none of the physical characteristics of a fire event; it is merely a *symbolic* representation. The *degree* to which the computer output represents a real-world event is an important and complex problem, involving the "external validity" of the simulation. Here, however, *factors which influence* this degree of representation are considered. In particular, there are two factors which largely determine the similarity between simulated events and their real-world referents: (1) the correctness of the simulation model, and (2) the deployment and application of the model to a given case study.

Even after analyzing BFIRES output, the user may find relatively few similarities between simulated and real-world events. When this occurs, must the user conclude immediately that BFIRES embodies an erroneous conceptualization of emergency egress behavior? Not necessarily. Perhaps the program was only incorrectly "tuned", or fitted, to the real-world case under study. For example, simulated occupants may have been improperly located on the floor, or their knowledge of exit locations may have been incorrectly assumed, with respect to actual locations and states of knowledge in the anticipated or historical real-world event. In such cases where the simulation is improperly deployed, computer output may be quite misleading (i.e., the output may represent some real event other than the one actually intended).

BFIRES constructs a complex network of interrelated variables, or parameters. Some of these are computed, varied, or fixed internally, and are thus outside the user's immediate control. Values of these parameters relate directly to the "correctness" of the underlying model: incorrect parameters detract from the model's correctness. The values of other parameters, however, are chosen and input by the user, in an attempt to match simulated conditions to those expected during a real-world case (or to those actually known to have occurred, as in the case of historical replications). This process of aligning program parameters with those describing the actual event is referred to here as calibration.

Calibration and external validity are closely related. When the user compares simulated with real-world data and finds some degree of variance between the two sets, he will attempt to adjust input parameters until a minimum variance is achieved. If the variance is still unacceptably high, or if low variance could only be achieved at the expense of employing obviously unrealistic parameter values or false assumptions, then the user may be justified in concluding that the model underlying the simulation program is inappropriate to the case under study.

The objective of this appendix is to introduce the user to parameters handeled within BFIRES, so that the program's range of application will be better understood. There are three classes of parameters with which the user must become familiar: (1) internal constants; (2) internal dynamic processes; and (3) user-supplied variable values.

INTERNAL CONSTANTS

Consensus Exit of Choice

Subroutines GROUP, OTHERS, and AGREE (refer to Appendix B) establish for given occupants the social environment through which they gather certain information necessary for making egress movement decisions. An important example involves the situation in which several occupants inhabiting a space have different opinions about the best exit from that space. The model embodied within this segment of BFIRES suggests that: (1) whenever all such occupants hold the same opinion, the choice of exit is clear-cut; but (2) where a difference of opinion exists, a consensus will have the effect of winning all occupants over to the majority view. But just how should "consensus" be defined: 51% of all occupants in the space? Or 67%? The literature on human behavior in fires provides no guidance. For practical purposes, however, the cut-off line was drawn at 60%. If 60% (or more) of the occupants inhabiting a space favor a particular exit from that space, they will "convince" the remaining occupants of the quality of their opinion, and all will seek that exit.

Penalty Thresholds

Subroutine EVAL20 simulates occupants' evaluation of their current "safety status" by comparing their egress progress to date against the total elapsed time they have spent in the danger zone. When evaluating their status with respect to the egress goal, they seek to ascertain that the distance separating themselves from the goal is not so great as to preclude their reaching it before the critical time is reached (the point at which life support becomes untenable). Similarly, when evaluating their status with respect to the location of the fire, they seek to ascertain that the distance between themselves and the fire is sufficiently large to permit escape prior to the critical time.

BFIRES establishes thresholds with respect to both threat evasion and exit goal seeking. These are the criteria against which occupants make evaluations. For example, if an occupant is farther from the exit than permissible at time t, EVAL20 will return a negative status evaluation. This will also occur if the occupant is closer to the fire than permissible at time t.

As the simulation progresses, the criteria become more difficult to satisfy, since the critical time is continually being approached. Accordingly, the penalty thresholds may be viewed as equations of lines which are functions of distance and time. On the practical assumption that such functions are linear, the slope and intercept of these lines must be established. BFIRES assumes an intercept of 0, and a slope of 1.0 for the case of threat penalty, and an intercept equal to the critical time, with a slope of -1 for the goal-seeking penalty threshold (see Figure A.1).

The consensus and threshold constants may not be manipulated at program execution time. The user may wish to alter their values, however, to reflect new empirical findings or to suit special conditions. This will require modifications to the program source code.

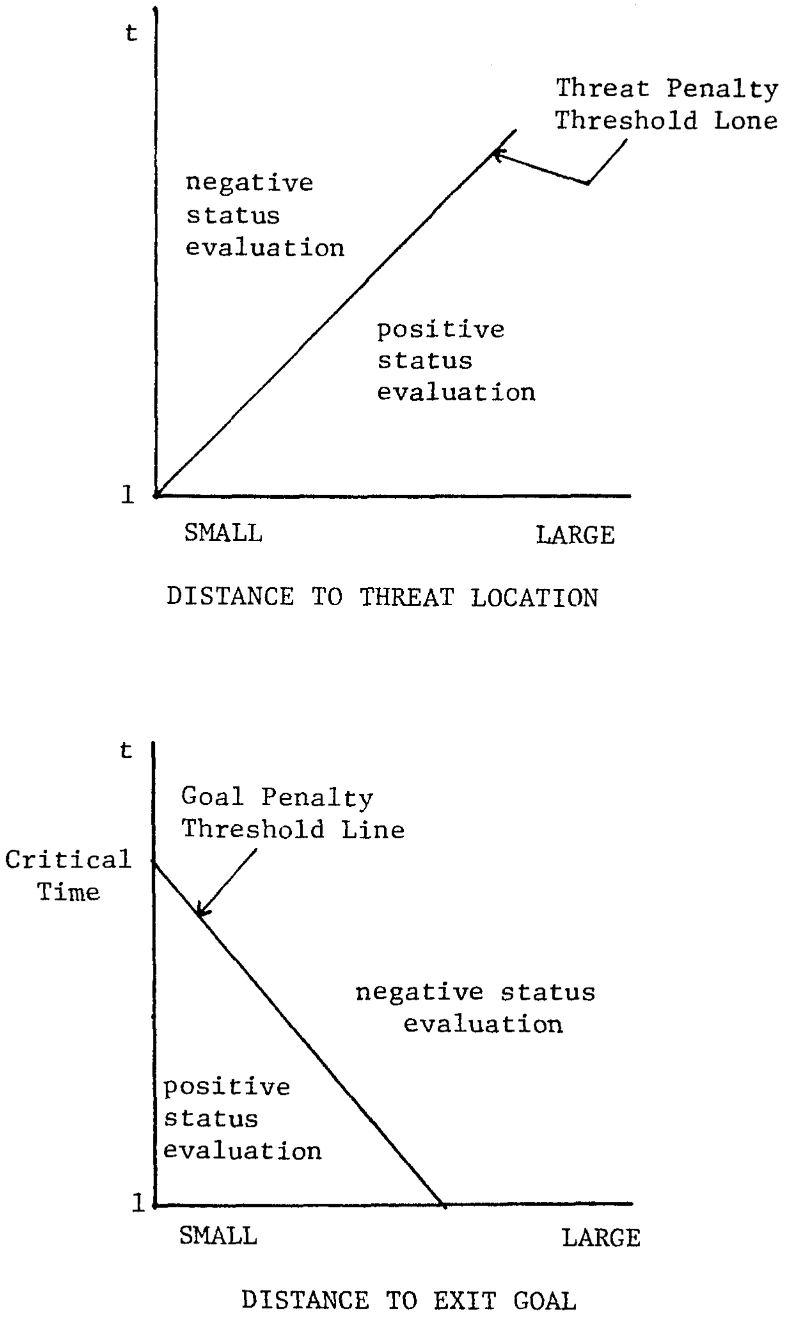


Figure A.1 Calibration of Penalty Thresholds in Subroutine EVAL20

Should a particular application of the program necessitate frequent variation to these values, the user may wish to establish them as input parameters.

INTERNAL DYNAMIC PROCESSES

Certain variables take on new values at the start of each time frame. However, these are determined entirely by internal processes, and are outside the user's immediate control. The most obvious example involves the computation of values of P(K), the probability that an occupant will, during a given time frame, select some move alternative, K. The actual values of P(K) are computed within subroutines EQUALZ, TBIAS, EBIAS, ASSIGN, or DOORS1, depending upon the biasing mode selected during execution of subroutine ASSIGN and the door-opening behavior generated by subroutine DOORS1.

To date, it has not been possible to calibrate computed values of P(K) against data from actual fire situations, since no data exist to describe emergency decision-making processes at so fine a level of detail. As new data become available, however, the user may wish to incorporate new hypotheses about decision biasing or probability value computation. This will require modifying the program source code.

USER SUPPLIED VARIABLE VALUES

Parameters describing most of the important initial conditions are determined by the user, and are input at program execution time.

There are four broad categories of input parameters: (1) fire descriptors; (2) occupant descriptors; (3) building descriptors; and (4) system descriptors.

Fire Descriptors

The current version of BFIRES permits the user to define only the initial spatial location of the fire threat (input variables XT and YT). Since BFIRES does not simulate any form of threat migration, the initial location specified by the user will remain constant throughout any simulation run. This factor may, however, be used as the basis for a number of realistic--and important--fire cases, e.g.: (1) simulation of egress from a particular compartment, while fire and smoke are confined to another compartment elsewhere on the same floor; (2) simulation of egress from one floor while fire and smoke are confined to another floor elsewhere within the building; and (3) simulation of egress during a fire drill, in which one exit has been blocked due to "mock fire" conditions.

When specifying the initial location of the threat, the user in effect blocks off one of the available exits from the floor, and thus assumes that the fire (occurring outside the immediate zone of interest) has effectively rendered that exit non-useable. When using BFIRES to test egress time requirements from floor plans, the user may establish exits wherever desired, and run simulations for any blocking conditions (i.e., threat location) chosen.

Occupant Descriptors

The model suggests that a variety of factors may interact to predispose occupants to respond in certain ways to the emergency environment. Principal factors include: (1) the number of occupants involved in a given fire event; (2) the initial spatial location of each; (3) the tolerance of each occupant to interruptions to goal-seeking behavior; (4) each individual's initial state of knowledge concerning the location of safe and threatened exits; (5) each occupant's initial mobility status; and (6) each occupant's predisposition toward opening and closing doors encountered along the egress route.

When preparing a given BFIRES simulation run, the user must determine values for each of these parameters. The user wishing to simulate a hypothetical fire in an actual facility must be careful to estimate the likely spatial positions of occupants, as well as calibrate each on the various parameters enumerated above. Spatial locations may often be estimated on the basis of information known about the building (or building type) under study (e.g., work stations, relative locations of beds and furnishings, etc.).

It should also be possible to estimate values for other occupant parameters. Predispositions toward opening and closing doors are input in the form of probability values: the variable POPEN specifies the probability that occupants will open closed doors they confront; PCLOSE specifies the probability that occupants close (manual type) doors they have just passed through. The user might wish to evaluate variation in door-manipulation behavior exhibited by occupants operating under different training philosophies. Several

BFIRES runs may be conducted for each of several values of PCLOSE and POPEN, and the varying effects (if any) of door manipulation upon egress time, etc., can be studied.

Similarly, the mobility status of occupants, and the exit knowledge of each, should be estimable from prior knowledge of a building type. Other parameters, however, such as interruption tolerance, may not be estimated on the basis of existing data from building fire cases.

Building Descriptors

BFIRES constructs building floor plans on a two-dimensional plane by laying walls out as orthogonal vectors on an x,y grid. Doorways are represented as breaks in wall lines. Such openings may or may not have door panels installed within them. When doors are present, they may be either manually- or automatically-closing. The user is free (within certain limitations) to enter into the computer a floor plan of almost any configuration. This is accomplished by reading in the x,y coordinates of points defining walls and doors. The principal limitation is that all walls must lie along orthogonal vectors (i.e., they must be parallel to either the x or the y axis). Accordingly, angular or curvelinear walls must be entered as "steps" (see Figure A.2).

The severity of this "steeping" condition is reduced as the size of the x,y grid units decreases. But this additional sensitivity comes at the cost of increased computer memory requirements. For example, a floor plan laid out on a 10 x 10 grid requires storage for no more than 100 points (wall, door, and person-occupyiable location identifiers). A much more sensitive simulation could be achieved if the same plan is laid out on, say, a 100 x 100 grid (e.g., much finer

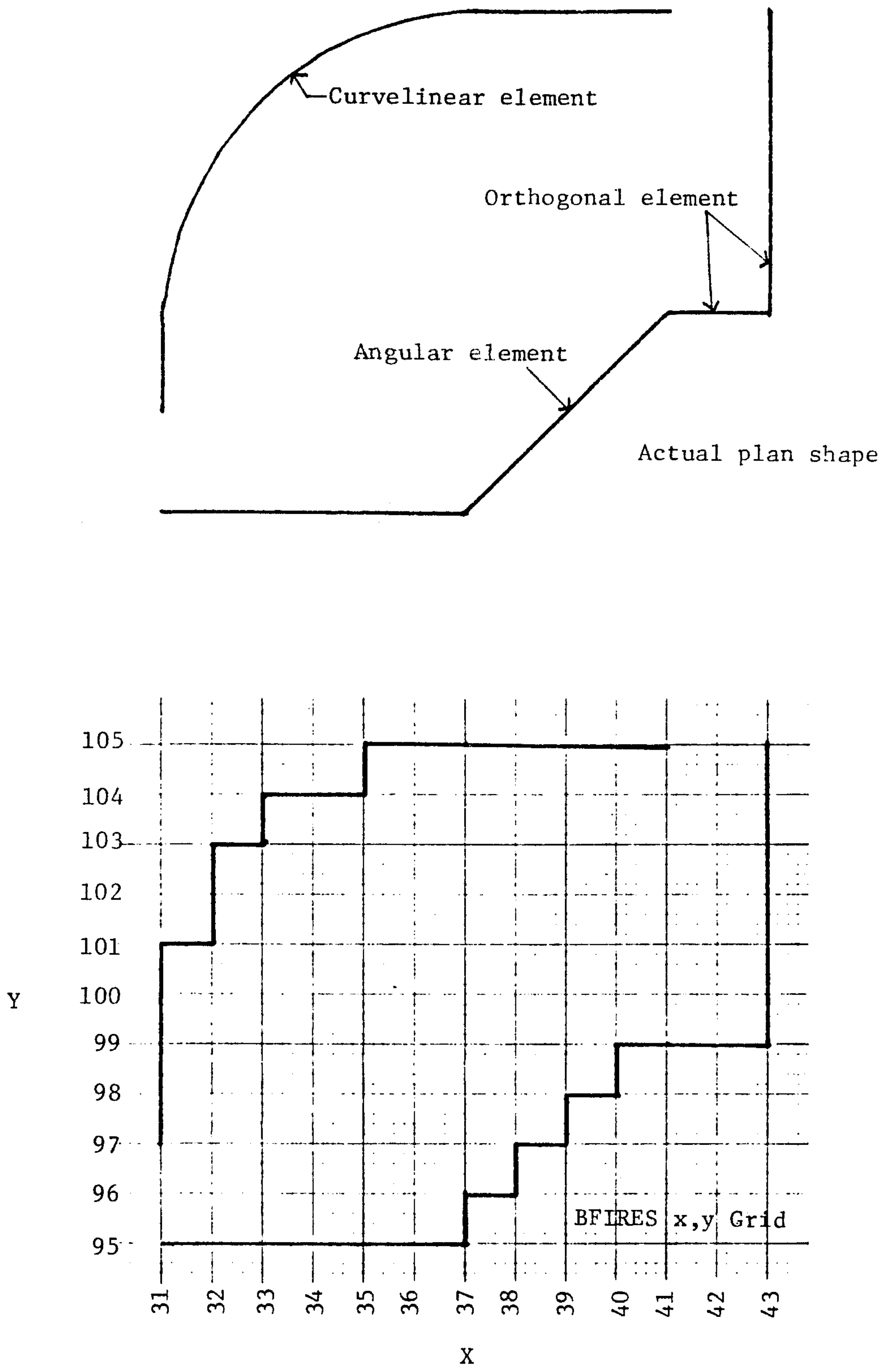


Figure A.2 Translating Orthogonal, Curvelinear, and Angular Wall Elements into BFIRES-readable Form changes in occupants' incremental movement will be generated with each passing time frame). However, this arrangement would require storage for 10,000 points, a 100-fold increase.

The user is free to use any size grid felt to be appropriate, considering the degree of sensitivity desired, and the amount of computer memory available. Once a grid has been laid over the floor plan (which must be "idealized" to meet the orthogonal vector criterion), wall designator points are entered through input variable IBAR (IS,I,J). Information concerning door location, operating type, and initial position (open or closed) is entered via input variable IDOOR(I,J). Of course, the user can vary the location of walls and doors (i.e., alter the floor plan) between simulation runs, and thereby study variations in egress phenomena relating to such environmental factors.

System Descriptors

Several input parameters are available which permit the user to establish system-wide rules. The number of replications of a given simulation is specified by NUMREP. If NUMREP is preset to "5", for example, the computer will generate five completely independent events which are identical in all respects--except for the outcomes of stochastic processes.

The user must also preset the desired length of each replication. TOTIME specifies the number of time frames a given simulation is to move through. When comparing simulation outcomes with real-world events, it is necessary to convert time frames to real time units (seconds). Table A.1 illustates such conversions for several typical situations. When using this table, the experimenter must: (1) make

Table A.1 Time Frame--Real Time Conversions, For Three Values of Walking Speed

		MEAN WALKING SPEED (V)		
		4 ft/s (1.22 m/s)	4.5 ft/s (1.37 m/s)	5 ft/s (1.53 m/s)
MEAN STEP LENGTH (D)	3.02 ft (0.92 m)	TF=0.76 s TF/min=79*	TF=0.67 s TF/min=90	TF=0.60 s TF/min=100
	6.04 ft (1.84 m)	TF=1.51 s TF/min=40	TF=1.34 s TF/min=45	TF=1.21 s TF/min=50
	12.07 ft (3.68 m)	TF=3.02 s TF/min=20	TF=2.68 s TF/min=23	TF=2.41 s TF/min=25

$$V = \frac{l_m}{s} \qquad (6)$$

$$D = \frac{l_o + l_d}{2} \qquad (7)$$

$$TF = \frac{D}{V} \qquad (8)$$

where:

l_m = mean step length

l_o = orthogonal step length

l_d = diagonal step length

TF = time frame in "real time" seconds

* time frames per second, rounded to the next higher frame

an assumption about the mean walking speed of all occupants in the event, and (2) use a mean step length which conforms to the grid size which has been superimposed over the floor plan. For example, assuming a mean walking speed of 4.5 feet per second (1.37 m/s), and a mean step length of 3.02 feet (0.92m), then a single time frame will equal about 0.67 seconds, and it will require about 90 time frames to simulate one minute of real time. Figure A.3 provides a convenient graphic conversion chart, and Figure A.4 illustrates its use in converting either from time frames to seconds (how many seconds simulated by a run of predetermined length), or from seconds to time frames (how long a simulation must be run in order to represent a desired period of real time).

"Step length" is not meant to imply walking stride. It merely refers to the mean distance between person-occupiable grid locations. The user can calibrate the x,y grid to assure that step length is similar to mean walking stride, but again, this may require large expeditures in terms of computer memory.

Another system-wide parameter preset for a given simulation run is the crowding factor, or permissible occupant density which is input via variable IALLOW. IALLOW specifies the maximum number of occupants permitted to inhabit any person-occupiable location during a single time frame. The value of IALLOW can easily be converted to a measure of maximum allowable density, in terms of persons per unit area, as follows:

$$D_m = \frac{I}{A_g} \qquad (9)$$

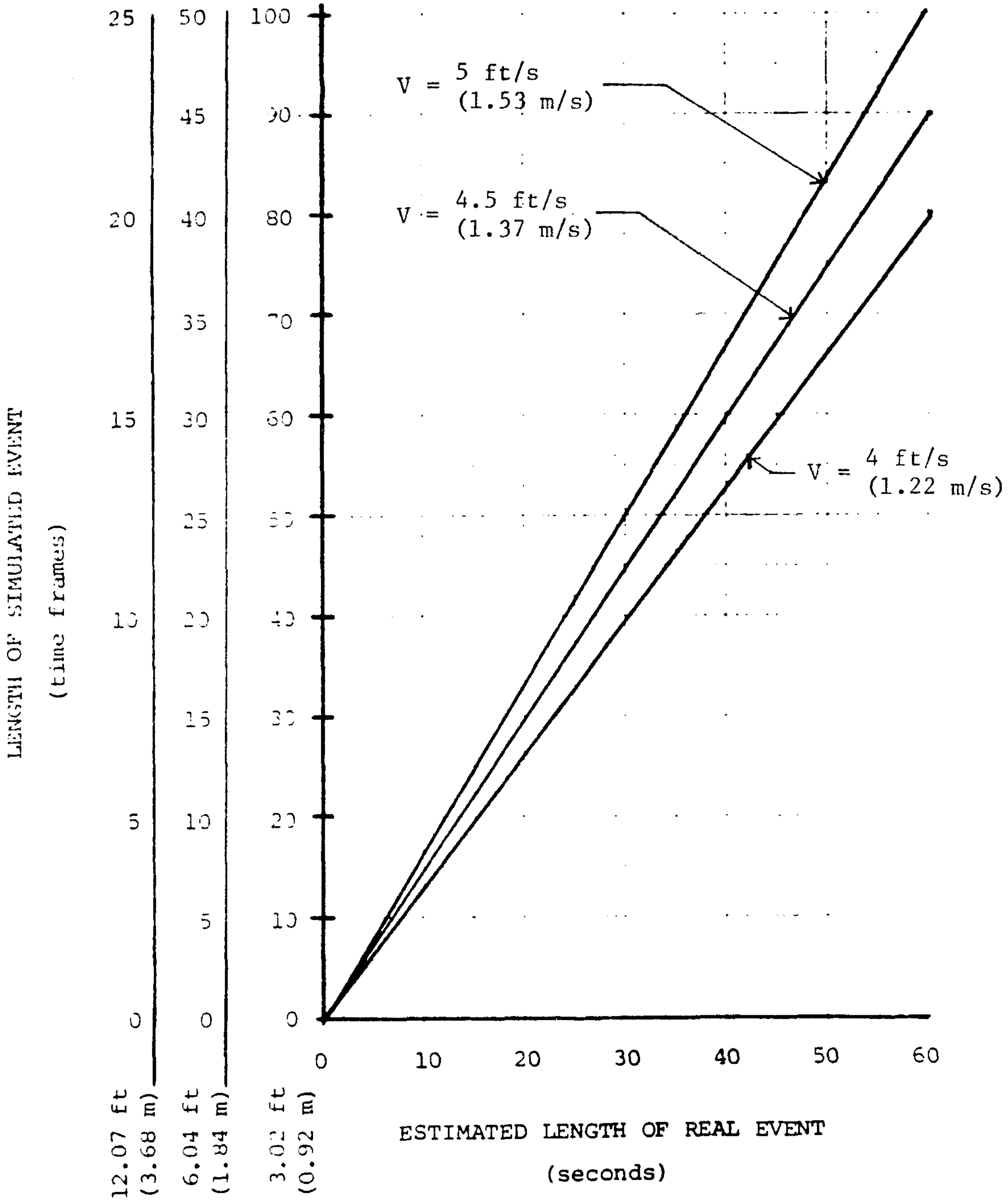


Figure A.3 Time Frames to Seconds Conversion Chart

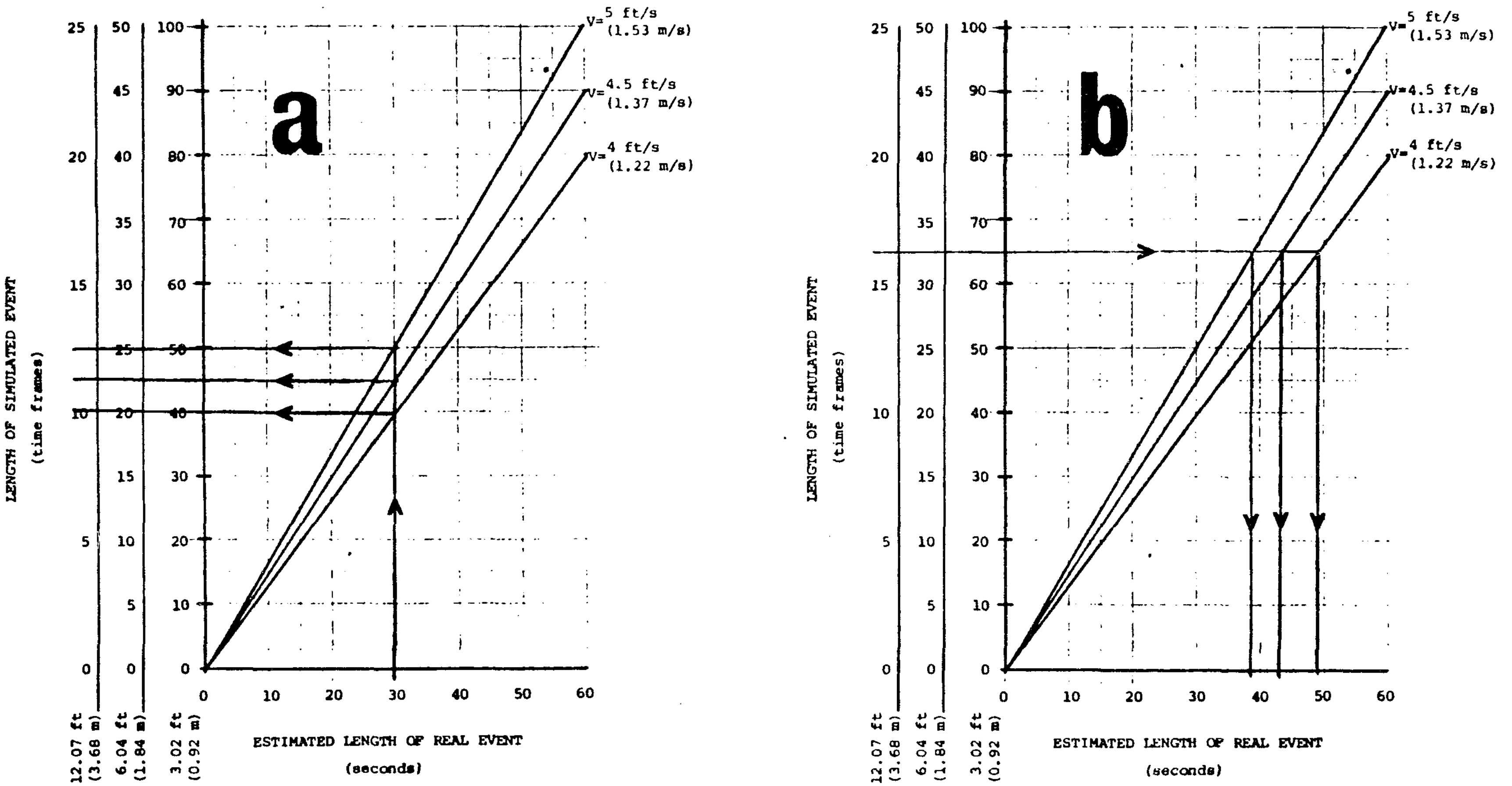


Figure A.4 Using the Time Frames to Seconds Conversion Chart: (a) determining the number of time frames necessary to simulate a desired number of seconds; (b) determining the number of seconds simulated by a computer run of given length.

where:

D_m = maximum allowable density

I = IALLOW

A_g = area of grid square, in feet or meters

Finally, the user must predetermine the likelihood that occupants will, during the simulated event, experience a "backtrack" interruption, a "remain-in-place" interruption, or no interruption at all (detailed in Appendix B, under discussions of Subroutines INTRPT and BACKUP). The probability of a backtrack interruption is input via variable PI2, and that of experiencing no interruption is input through variable PI0. The probability of experiencing a remain-in-place interruption is computer internally as the difference between PI2 and PI0.

SUMMARY

Appendix A dealt with the calibration of the BFIRES simulation program. A variety of parameters were considered, and particular attention was paid to the problem of aligning these with parameters which describe real-world fire events. Three broad categories of parameters were discussed: Values of internal constants and internal dynamic processes are either written into, or are determined, by BFIRES, and are therefore outside the user's direct control. Important parameters which describe the fire, the occupants, the building, and other aspects of the simulation event are user supplied at execution time.

Appendix B

RATIONALE AND THEORETICAL ELEMENTS UNDERLYING "BFIRES" SUBROUTINES

Introduction

In this Appendix, the rationale behind BFIRES subroutines is presented. The reader will note that the complete simulation program stands as a collection of interrelated hypothetical propositions about the manner in which people respond to building fire events, as these have been "programmed into" the various subroutines comprising BFIRES.

Subroutines Which Simulate Perception and Information Gathering

Subroutines GROUP, OTHERS AND AGREE

Through its functions of informing the occupant about the existence of other persons within the immediate environment, of providing certain information about these others, and of communicating with them, the GROUP package serves as the occupant's sensory and communicative apparatus. These are deterministic routines, in the sense that a given space either is or is not cooccupied by several persons at once, occupants either do or do not possess certain kinds of information, they either are or are not injured or handicapped, etc. The program provides information only in this binary manner, ignoring the possibility that occupants' perceptual mechanisms may occasionally distort the "facts".

Subroutine AGREE raises issues much more relevant to the interpretation of information from the social environment. For example, when an occupant confronts several others in a space, and each agrees upon the best exit route, then they may interpret such agreement as a reinforcement of their own individual initial perception. But when there is disagreement among co-occupants, who is right? The "consensus" notion written into subroutine AGREE[1] assumes that people can be convinced they are wrong, if the pressures to change are sufficiently great. It further assumes that, in those cases where no consensus is attained, a person will develop stress resulting from the inability to replace an eroded perception by a better one. According to AGREE, this stress is manifest in the form of "goal seeking in the absence of any specific goal," or wandering.

Unfortunately, the literature on human behavior in fires provides no empirical evidence concerning interoccupant communications during fire events. Consequently, no means for examining the validity of the consensus concept, or for calibrating the threshold for consensus attainment, seem readily available at the present time.

Subroutine JAMMED

BFIRES contains no "queuing" mechanism, as such, for the purpose of regulating the flow of persons between spatial locations. Queues

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[1] Note equation (10), Appendix C.

are typically used in simulations whenever the number of elements requiring passage through a channel is greater than the channel's carrying capacity. Normally, waiting elements "line up" in the queue, and remain in line until their turns come to enter the channel. In the simplest case, an element's immediate future is fully determined once it enters the queue: it waits its turn, and then moves through the channel.

It is not clear, however, that person in stressful (e.g., life threathening) situations will respond to physical crowding in so mechanistic a manner, oblivious to events around them. An individual may first seek passage through a particular doorway (for example), but upon finding the vicinity of the door to be occupied by a large number of other occupants, may not join any "queue" at all; but rather might seek some other route.

Moreover, seeking an alternative egress path may not be a straightforward task, if occupants are not actually aware of any such route. If there are no alternatives available (or if occupants perceives none), their level of stress is assumed to increase, and their goal-directed egress performance is expected to suffer. BFIRES simulates the resulting behavior either as goalless wandering, or as remaining "frozen" in place. The latter behavior may continue until occuapnts perceive a significant reduction in the crowding of the space leading to their objective.

Subroutine KPOSS

This program employs a stimulus-response function, in which information from the environment results in some specific behavioral outcome. Namely, whenever a more alternative, k, is perceived to be impossible to attain (i.e., it is already physically crowded, or is blocked by a physical barrier such as a wall), it is removed from the array of alternatives, and is accorded no further consideration by the occupant during the current time frame. Whenever an alternative is perceived to be possible to attain, on the other hand, occupants "store" it away for comparison against other such alternatives, and include information about it in their current decisionmaking task. This function has been programmed to remain constant throughout a given simulation run, and not to alter through interaction with other psychological or environmental processes.

Subroutine KPOSS assumes a clear visual field. Future investigators may wish to build a capacity to accommodate such intrusions to the visual field as smoke (of varying density). The inclusion of such factors might result, operationally, in the introduction of a stochastic component to the subroutine: for example, the probability of a correct perception of the immediate physical environment would decrease as smoke density increased.

Subroutines Which Simulate Information Processing, Decisionmaking and Action

Subroutine INTRPT

According to Simon (1967), interruptions to goal seeking behavior provide useful means for introducing emotional controls over behavior particularly in a computer-simulated environment. Interruptions, detours, etc., require individuals to temporarily suspend their goal seeking activity. In a stressful environment, this should lead --according to Simon--to increased stress for the occupant, resulting in an increased likelihood of maladaptive behavior.

Within the fire environment, the causes and effects of interruptions may be difficult to specify exactly. The empirical literature on fires is of extremely little assistance and consequently, INTRPT is rather simplistic in its treatment of this phenomenon.

Only two forms of interruption have been built into BFIRES: remaining in place, and backtracking. Remaining in place is meant to simulate any response in which the normal decisionmaking processes are bypassed, and through which an occupant rejects all other move choices available at a certain point in time. But INTRPT makes no attempt to simulate specific causes of this form of interruption, which may be cognitive, physiological, or environmental in origin. Backtracking is meant to simulate the frequently noticed phenomenon in which occupants may return to some earlier location to, for example, retrieve valuables, close doors, etc. (Wood, 1972; Bryan, 1977).

Subroutine BACKUP

The main purpose of this routine is to waste occupants' time by causing them to temporarily suspend egress behavior and instead move toward some seemingly irrelevant location on the floor. BFIRES affects this activity by retracing each and every step occupants have already taken, until the goal of backtracking has been reached. This is a rather simplistic approach, since once an alternative goal has been selected, occupants may be more likely to determine "for themselves" the most effective route to that goal, than to merely retrace their steps. But even in the absence of empirical guidance on this point, BACKUP serves the purpose of detouring occupants, and wasting valuable time.

Subroutines ASSIGN, DOORS1 and DOORS2

The "biasing" function of subroutine ASSIGN is intended to introduce into BFIRES the concept of weighting, based on occupants' perceptions of current events. Biased (i.e., weighted) probability values assigned to move alternatives provides a means for achieving Brunswik's (1956) "best bet": in a given situation, a person will probably--but not certainly--respond with a particular action. While biasing contributes to the selection of the best alternative, the stochastic aspect of ASSIGN assures that in a certain proportion of cases, an occupant will make wrong decisions (even in the presence of correct information).

The inclusion of door manipulation functions responds directly to the frequently raised issued of door closing during fires (Wood, 1972; Bryan, 1977). In particular, while doors may provide effective barriers to smoke and fire, they also serve as perceptual barriers which may limit communications and other forms of information flow. BFIRES treats door opening and closing as stochastic processes. Prior to a simulation run, the user assigns to occupants values describing the probability that they will open closed doors in their paths, or close doors they have just passed through.

Subroutine EQUALZ

This routine is called whenever the current events perceived by an occupant make it difficult--or impossible--to decide upon a specific objective (e.g., to evade the threat, or to seek an exit goal). The principal assumption underlying EQUALZ is the notion that certain combinations of information will cause an individual to be (at least momentarily) confused, and that this confusion will make goal oriented decisionmaking difficult.

When a "confused" occupant selects a move from among the equalized move alternatives, the resulting move cannot be considered to be toward any particular goal. Rather, it must be viewed as "wandering". EQUALZ generates such behavior when a state of insufficient information is coupled with a negative perception of current safety status. Other causes (not actually considered within BFIRES) might include cognitive overload (Cohen, 1975; Saegert, 1976), in which individuals are forced to respond to more information than they are capable of processing within a given period of time. Another cause (also not considered by BFIRES) might be the presence of contradictory information elements.

Subroutine TBIAS

As occupants scan the move alternatives, "k"s, currently available, they "measure" the distance between each alternative location and the location of the threat[1]. This is assumed to be the "straight line" distance (through walls, if necessary), on the assumption that the occupant has already received information concerning the location of the threat. The selection probability for a given alternative will increase as the distance between the new location and the threat

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[1] See equation (14), Appendix C.

location increases. That is, the more threat-reducing an alternative is judged to be, the more likely is the occupant to select it.

Subroutine EBIAS

As occupants look ahead to the move alternatives currently available, they make measurements similar to those described above. In this case, however, the distance between alternative locations, and the location of the occupants' next egress objective is considered[1]. Here, the selection probability increases for a given move alternative as the distance between that alternative and the egress objective decreases. That is, the more goal-directed an alternative is perceived to be, the more likely is the occupant to select it.

Egress routes are subject to change during the course of the fire event, as the occupant receives new information. EBIAS establishes move selection probabilities on the basis of the occupant's current route.

Status Evaluation: Subroutines EVAL8 and EVAL20

BFIRES allows the program user to select either of two modes of egress status evaluation. Only one of these is actually employed during any given simulation run. Subroutine EVAL8 constructs status evaluation outcomes on the basis of straight line distance measurements between an occupant's current location, and the locations of threats and/or exits. A positive evaluation results whenever the occupant's status is perceived to be "better" at time t than it was at t-1. EVAL20, on the other hand, evaluates egress progress as a function of the total

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[1] See Equation (17), Appendix C.

amount of time the occupant has spent in the danger zone. A move in a threatening direction may not initially be perceived as negative if occupants think--on the whole--they still have ample time left to escape.

EVAL8. The distance measurement approach was adopted from the simulation by Wolpert and Zillmann (1969). Their study focused on fires in large, single spaces. In these settings, occupants--regardless of their particular locations--are continuously provided with unobstructed visual access. Hence, the assumption that occupants can judge relative distances, and make evaluations based on these judgments, seems a safe one.

But most fires of interest for simualtion using BFIRES are likely to involve multispatial facilities (e.g., apartments). The question arises, then, as to the ability of occupants to judge distances when visual access to key elements (fire and exits) may in fact be blocked by walls or other environmental elements. The principal assumption underlying EVAL8, therefore, is that occupants have up-to-date information about the location of key elements from mental maps of their environment (see for example, Moore and Golledge, 1976; Downs and Stea, 1973). Judgments of distances are seen to derive from these maps, rather than from direct visual experience (except where direct visual access is possible).

EVAL20. This program assumes that the occupant is less dependent upon distance estimations, and puts more emphasis on the question of time estimation. EVAL20 is based on the notion that all occupants have their own perceptions of the total amount of time needed to escape the danger zone. Regardless of what movements they make, they are assumed to maintain a positive status evaluation as long as they believe they are within their perceived time limit. Negative evaluations begin to result when occupants approach their time limit, realizing that they are still too far from their objective.

A negative status evaluation may be interpreted as the frustration encounted when one realizes a time limit has been reached, but has failed to achieve a goal. By returning a negative status evaluation to other BFIRES subroutines, EVAL20 causes the occupant to respond to this frustration with nongoal-directed movement behavior (i.e., wandering).

Unlike EVAL8, which faithfully generates incremental status evaluations for each time frame, EVAL20 permits the program user to infer that occupants start off with some overview of the fire situation, and that they consider the following the kind of questions: "There is only so much time available to accomplish the egress task; how will I use it? How much flexibility is there?"

APPENDIX C

"BFIRES" PROGRAM DOCUMENTATION

INTRODUCTION

This appendix provides documentary material which describes the BFIRES computer program. The program is presented as a "package" composed of a network of interrelated subroutines. These are linked through the EXECUTIVE program, as shown in Figure C.1. The subroutines are displayed individually as units, in a sequence which approximates the order in which they are called and executed. For each unit, the following information is provided:

(1) program or subroutine name;
(2) loop within which the program functions;
(3) description of the program's purpose or function;
(4) description of computational formulas, if any;
(5) description of program logic, by means of flow diagrams[1];
(6) FORTRAN listing.

---

[1] Not included with I/O and non-behavioral subroutines.

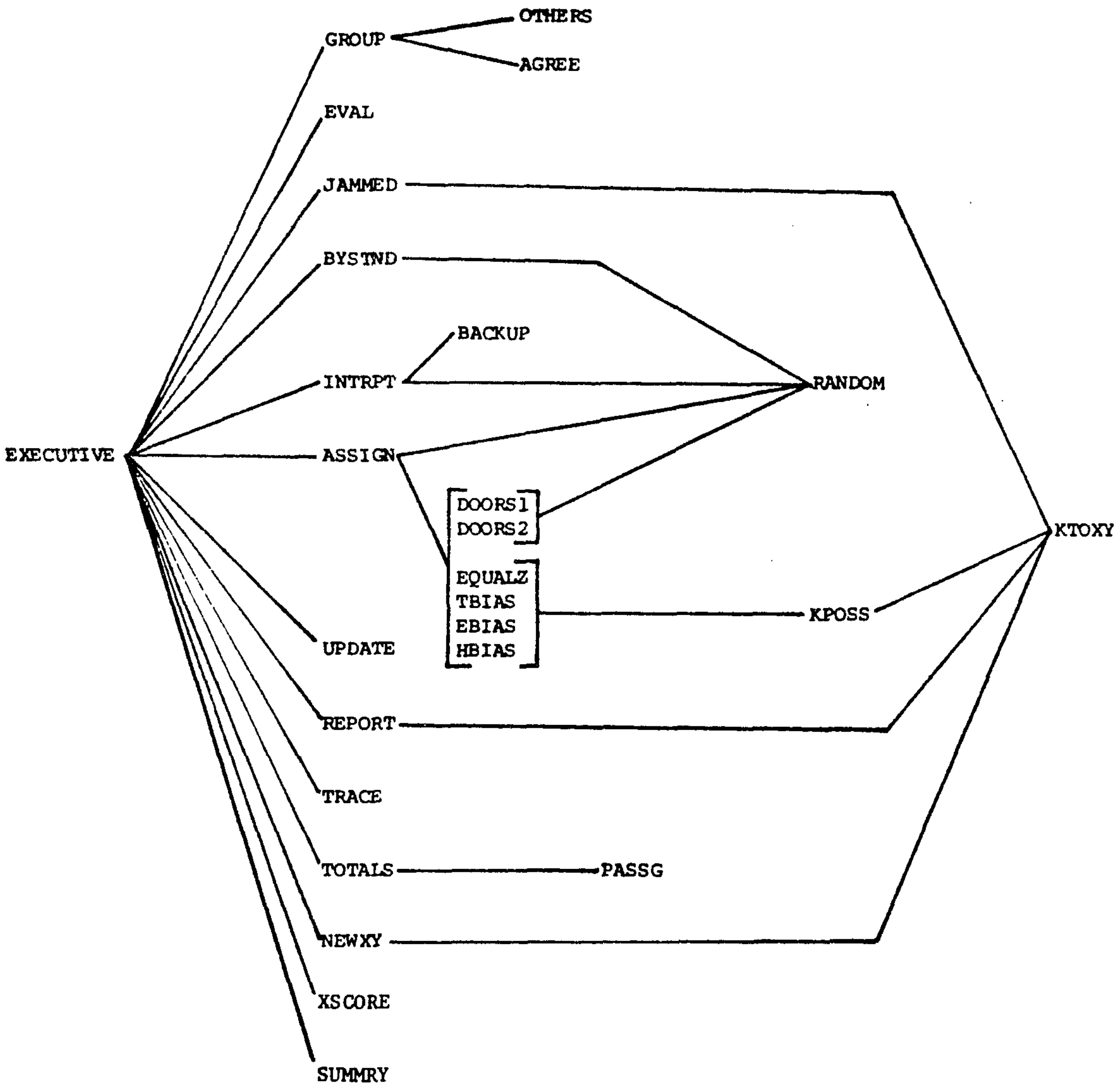
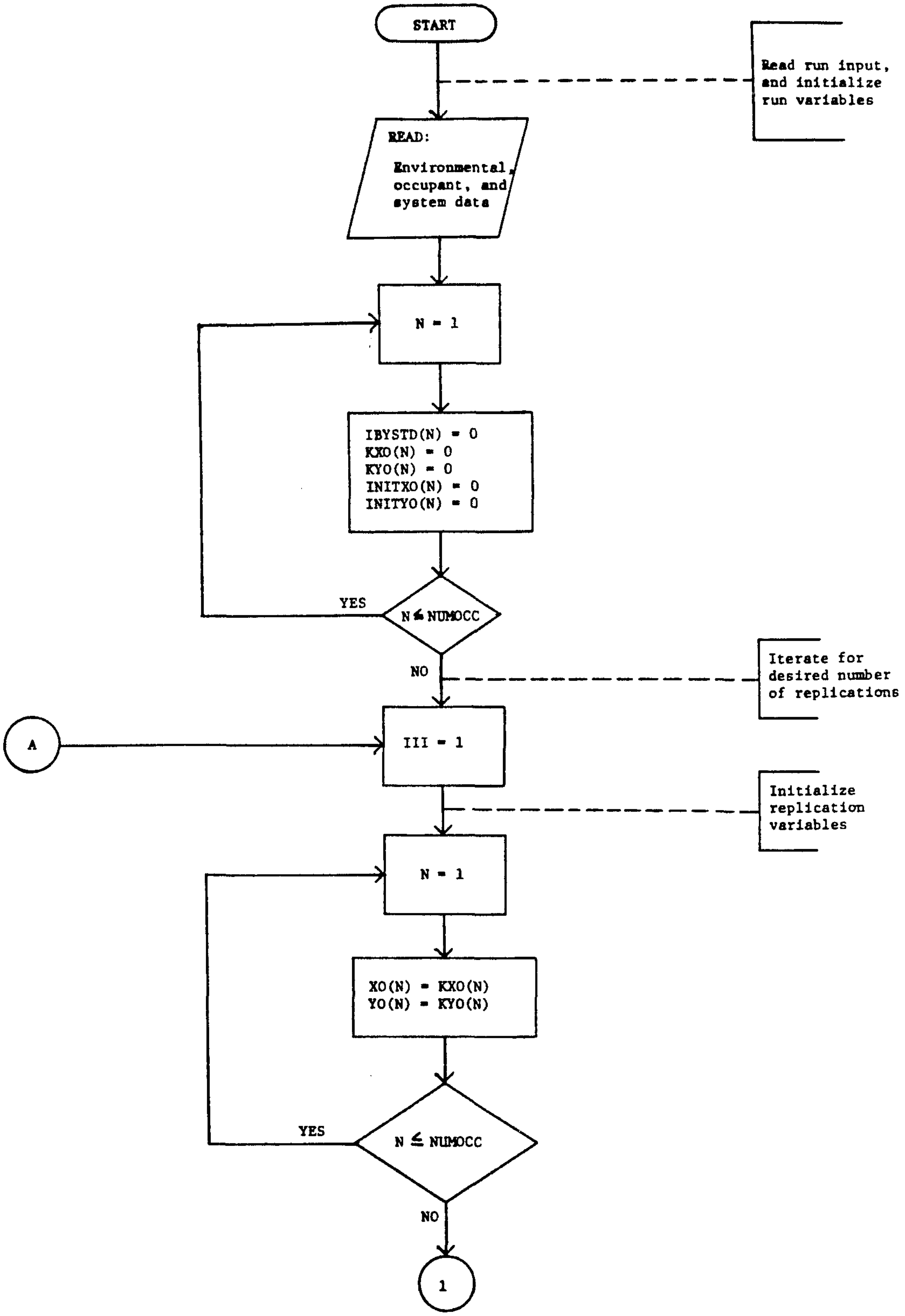
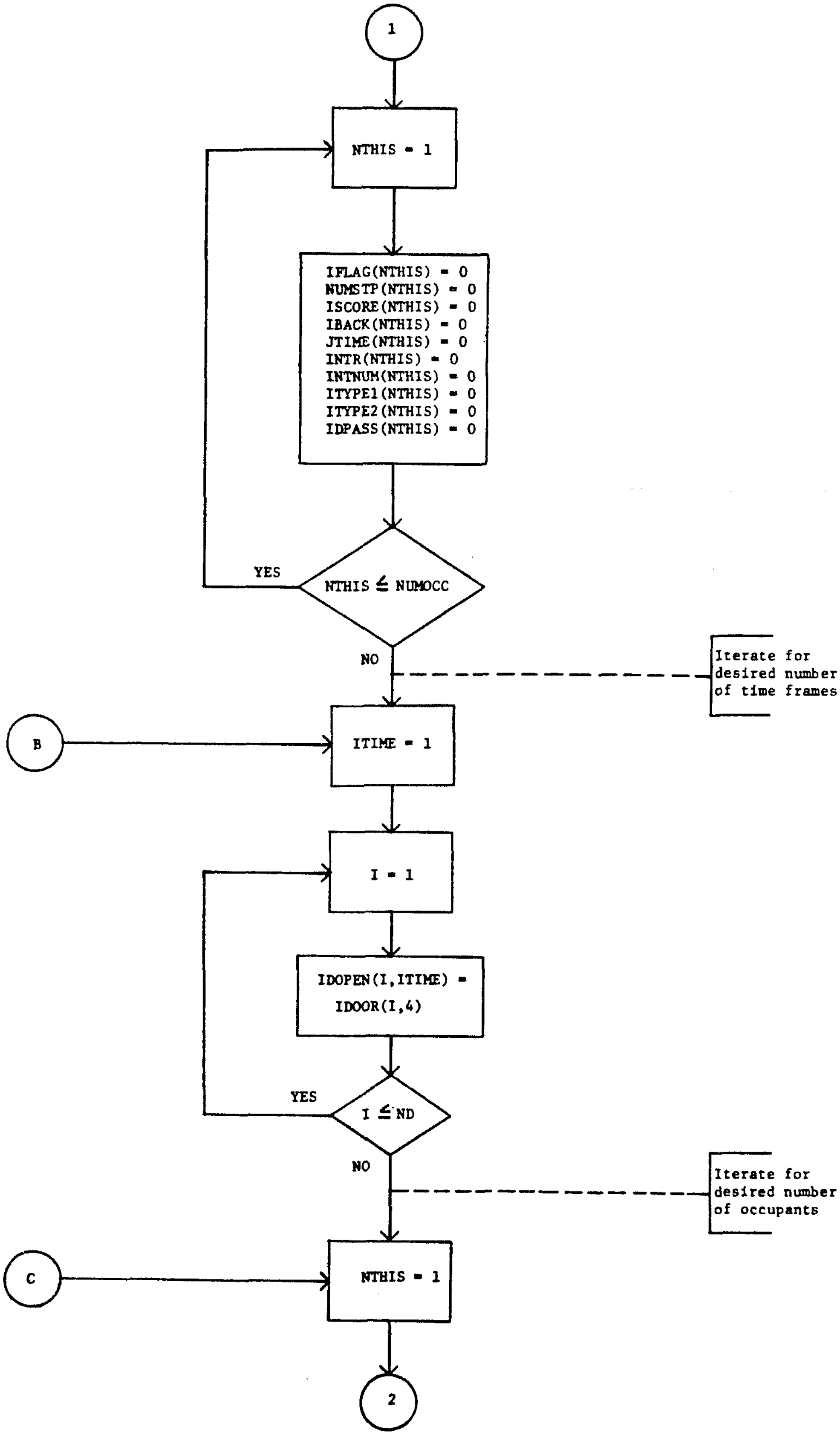
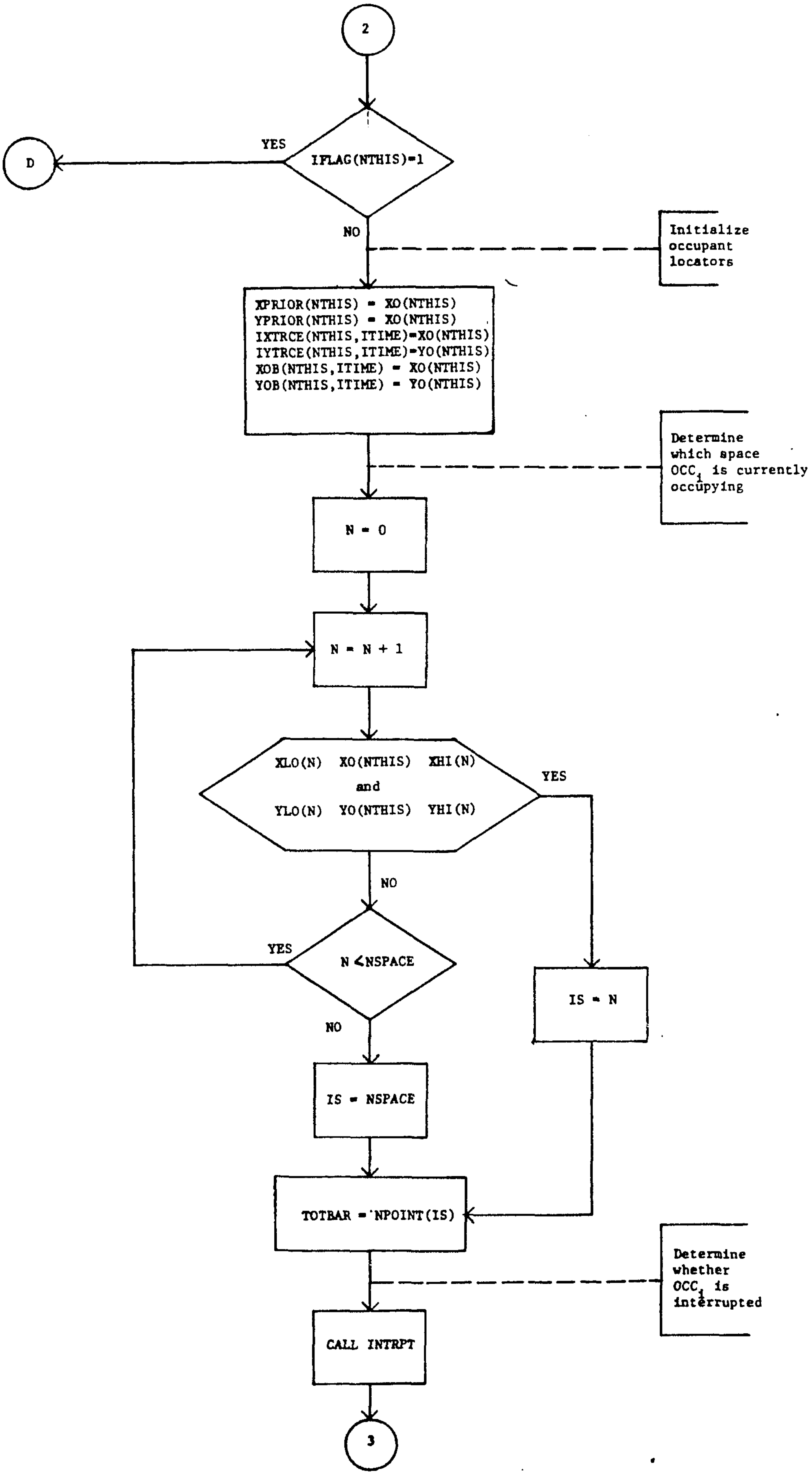


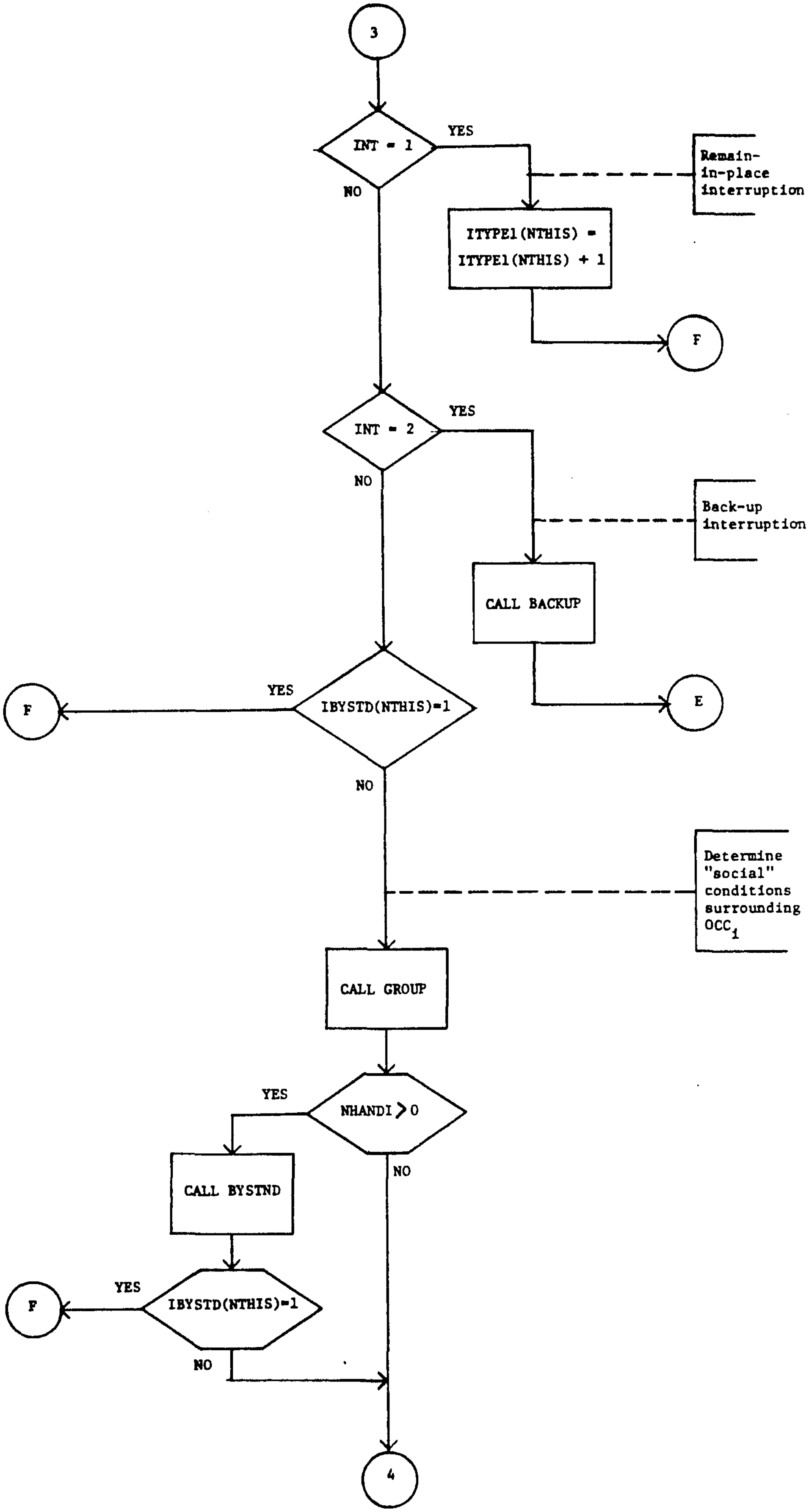
Figure C.1 Subroutine Network and Flow of Control

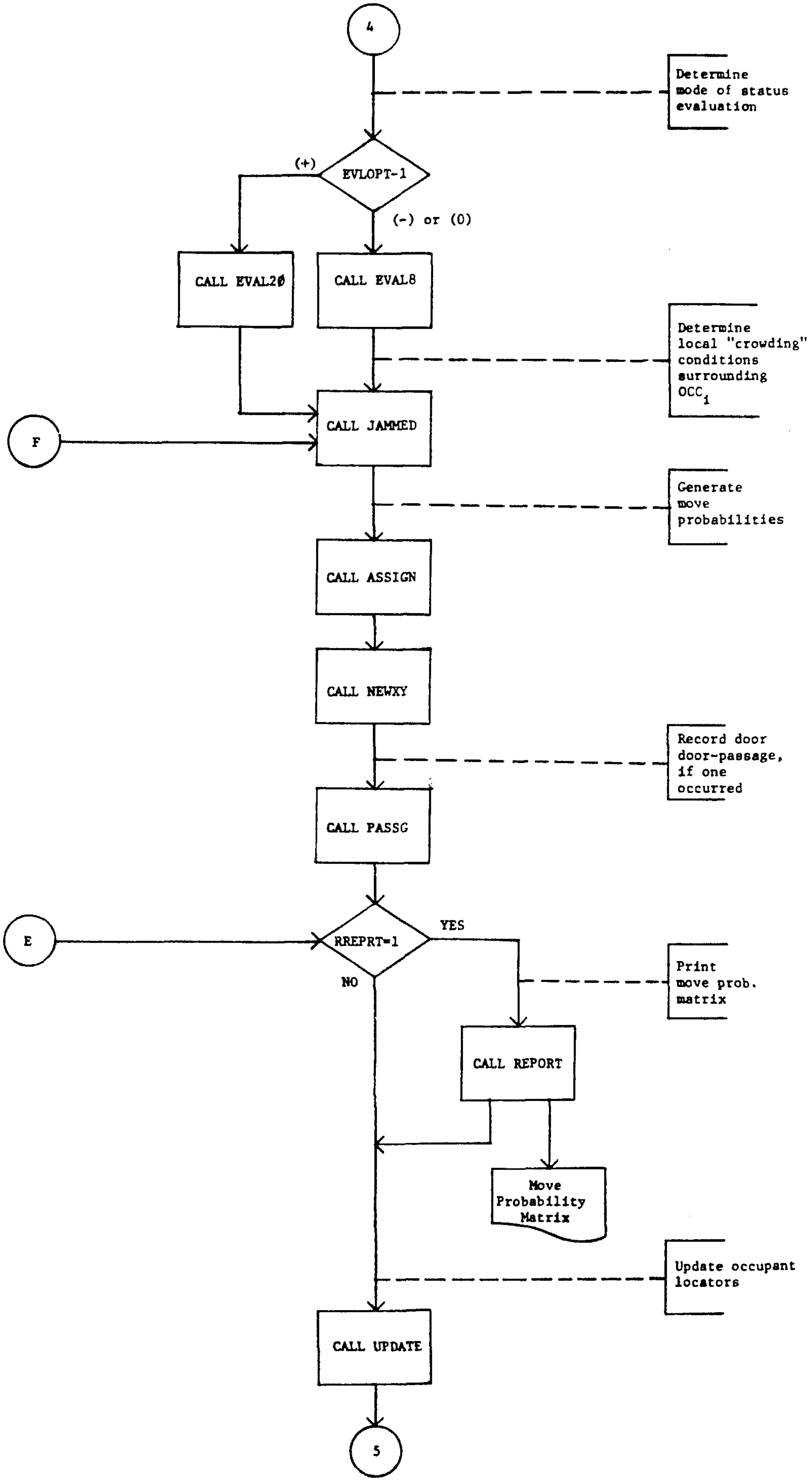
Routine	EXECUTIVE
Loop	Replication
Purpose	(1) Reads-in input data files; (2) processes complete replications of fire events; (3) accumulates event outcome data; (4) summarizes outcome data in tabular form.
Formulas	n/a

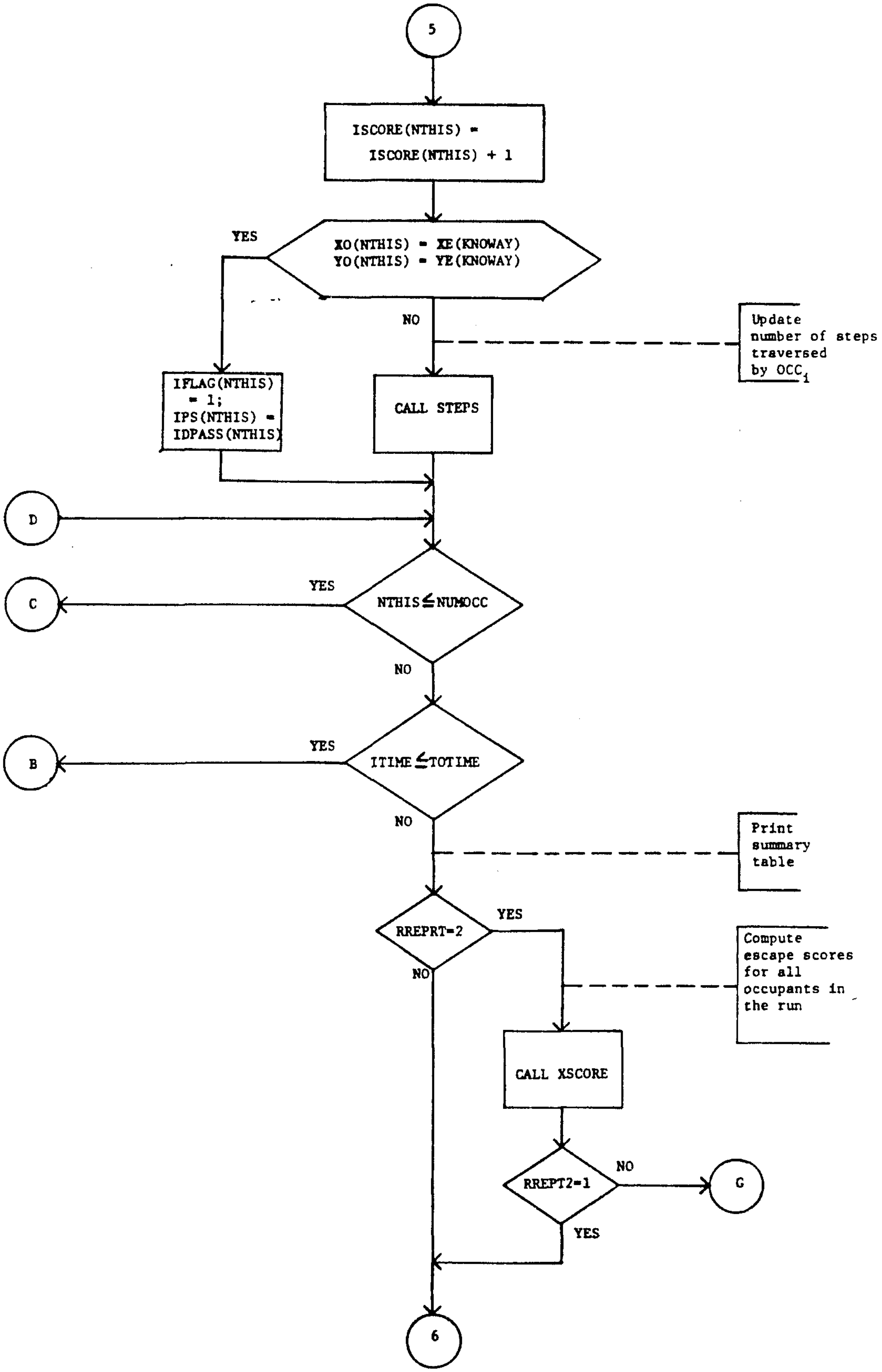

START
Read run input, and initialize run variables
READ:
Environmental, occupant, and system data
N = 1
IBYSTD(N) = 0
KXO(N) = 0
KYO(N) = 0
INITXO(N) = 0
INITYO(N) = 0
YES
N ≤ NUMOCC
NO
Iterate for desired number of replications
A
III = 1
Initialize replication variables
N = 1
XO(N) = KXO(N)
YO(N) = KYO(N)
YES
N ≤ NUMOCC
NO
1

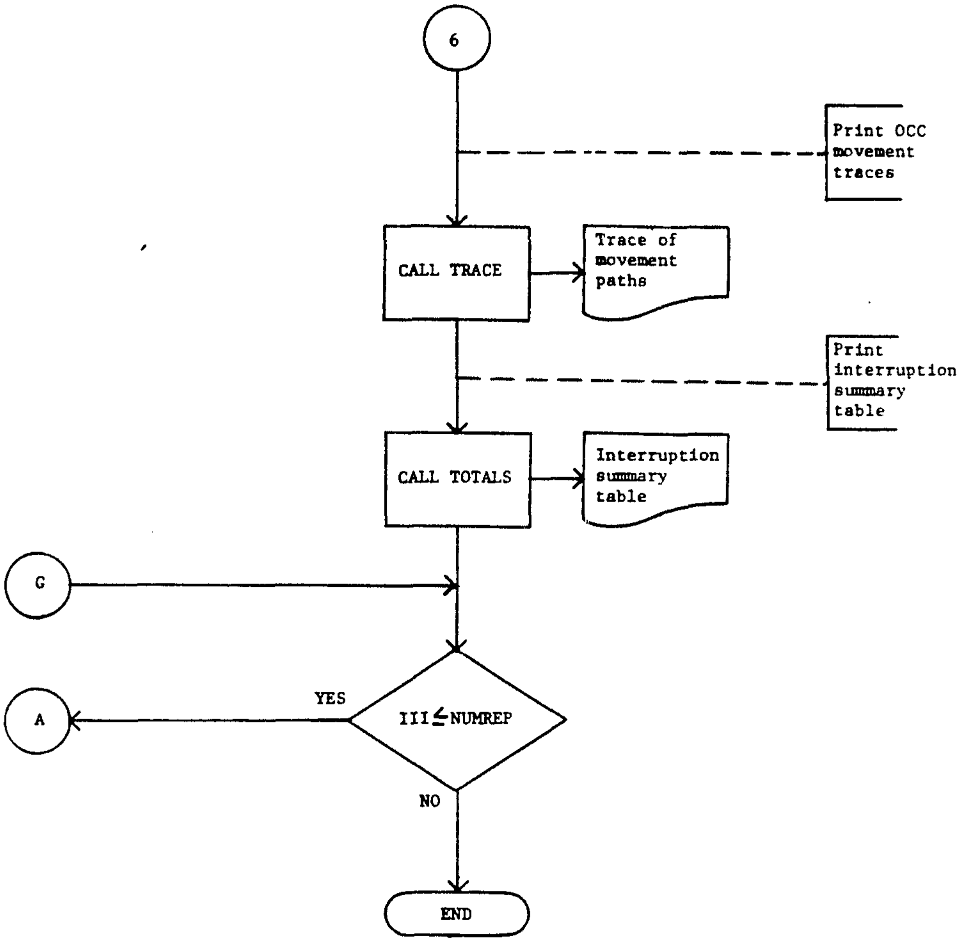

1
NTHIS = 1
IFLAG(NTHIS) = 0
NUMSTP(NTHIS) = 0
ISCORE(NTHIS) = 0
IBACK(NTHIS) = 0
JTIME(NTHIS) = 0
INTR(NTHIS) = 0
INTNUM(NTHIS) = 0
ITYPE1(NTHIS) = 0
ITYPE2(NTHIS) = 0
IDPASS(NTHIS) = 0
YES
NTHIS ≤ NUMOCC
NO
Iterate for desired number of time frames
B
ITIME = 1
I = 1
IDOPEN(I,ITIME) = IDOOR(I,4)
YES
I ≤ ND
NO
Iterate for desired number of occupants
C
NTHIS = 1
2


2
YES
D
IFLAG(NTHIS)=1
NO
Initialize occupant locators
XPRIOR(NTHIS) = XO(NTHIS)
YPRIOR(NTHIS) = XO(NTHIS)
IXTRCE(NTHIS,ITIME)=XO(NTHIS)
IYTRCE(NTHIS,ITIME)=YO(NTHIS)
XOB(NTHIS,ITIME) = XO(NTHIS)
YOB(NTHIS,ITIME) = YO(NTHIS)
Determine which space OCC$_i$ is currently occupying
N = 0
N = N + 1
XLO(N) XO(NTHIS) XHI(N)
and
YLO(N) YO(NTHIS) YHI(N)
YES
NO
YES
N <NSPACE
NO
IS = N
IS = NSPACE
TOTBAR = NPOINT(IS)
Determine whether OCC$_i$ is interrupted
CALL INTRPT
3


3
INT = 1
YES
NO
Remain-in-place interruption
ITYPE1(NTHIS) = ITYPE1(NTHIS) + 1
F
INT = 2
YES
NO
Back-up interruption
CALL BACKUP
E
F
YES
IBYSTD(NTHIS)=1
NO
Determine "social" conditions surrounding OCC$_1$
CALL GROUP
YES
NHANDI > 0
NO
CALL BYSTND
F
YES
IBYSTD(NTHIS)=1
NO
4


4
Determine mode of status evaluation
EVLOPT-1
(+)
(-) or (0)
CALL EVAL20
CALL EVAL8
Determine local "crowding" conditions surrounding OCC_i
F
CALL JAMMED
Generate move probabilities
CALL ASSIGN
CALL NEWXY
Record door door-passage, if one occurred
CALL PASSG
E
RREPRT=1
YES
NO
Print move prob. matrix
CALL REPORT
Move Probability Matrix
Update occupant locators
CALL UPDATE
5


5
ISCORE(NTHIS) =
ISCORE(NTHIS) + 1
YES
XO(NTHIS) = XE(KNOWAY)
YO(NTHIS) = YE(KNOWAY)
NO
Update number of steps traversed by OCC$_i$
IFLAG(NTHIS) = 1;
IPS(NTHIS) = IDPASS(NTHIS)
CALL STEPS
D
YES
C
NTHIS≤NUMOCC
NO
YES
B
ITIME≤TOTIME
NO
Print summary table
RREPRT=2
YES
NO
Compute escape scores for all occupants in the run
CALL XSCORE
RREPT2=1
NO
G
YES
6


6
Print OCC movement traces
CALL TRACE
Trace of movement paths
Print interruption summary table
CALL TOTALS
Interruption summary table
G
A
YES
III≤NUMREP
NO
END

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3. Photographs with dark background ________
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8. Computer printout pages with indistinct print ________
9. Page(s) ________ lacking when material received, and not available from school or author ________
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C
C***** THIS VERSION IS FOR THE INTERDATA 7/32 AND OTHER 32-BIT UNITS *******
C
C***********************************************************************
C***********************************************************************
C*                                                                     *
C*                                                                     *
C*      BFIRES -- HUMAN EGRESS BEHAVIOR DURING BUILDING FIRES          *
C*                                                                     *
C*                                                                     *
C***********************************************************************
C***********************************************************************
C*                                                                     *
C*      WRITTEN BY FRED I. STAHL, RESEARCH PSYCHOLOGIST                *
C*                 ARCHITECTURAL RESEARCH PROGRAM                      *
C*                 ENVIRONMENTAL DESIGN RESEARCH DIVISION              *
C*                 CENTER FOR BUILDING TECHNOLOGY,NEL                  *
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C*                 WASHINGTON, DC  20234                               *
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C*                 NATIONAL BUREAU OF STANDARDS                        *
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C*                                                                     *
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C*                                                                     *
C***********************************************************************
C*                                                                     *
C*                 REVISED  AUGUST 30,1978                             *
C*                                                                     *
C***********************************************************************
C***********************************************************************
C
C
C
C
C         THE BFIRES PROGRAM SIMULATES HUMAN EGRESS BEHAVIOR DURING BUILDING
C     FIRES.  BFIRES IS A DISCRETE TIME STOCHASTIC SIMULATION BASED ON A NON-
C     STATIONARY MARKOV MODEL OF THE BUILDING FIRE PROCESS.  ACCORDING TO THIS
C     MODEL, FIRES MAY BE UNDERSTOOD IN TERMS OF THREE INTERACTING COMPONENTS.
C     THESE ARE  (1) THE FIRE AND ITS BI-PRODUCTS,  (2) THE BUILDING ENCLOSURE,
C     AND  (3) THE HUMAN OCCUPANTS.  EACH POSSESSES UNIQUE CHARACTERISTICS,
C     AND THE BEHAVIOR OF EACH CONTRIBUTES TO THE OVERALL OUTCOME OF ANY FIRE
C     EVENT (I.E., HOW MANY PEOPLE ESCAPED, HOW MUCH TIME WAS REQUIRED FOR ESCAPE,
C     ETC.).
C
C         EXEC2 IS THE SECOND VERSION OF THE BFIRES EXECUTIVE ROUTINE.  THE
C     PURPOSE OF EXEC2 IS TO READ-IN ALL USER-SUPPLIED DATA, AND THEN TO RUN A
C     FIRE EVENT FOR A GIVEN PERIOD OF TIME.  IN ADDITION, EXEC2 PERMITS THE USER


C     TO CONDUCT A NUMBER (UP TO 20) OF REPLICATIONS OF A GIVEN FIRE EVENT, IN A
C     SINGLE COMPUTER RUN.
C
C
C         THE FOLLOWING DATA MUST BE PROVIDED BY THE USER.  THESE DESCRIBE THE
C     FIRE, THE BUILDING ENCLOSURE, AND THE OCCUPANTS FOR THE COMPUTER.
C
C       XT,YT          X,Y COORDINATES OF INITIAL THREAT LOCATION
C       NUMEXT         NUMBER OF EXITS FROM THE FLOOR (NOT MORE THAN 2)
C       MXTIME         OCCUPANTS' PERCEIVED TIME FOR EGRESS(LESS THAN TOTIME)
C       NSPACE         NUMBER OF SPATIAL SUBDIVISIONS ON THE FLOOR (NOT MORE THAN
C                        20)
C       EVLOPT         STATUS EVALUATION OPTION SELECTOR
C       MK             PRESET TO ZERO
C       C              PRESET TO ZERO
C       IALLOW         SPATIAL CROWDING FACTOR
C       ND             NUMBER OF DOORS ON THE FLOOR (NOT MORE THAN 30)
C       RREPRT         SUMMARY TABLE OPTION SELECTOR
C       RREPT2         SUMMARY TABLE OPTION SELECTOR
C       XE,YE          X,Y COORDINATES OF EXITS FROM THE FLOOR
C       NE             NUMBER OF EXITS FROM A SPATIAL SUBDIVISION
C       NPOINT         NUMBER OF POINTS COMPRISING WALLS WHICH ENCLOSE A SPATIAL
C                        SUBDIVISION (NOT MORE THAN 75)
C       IBAR(IS,1,J) X COORDINATE OF THE JTH POINT OF A WALL WHICH ENCLOSES
C                        SUBDIVISION IS
C       IBAR(IS,2,J) Y COORDINATE OF THE JTH POINT OF A WALL WHICH ENCLOSES
C                        SUBDIVISION IS
C       IGOALX         X COORDINATE OF AN EXIT FROM A SUBDIVISION
C       IGOALY         Y COORDINATE OF AN EXIT FROM A SUBDIVISION
C       XLO,XHI        RANGE OF X COORDINATES OF POINTS COMPIRISING WALLS WHICH
C                        ENCLOSE A SUBDIVISION
C       YLO,YHI        RANGE OF Y COORDINATES OF POINTS COMPRISING WALLS WHICH
C                        ENCLOSE A SUBDIVISION
C       IDOOR(1,J)     X COORDINATE OF LOCATION OF JTH DOOR
C       IDOOR(2,J)     Y COORDINATE OF LOCATION OF JTH DOOR
C       IDOOR(3,J)     DOOR-TYPE IDENTIFIER FOR JTH DOOR
C       IDOOR(4,J)     DOOR POSITION IDENTIFIER FOR JTH DOOR
C       NUMOCC         NUMBER OF OCCUPANTS IN THE EVENT (NOT MORE THAN 20)
C       TOTIME         TOTAL NUMBER OF SIMULATED TIME FRAMES TO BE RUN (I.E.,
C                        LENGTH OF THE FIRE EVENT -- NOT MORE THAN 100 FRAMES)
C       IRAND          RANDOM NUMBER SEED (NECESSARY FOR 32 BIT COMPUTER ONLY), ANY
C                        5 DIGIT ODD NUMBER.   FOR UNIVAC-1108 VERSION, INSERT ANY
C                        5 DIGIT DUMMY NUMBER.
```

```
C      NUMREP        TOTAL NUMBER OF REPLICATIONS DESIRED
C      PI2           PROBABILITY OF A TYPE-2 INTERRUPTION
C      PI0           PROBABILITY OF NO INTERRUPTION
C      INTLIM        OCCUPANTS' INTERRUPTION LIMIT
C      LBYSTD        OCCUPANTS' INTERVENTION LIMIT
C      IHANDI        OCCUPANTS' MOBILITY STATUS
C      KNOWAY        OCCUPANTS' INITIAL KNOWLEDGE OF BEST EXIT
C      XO,YO         X,Y COORDIATES OF OCCUPANTS' INITIAL SPATIAL LOCATIONS
C      POPEN         PROBABILITY THAT OCCUPANT WILL OPEN A CLOSED DOOR
C      PCLOSE        PROBABILITY THAT OCCUPANT WILL CLOSE AN OPEN DOOR
C

C   THESE DATA ARE ENTERED IN THE FOLLOWING SEQUENCE...
C
C        TITLE  (ANY 80 CHARACTER COMMENT)
C             (20A4)
C        IFMT  (USER SUPPLIED FORMAT STATEMENT)
C             (20A4)
C        JFMT  (USER SUPPLIED FORMAT STATEMENT)
C             (20A4)
C        KFMT  (USER SUPPLIED FORMAT STATEMENT)
C             (20A4)
C        XT,YT,NUMEXT,MXTIME,NSPACE,EVLOPT.MK.C.IALLOW.ND,RREPRT,RREPT2
C             (5(I2,1X),2(I1,1X),F1.0,1X,2(1X,I2),2(1X,I1))
C        XE,YE      ALL XC OORDINATES FOLLOWED BY ALL YC OORDINATES
C             (IFMT)
C
C        REPEAT THE FOLLOWING SEQUENCE FOR EACH SPATIAL SUBDIVISION
C
C           NE,NPOINT
C             (IFMT)
C           IBAR(IS,1,J)  COORDIATES 1-NPOINT IN ADJACENT FIELDS
C             (JFMT)
C           IBAR(IS,2,J) C OORDINATES 1-NPOINT IN ADJACENT FIELDS
C             (JFMT)
C           IGOALX,IGOALY     ALL X COORDINATES, FOLLOWED BY ALL Y COORDINATES
C             (IFMT)
C           XLO,XHI,YLO,YHI
C             (IFMT)
C
C        IDOOR(1,J)    (COORDINATES 1-ND IN ADJACENT FIELDS)
C             (JFMT)
C        IDOOR(2,J)    (COORDINATES 1-ND IN ADJACENT FIELDS)
C             (JFMT)
C        IDDOR(3,J)    (IDENTIFIERS 1-ND IN ADJACENT FIELDS)
C             (JFMT)
C        IDOOR(4,J)    (IDENTIFIERS 1-ND IN ADJACENT FIELDS)
C             (JFMT)
C        NUMOCC,TOTIME,IRAND.NUMREP,PI2,PI0
C             (2(I2,1X),I5,1X,I2,2(1X,F4.2))
C
C        REPEAT THE FOLLOWING LINE FOR EACH OCCUPANT IN THE RUN...
C
C           INTLIM,LBYSTD,IHANDI,KNOWAY,XO,YO,POPEN,PCLOSE
C             (KFMT)
C
C
C
C
C
C
      DIMENSION ITYPE1(20),ITYPE2(20),IDPASS(20),IPS(20)
      DIMENSION IXTRCE(20,100),IYTRCE(20,100)
      DIMENSION IBACK(20),JTIME(20),INITYO(20),INITXO(20)
      DIMENSION INTR(20),INTNUM(20),TITLE(20)
      DIMENSION IFMT(20),JFMT(20),KFMT(20),IENTER(9)
      DIMENSION IBAR(20,75,2),LBYSTD(20),IHANDI(20),KNOWAY(20)


      DIMENSION INTLIM (20),IBYSTD(20),NE(20),NPOINT(20)
      DIMENSION PTDIST(20),PEDIST(20),P(9)
      DIMENSION IGOALX(20,10),IGOALY(20,10),KXO(20),KYO(20)
      DIMENSION POPEN(20),PCLOSE(20),IDOOR(30,4),IDOPEN(30,100)
      DIMENSION IFLAG(20),ISCORE(20),NUMSTP(20)
       INTEGER XPRIOR(20),YPRIOR(20),SCORE(20)
      INTEGER XT,YT,XO(20),YO(20),XE(10),YE(10),TOTBAR,TOTIME
      INTEGER XLO(20),XHI(20),YLO(20),YHI(20),EVLOPT
      INTEGER XOB(20,100),YOB(20,100),RREPRT,RREPT2
C
C  READ RUN INPUT AND INITIALIZE RUN VARIABLES
      READ (5,101) TITLE
C
      READ (5,101) IFMT
      READ (5,103) JFMT
      READ (5,104) KFMT
C
C: INITIALIZE THE SIMULATION...
C:  (1) ENVIRONMENTAL PARAMETERS:
      READ (5,100) XT,YT,NUMEXT,MXTIME,NSPACE,EVLOPT,MK,C,
     1   IALLOW,ND,RREPRT,RREPT2
      READ (5,IFMT) (XE(I),I=1,NUMEXT),(YE(I),I=1,NUMEXT)
      DO 10 IS=1,NSPACE
      READ (5,IFMT) NE(IS),NPOINT(IS)
      NEXIT=NE(IS)
      TOTBAR=NPOINT(IS)
      READ (5,JFMT)(IBAR(IS,I,1),I=1,TOTBAR)
      READ (5,JFMT)(IBAR(IS,I,2),I=1,TOTBAR)
      READ (5,IFMT)(IGOALX(IS,JEXIT),JEXIT=1,NUMEXT),
     1   (IGOALY(IS,JEXIT),JEXIT=1,NUMEXT)
```

```
10    READ (5,IFMT) XLO(IS),XHI(IS),YLO(IS),YHI(IS)
      READ (5,JFMT) (IDOOR(I,1),I=1,ND)
      READ (5,JFMT) (IDOOR(I,2),I=1,ND)
      READ (5,JFMT) (IDOOR(I,3),I=1,ND)
      READ (5,JFMT) (IDOOR(I,4),I=1,ND)
C:  (2) SYSTEM PARAMETERS:
      READ (5,102) NUMOCC,TOTIME,IRAND,NUMREP,P12,P10
      DO 40 I=1,NUMOCC
      IBYSTD(I)=0
40    CONTINUE
C:  (3) OCCUPANT PARAMETERS:
      DO 45 N=1,NUMOCC
      READ (5,KFMT) INTLIM(N),LBYSTD(N),IHANDI(N),KNOWAY(N),XO(N),YO(N)
     1   ,POPEN(N),PCLOSE(N)
      KXO(N)=XO(N)
      KYO(N)=YO(N)
      INITXO(N)=XO(N)
      INITYO(N)=YO(N)
45    CONTINUE
C
C ** EXECUTE THE SIMULATION EXPERIMENT **
C
C  ITERATE FOR DESIRED NUMBER OF REPLICATIONS
      DO 90 III=1,NUMREP

C  INITIALIZE REPLICATION VARIABLES
      DO 91 N=1,NUMOCC
      XO(N)=KXO(N)
91    YO(N)=KYO(N)
C
      DO 92 NTHIS=1,NUMOCC
      IFLAG(NTHIS)=0
      NUMSTP(NTHIS)=0
      ISCORE(NTHIS)=0
      IBACK(NTHIS)=0
      JTIME(NTHIS)=0
      INTR(NTHIS)=0
      INTNUM(NTHIS)=0
      ITYPE1(NTHIS)=0
      ITYPE2(NTHIS)=0
92    IDPASS(NTHIS)=0
C
C  ITERATE FOR DESIRED NUMBER OF TIME FRAMES
C
      DO 50 ITIME=1,TOTIME
C
      DO 501 I=1,ND
501   IDOPEN(I,ITIME)=IDOOR(I,4)
C
C  ITERATE FOR DESIRED NUMBER OF OCCUPANTS
      DO 60 NTHIS=1,NUMOCC
      IF (IFLAG(NTHIS).EQ.1) GO TO 60
C  INITALIZE OCCUPANT LOCATORS
      XPRIOR(NTHIS)=XO(NTHIS)
      YPRIOR(NTHIS)=YO(NTHIS)
      IXTRCE(NTHIS,ITIME)=XO(NTHIS)
      IYTRCE(NTHIS,ITIME)=YO(NTHIS)
      XOB(NTHIS,ITIME)=XO(NTHIS)
      YOB(NTHIS,ITIME)=YO(NTHIS)
C  DETERMINE WHICH SPACE THE OCCUPANT IS CURRENTLY OCCUPYING
      N=0
15    N=N+1
      IF (((XLO(N).LT.XO(NTHIS)).AND.
     1   (YLO(N).LT.YO(NTHIS))).AND.
     2   ((XHI(N).GT.XO(NTHIS)).AND.
     3   (YHI(N).GT.YO(NTHIS)))) GO TO 25
      GO TO 20
25    IS=N
      GO TO 26
20    IF (N.LT.NSPACE) GO TO 15
      IS=NSPACE
26    TOTBAR=NPOINT(IS)
C  DETERMINE WHETHER THE OCCUPANT IS INTERRUPTED
      CALL INTRPT (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X,INTLIM,INTR,INTNUM,P12,P10)
      IF (INT.EQ.1) GO TO 27
      IF (INT.EQ.2) GO TO 30


      GO TO 31
C  REMAIN-IN-PLACE INTERRUPTION
27    ITYPE1(NTHIS)=ITYPE1(NTHIS)+1
      GO TO 70
C  BACK-TRACK INTERRUPTION
30    CALL BACKUP (IBACK,XO,YO,INITXO,INITYO,XOB,YOB,
     1   ITIME,NTHIS,NEWXO,NEWYO,INTR,JTIME)
      ITYPE2(NTHIS)=ITYPE2(NTHIS)+1
      IF(INTR(NTHIS).EQ.0) GO TO 31
      GO TO 71
31    CONTINUE
      IF (IBYSTD(NTHIS).EQ.1) GO TO 70
C  DETERMINE SOCIAL CONDITIONS SURROUNDING THE OCCUPANT
      CALL GROUP (NTHIS,NUMOCC,IHANDI,KNOWAY,KOOCC,NHANDI,NKNOW,NAGREE,
     1   IAGREE)
```

```
      IF (NHANDI.GT.0) GO TO 65
      GO TO 67
65    CALL BYSTND (IBYSTD,NTHIS)
      IF (IBYSTD(NTHIS).EQ.1) GO TO 70
C  DETERMINE MODE OF STATUS EVALUATION
67    IF (EVLOPT-1) 68,68,69
68    CALL EVAL0(XO,YO,XT,YT,XE,YE,NTHIS,IAGREE,ITIME,IEVAL,
     1   PTDIST,TDIST,PEDIST,EDIST,IS,IGOALX,IGOALY)
      GO TO 70
69    CALL EVAL20 (MOTIME,MK,XO,YO,XE,YE,NTHIS,IAGREE,
     1   ITIME,C,IEVAL,TOTIME)
C  DETERMINE LOCAL CROWDING CONDITIONS SURROUNDING THE OCCUPANT
70    CALL JAMMED (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2   P,MOVE,XK,YK,K,IALLOW,NUMOCC,IENTER)
C  GENERATE MOVE PROBABILITIES
      CALL ASSIGN (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X,IDOOR,POPEN,ND,MDOOR,PCLOSE)
      CALL NEWXY (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,NEWXO,NEWYO)
C  RECORD DOOR-PASSAGE, IF ONE OCCURRED
      CALL PASSG (IDPASS,IDOOR,XO,YO,NTHIS,ND,NEWXO,NEWYO)
71    IF (RREPRT.EQ.1) GO TO 72
      GO TO 61
C  PRINT MOVE PROBABILITY MATRIX, IF THIS OPTION IS SELECTED
72    CALL REPORT (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1 XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2 IRAND,P,MOVE,XK,YK,K,NUMEXT,NUMOCC,TOTIME,INTLIM,
     3 LBYSTD,KNOWAY,PTDIST,TDIST,PEDIST,EDIST,NEWXO,NEWYO,
     4  EVLOPT,IDOOR,IDOPEN,ND,INTR)
C  UPDATE OCCUPANT LOCATORS
61    CALL UPDATE (XO,YO,NTHIS,NEWXO,NEWYO)
      ISCORE(NTHIS)=ISCORE(NTHIS)+1
      IF ((XO(NTHIS).EQ.XE(KNOWAY)).AND.
     1   (YO(NTHIS).EQ.YE(KNOWAY))) GO TO 62
      GO TO 66


62    IFLAG(NTHIS)=1
      IPS(NTHIS)=IDPASS(NTHIS)
      GO TO 60
C  UPDATE NUMBER OF STEPS TRAVERSED BY THE OCCUPANT
66    CALL STEPS (XPRIOR,YPRIOR,XO,YO,NUMSTP,NTHIS)
60    CONTINUE
50    CONTINUE
C  PRINT SUMMARY TABLE, IF THIS OPTION IS SELECTED
      IF (RREPRT.EQ.2) GO TO 63
      GO TO 64
C  COMPUTE ESCAPE SCORES FOR ALL OCCUPANTS IN THE RUN
63    CALL XSCORE (TOTIME,ISCORE,NUMOCC,SCORE)
      CALL SUMMRY (INITXO,INITYO,INTLIM,LBYSTD,IHANDI,KNOWAY,POPEN,
     1   PCLOSE,SCORE,NUMSTP,IPS,III,NUMREP,NUMOCC,TOTIME,XO,YO,XE,YE,
     2   TITLE)
      IF (RREPT2.EQ.1) GO TO 64
      GO TO 90
64    CONTINUE
C  PRINT OCCUPANT MOVEMENT RACES, IF THIS OPTION IS SELECTED
      CALL TRACE (IXTRCE,IYTRCE,NTHIS,ITIME,NUMOCC,TOTIME)
C  PRINT INTERRUPTION SUMMARY TABLE, IF THIS OPTION IS SELECTED
      CALL TOTALS (IDPASS,ITYPE1,ITYPE2,NTHIS,NUMOCC)
90    CONTINUE
C
C: INPUT FORMATING
C
100   FORMAT (5(I2,1X),2(I1,1X),F1.0,1X,I2,1X,I2,2(1X,I1))
101   FORMAT (20A4)
102   FORMAT (2(I2,1X),I5,1X,I2,2(1X,F4.2))
103   FORMAT (20A4)
104   FORMAT (20A4)
      END
```

Routines GROUP, OTHERS and AGREE

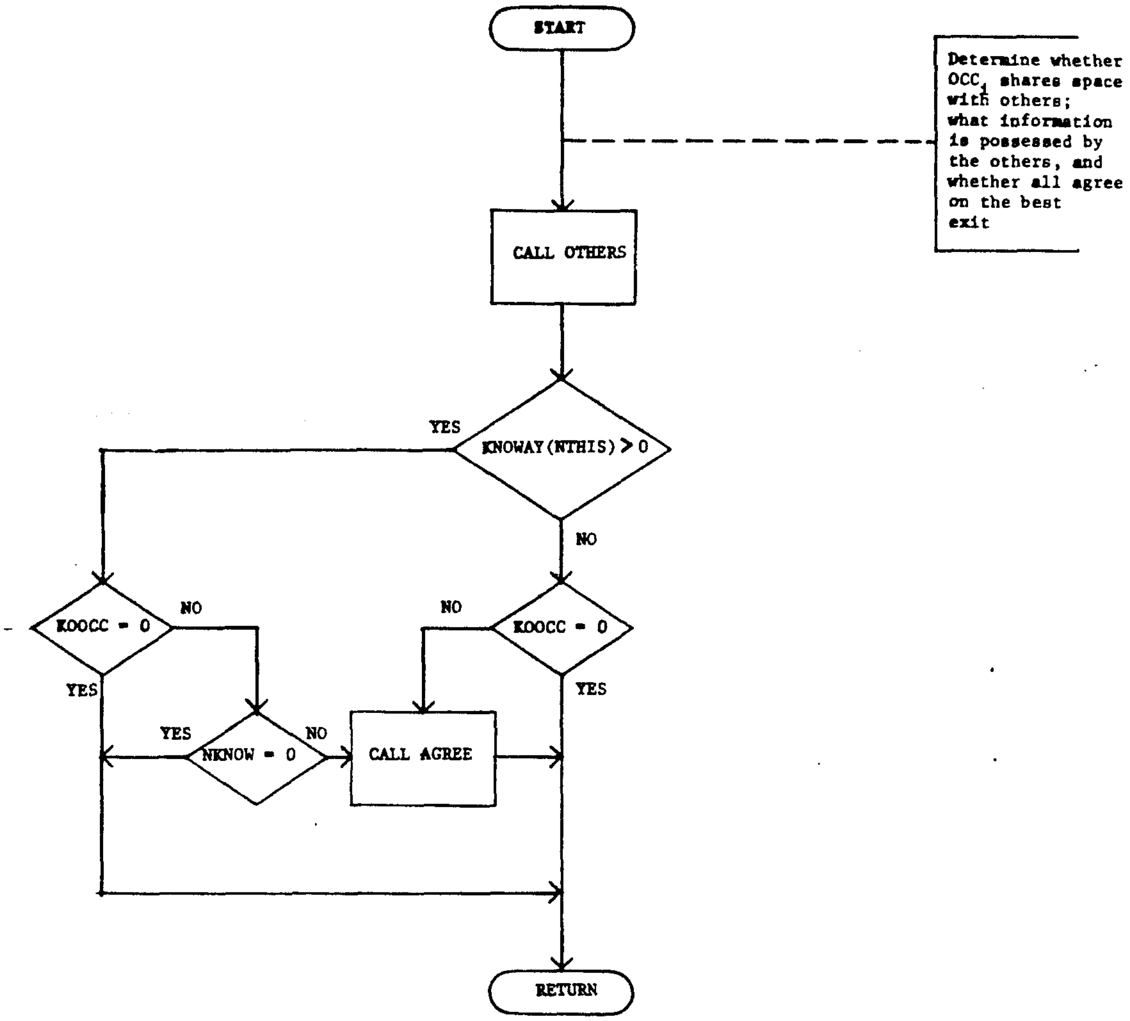
Loop Occupant

Purpose This is a collection of subprograms which establishes the social environment of occupants as they progress through the simulated fire event. By calling upon the routines OTHERS and AGREE, GROUP informs a given occupant: (1) whether any other occupants co-occupy the space with him; (2) whether any of the others in the space possess information currently unknown to him; (3) whether any of the others in the space is injured or otherwise in need of assistance; and (4) whether all the occupants in the space are able to agree upon an effective exit route.

Formulas

$$PSUM = 0.60 * SUM \tag{10}$$

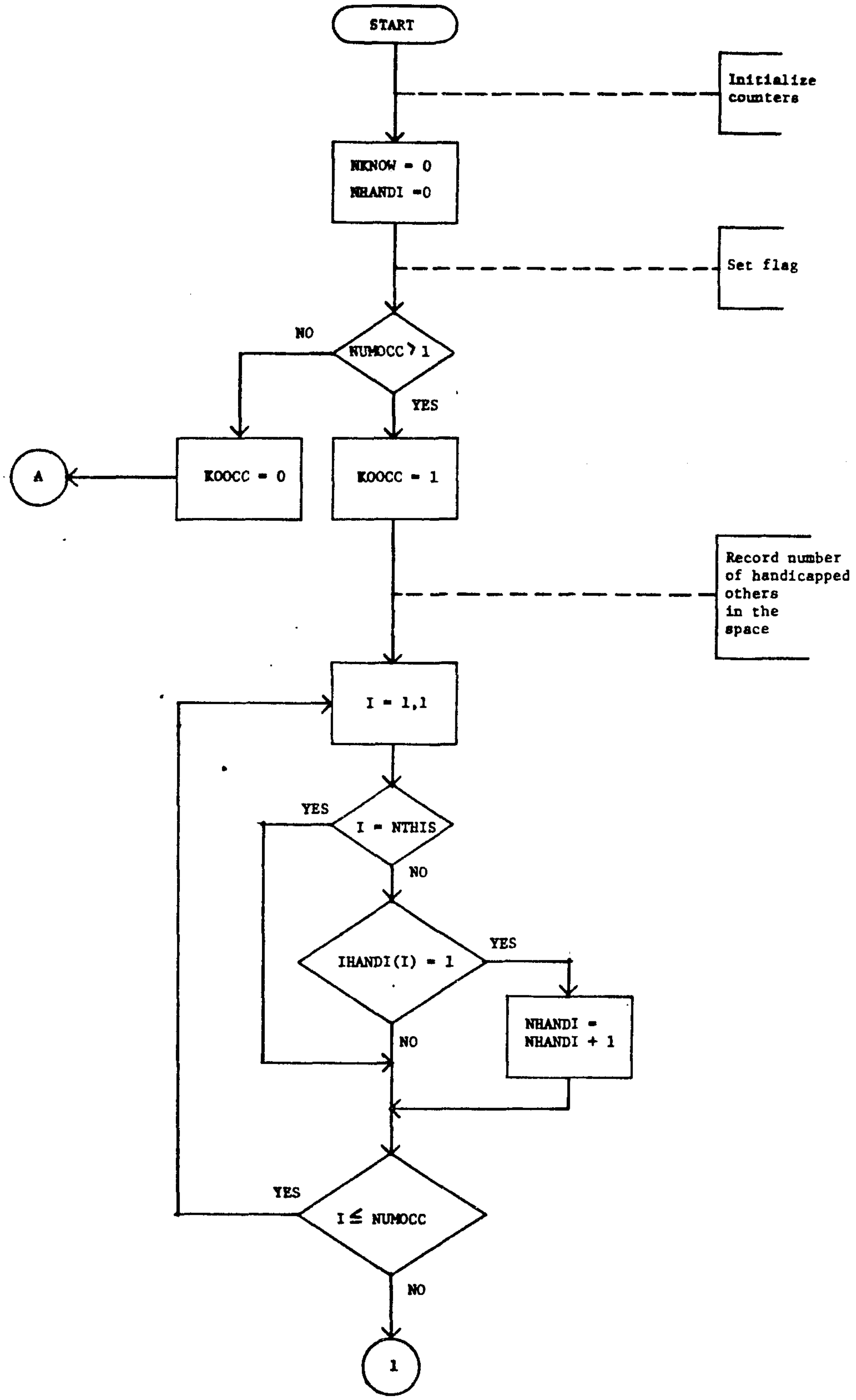
where: PSUM = the minimum number of occupants who must agree upon a single exit;
SUM = the total number of occupants impacting the consensus process.



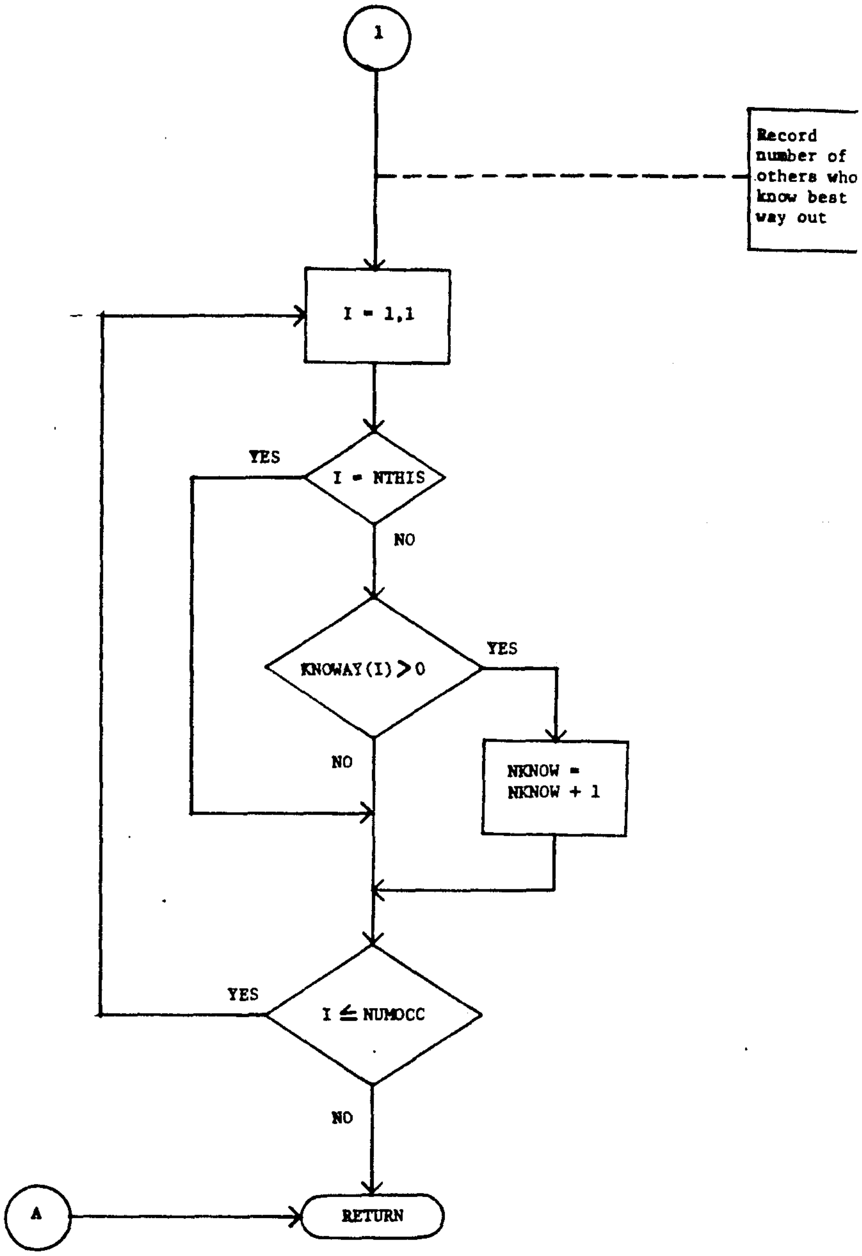
Subroutine GROUP

```
C
C
C
C
C
C     SUBROUTINE GROUP
C
C     THE PURPOSE OF GROUP IS TO ESTABLISH AND UPDATE THE SOCIAL ENVIRONMENT OF
C     OCCUPANTS AS THEY PROGRESS THROUGH THE SIMULATED FIRE EVENT.
C
        SUBROUTINE GROUP (NTHIS,NUMOCC,IHANDI,KNOWAY,KOOCC,NHANDI,
     -1   NKNOW,NAGREE,IAGREE)
        DIMENSION KNOWAY(20)
C     DETERMINE WHETHER THE OCCUPANT SHARES THE SPATIAL SUBDIVISION WITH OTHER
C     OCCUPANTS, WHAT INFORMATION IS POSSESSED BY THE OTHERS, AND WHETHER ALL
C     SUBDIVISION AGREE ON THE BEST EXIT
        CALL OTHERS (NTHIS,NUMOCC,IHANDI,KNOWAY,KOOCC,NHANDI,NKNOW)
        IF (KNOWAY(NTHIS).GT.0) GO TO 1
        IF (KOOCC.EQ.0) GO TO 999
        GO TO 2
1       IF (KOOCC.EQ.0) GO TO 999
        IF (NKNOW.EQ.0) GO TO 999


2       CALL AGREE (NTHIS,NUMOCC,IHANDI,KNOWAY,KOOCC,NHANDI,
     1  NKNOW,NAGREE,IAGREE)
999      RETURN
        END
```

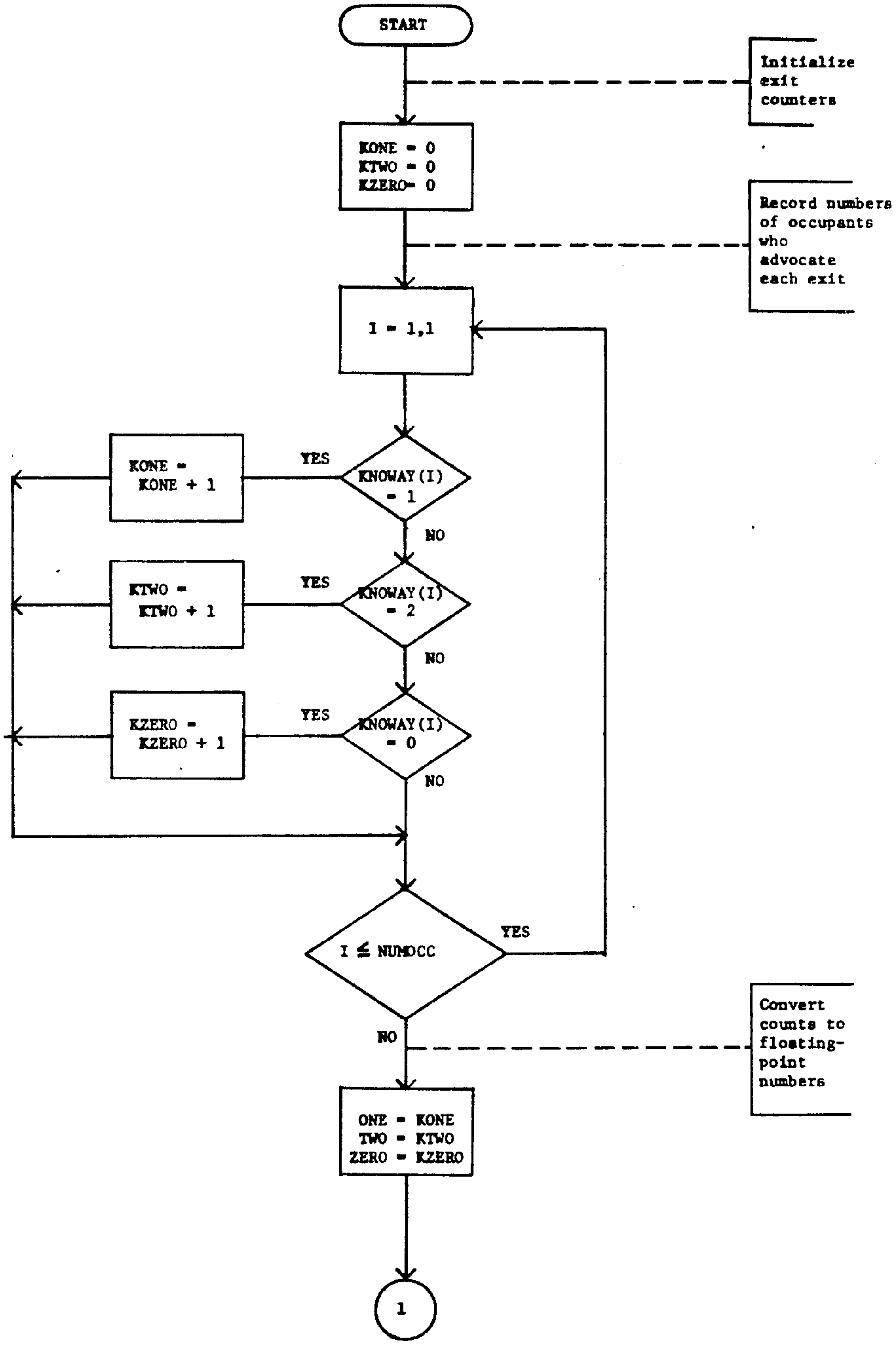


Subroutine OTHERS

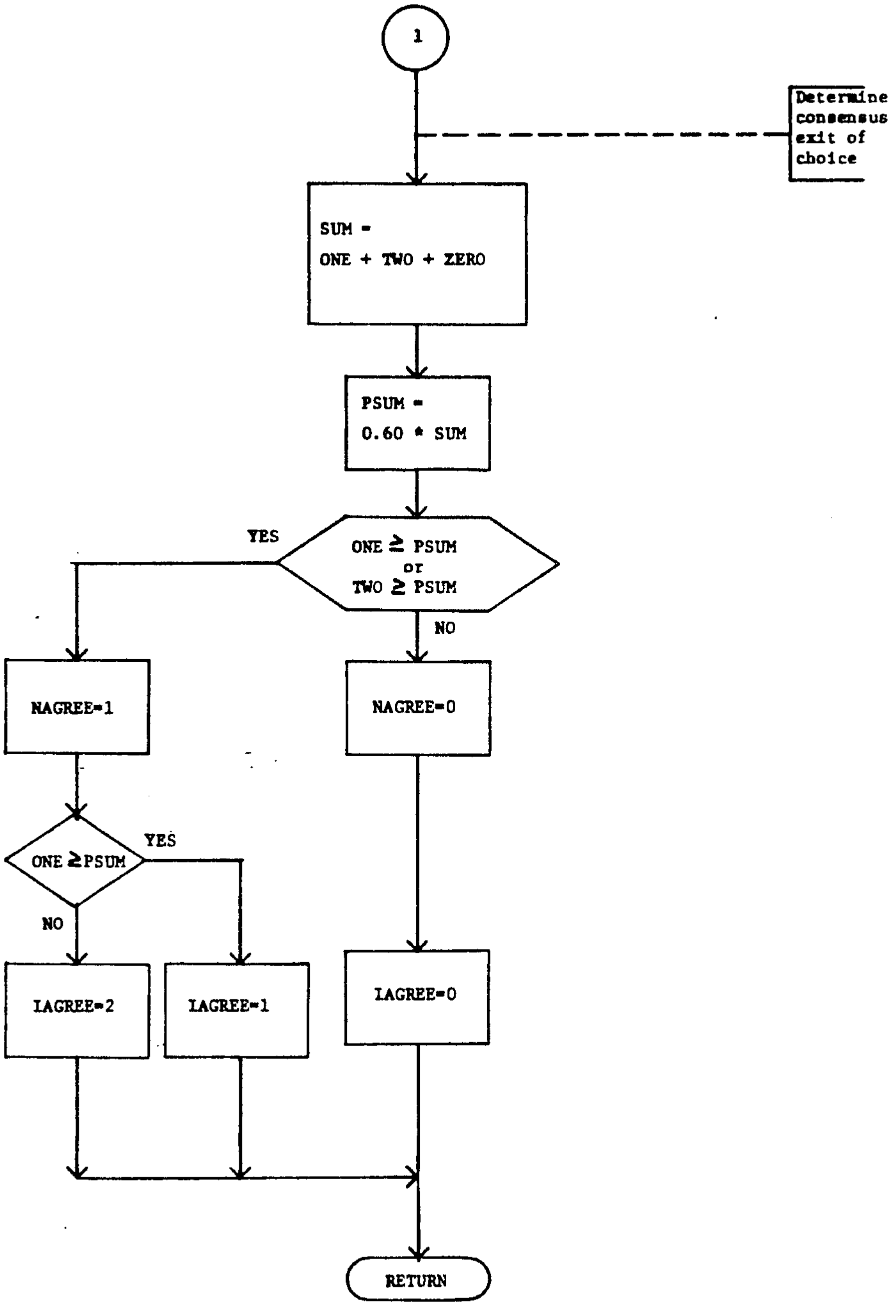


Subroutine OTHERS

```
C
C
C
C
C
C     SUBROUTINE OTHERS
C
C     THE PURPOSE OF OTHERS IS TO RECORD THE NUMBER OF OTHER OCCUPANTS IN THE
C     SUBDIVISION.  OTHERS ESTABLISHES SEPARATE RECORDS FOR THE NUMBER OF MOBILITY
C     -IMPAIRED (HANDICAPPED) OTHERS, AND FOR THOSE KNOWING THE WAY OUT.
C
      SUBROUTINE OTHERS (NTHIS,NUMOCC,IHANDI,KNOWAY,KOOCC,NHANDI,
     1   NKNOW)
      DIMENSION IHANDI(20),KNOWAY(20)
C     INITIALIZE COUNTERS
      NKNOW=0
      NHANDI=0
C     SET FLAG
      IF (NUMOCC.GT.1) GO TO 1
      KOOCC=0
      GO TO 999
1     KOOCC=1
C     RECORD NUMBER OF MOBILITY-IMPAIRED OTHERS IN THE SUBDIVISION
      DO 50 I=1,NUMOCC
      IF (I.EQ.NTHIS) GO TO 50
      IF (IHANDI(I).EQ.1) GO TO 51
      GO TO 50
51    NHANDI=NHANDI+1
50    CONTINUE
C     RECORD THE NUMBER OF OTHERS WHO KNOW THE BEST EXIT
      DO 60 I=1,NUMOCC
      IF (I.EQ.NTHIS) GO TO 60
      IF (KNOWAY(I).GT.0) GO TO 61
      GO TO 60
61    NKNOW=NKNOW+1
60    CONTINUE
999   RETURN
      END
```



Subroutine AGREE



Subroutine AGREE

```
C
C
C
C
C
C    SUBROUTINE AGREE
C
C    THE PURPOSE OF AGREE IS TO DETERMINE A CONSENSUS-EXIT-OF-CHOICE AMONG ALL
C    OCCUPANTS OF A GIVEN SPATIAL SUBDIVISION
C
      SUBROUTINE AGREE (NTHIS,NUMOCC,IHANDI,KNOWAY,KOOCC,
     1  NHANDI,NKNOW,NAGREE,IAGREE)

      DIMENSION KNOWAY(20)
C    INITIALIZE EXIT COUNTERS
      KONE=0
      KTWO=0
      KZERO=0
C    RECORD NUMBERS OF OCCUPANTS WHO ADVOCATE EACH EXIT
      DO 50 I=1,NUMOCC
      IF (KNOWAY(I).EQ.1) GO TO 51
      IF (KNOWAY(I).EQ.2) GO TO 52
      IF (KNOWAY(I).EQ.0) GO TO 53
      GO TO 50
51    KONE=KONE+1
      GO TO 50
52    KTWO=KTWO+1
      GO TO 50
53    KZERO=KZERO+1
50    CONTINUE
C    CONVERT COUNTS TO FLOATING POINT NUMBERS
      ONE=KONE
      TWO=KTWO
      ZERO=KZERO
C    DETERMINE CONSENSUS EXIT OF CHOICE
      SUM=ONE+TWO+ZERO
      PSUM=.60*SUM
      IF ((ONE.GE.PSUM).OR.(TWO.GE.PSUM)) GO TO 1
      NAGREE=0
      IAGREE=0
      GO TO 2
1     NAGREE=1
      IF (ONE.GE.PSUM) GO TO 3
      IAGREE=2
      GO TO 2
3     IAGREE=1
2     RETURN
      END
```

<u>Routine</u> KPOSS

<u>Loop</u> Occupant

<u>Purpose</u> As an occupant moves through a bounded environment, motion in certain directions may be possible, while in others it may be constrained. When he arrives at a particular point in space, the individual begins looking ahead and scanning possibilities for his next move decision. He requires a perceptual apparatus which permits him to distinguish open paths from those constrained by walls or other physical barriers. As subroutine GROUP provides the occupant with means of perceiving the <u>social</u> environment, subroutine KPOSS provides "eyes" through which to discern his immediate <u>physical</u> environment. Namely, as the occupant scans each potential move alternative, k, he determines which are physically possible to attain, and which are blocked. Blocking by architectural features, e.g., walls, is illustrated in Figure C.2. KPOSS also responds to inputs from subroutine JAMMED. A spatial location which is crowded beyond an occupant's level of acceptance will be treated as though it was blocked off by an inanimate physical barrier: the individual will eliminate that alternative, k, from the array of possibilities available at time frame t.

<u>Formulas</u> n/a

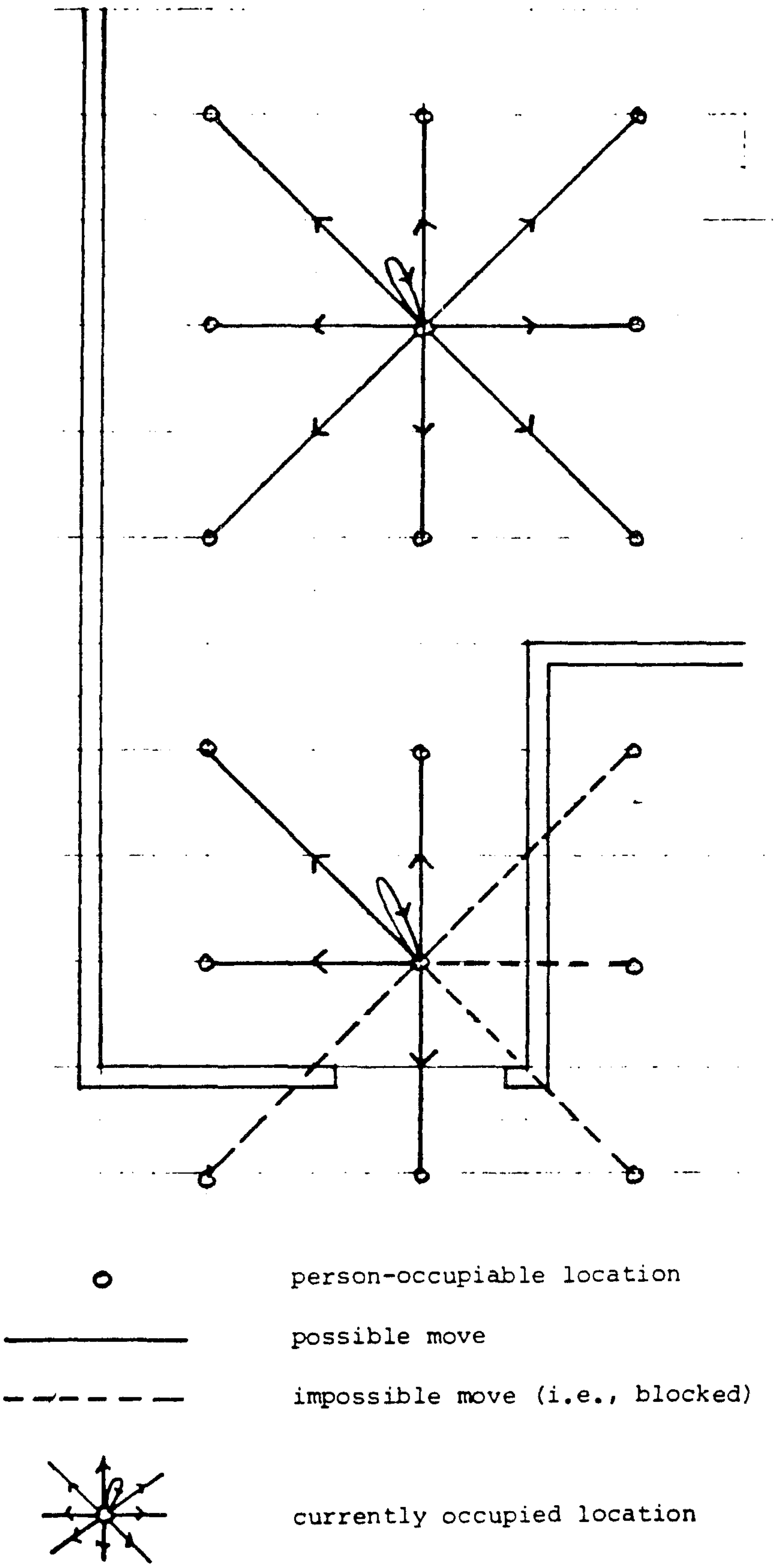
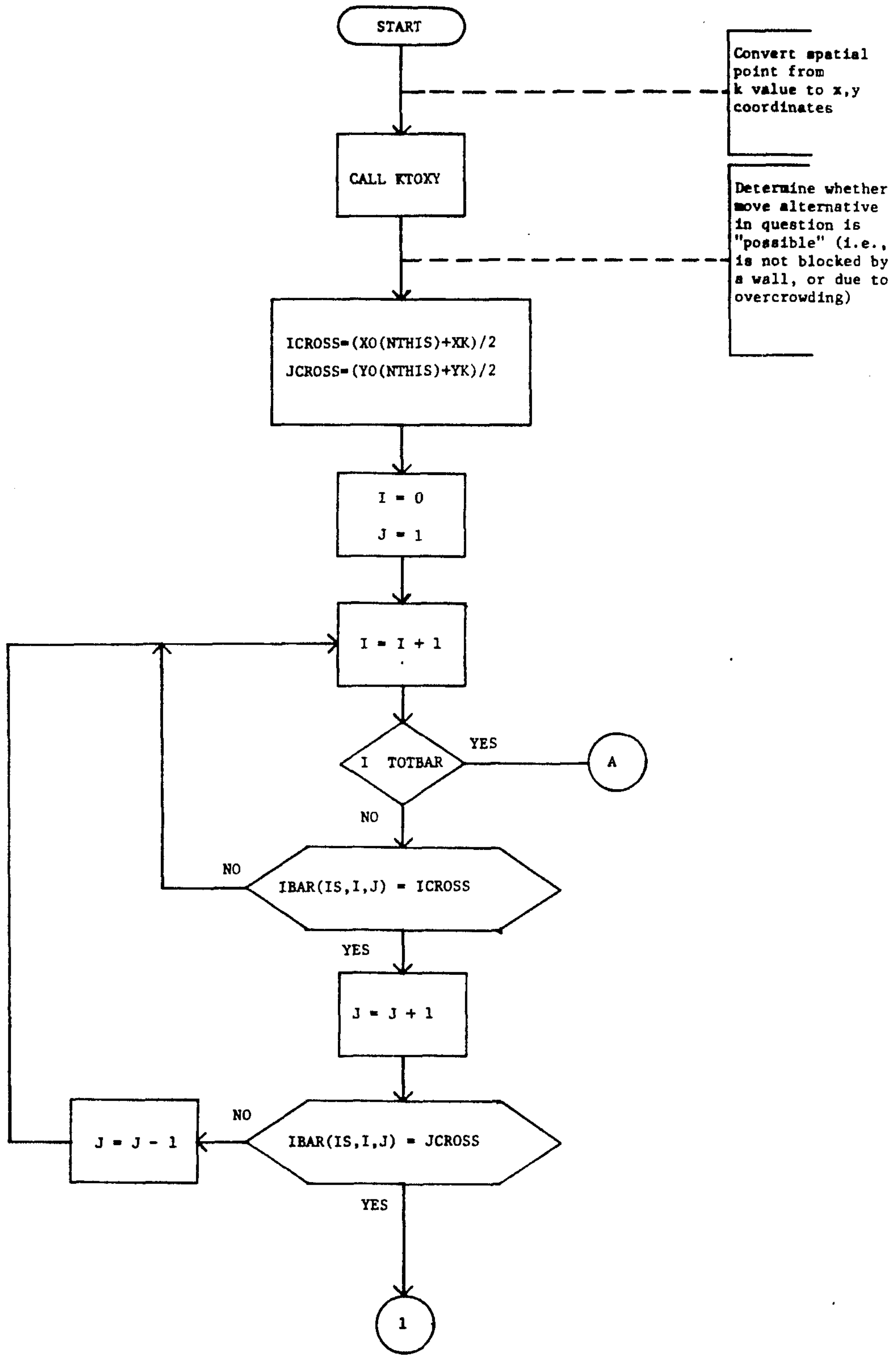
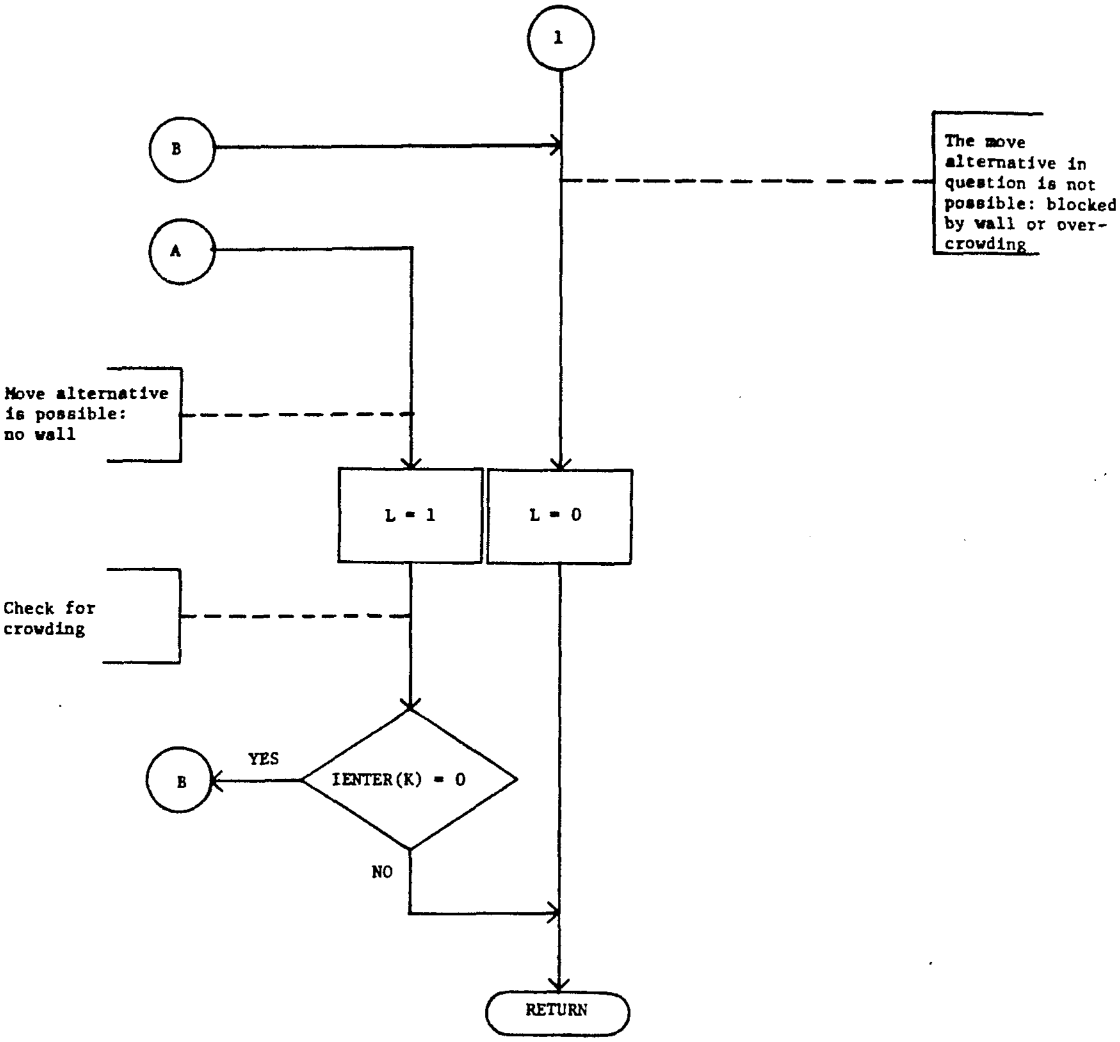


FIGURE C.2 Possible vs. Impossible Spatial Movements



Subroutine KPOSS



Subroutine KPOSS

```
C
C
C
C
C
C   SUBROUTINE KPOSS
C
C   THE PURPOSE OF KPOSS IS TO SCAN THE OCCUPANT'S IMMEDIATE PHYSICAL
C   ENVIRONMENT, AND TO DETERMINE WHETHER A MOVE ALONG ANY DIRECTION IS
C   RENDERED IMPOSSIBLE BECAUSE OF EITHER A PHYSICAL CONSTRAINT (WALL) OR
C   OVERCROWDING BY OTHER OCCUPANTS
C
      SUBROUTINE KPOSS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2  P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
      DIMENSION IBAR (20,75,2),IENTER(9)
      INTEGER XD(20),YD(20),XK,YK,TOTBAR
C   CONVERT SPATIAL POINT FROM K VALUE TO X,Y COORDINATES
      CALL KTOXY (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2  P,MOVE,XK;YK,K)
C   DETERMINE WHETHER THE MOVE ALTERNATIVE UNDER REVIEW IS POSSIBLE,
C   I.E., IS NOT BLOCKED BY A WALL, OR DUE TO OVERCROWDING
      ICROSS=(XD(NTHIS)+XK)/2
      JCROSS=(YD(NTHIS)+YK)/2
      I=0
      J=1
1     I=I+1
      IF (I.GT.TOTBAR) GO TO 5
      IF (IBAR(IS,I,J).EQ.ICROSS) GO TO 2
      GO TO 1


2     J=J+1
      IF (IBAR(IS,I,J).EQ.JCROSS) GO TO 4
      J=J-1
      GO TO 1
4      CONTINUE
C   THE MOVE ALTERNATIVE UNDER REVIEW IS NOT POSSIBLE...IT IS BLOCKED BY A WALL
C   OR BECAUSE OF OVERCROWDING
      L=0
      GO TO 6
5     L=1
      IF (IENTER(K).EQ.0) GO TO 4
6     RETURN
      END
```

Routine KTOXY

Loop Occupant

Purpose Two spatial notation systems are employed by BFIRES:

The orthogonal x,y coordinate system keeps track of the spatial locations of wall and door elements, and of occupants. The k-grid system is used in connection with the move alternative selection process. The k-grid may be thought of in terms of a compass dial, with eight vectors radiating outward from a central point (note Figure C.2). This point denotes the current location of occupant n, while the vectors represent potential movement paths. A ninth vector also exists to denote the condition of remaining-in-place. Each vector on the k-grid is designated by a number ("1" through "9"). As an occupant moves through space, he "carries" his personal k-grid along with him, such that the central point (k=5) always coincides with his current location. Execution of the various subroutines often requires transformations between the x,y and k grids. This is accomplished by subroutine KTOXY ("k to x,y").

Formulas

$$XK = XO + c \tag{11}$$

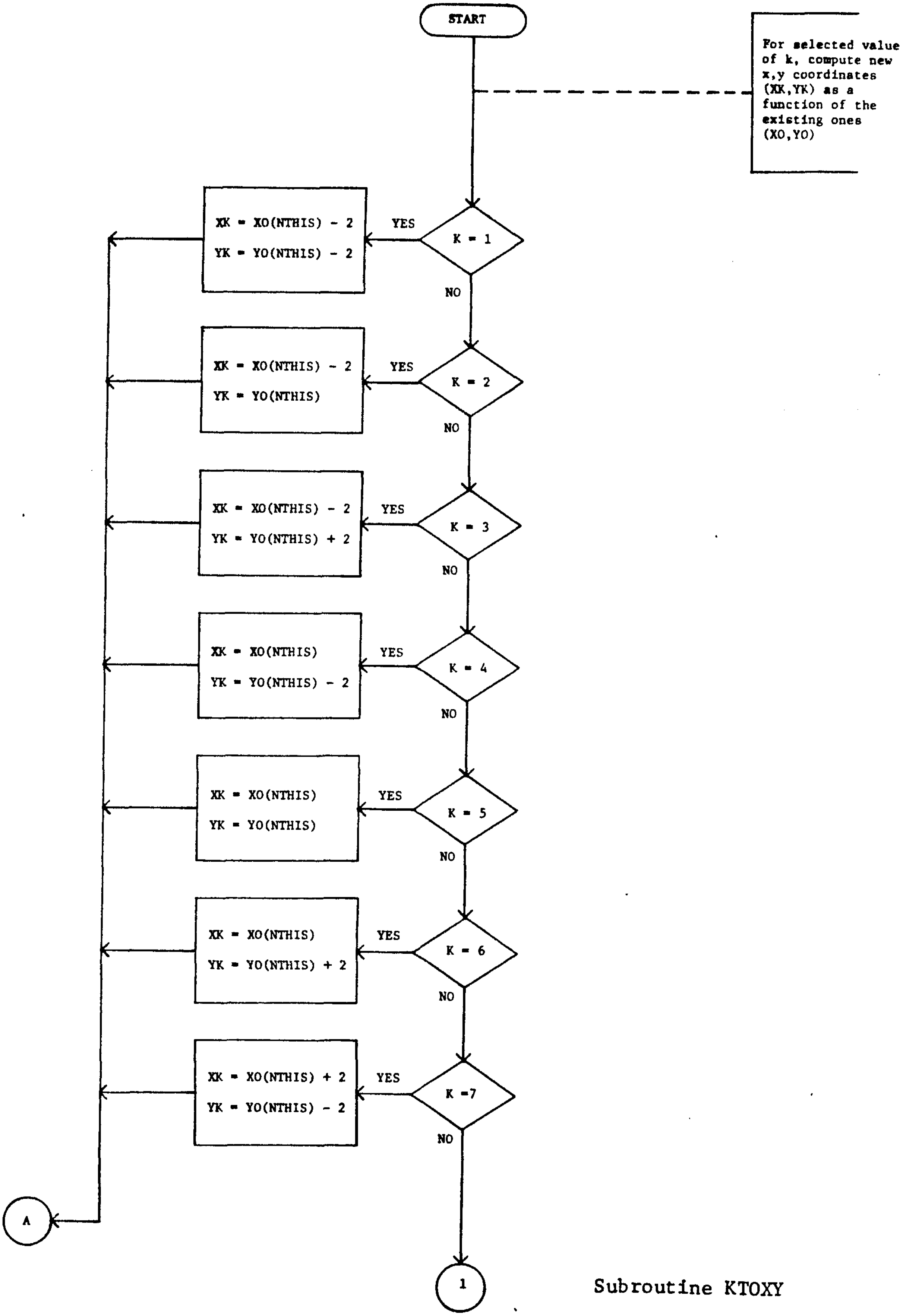
$$YK = YO + c \tag{12}$$

where:

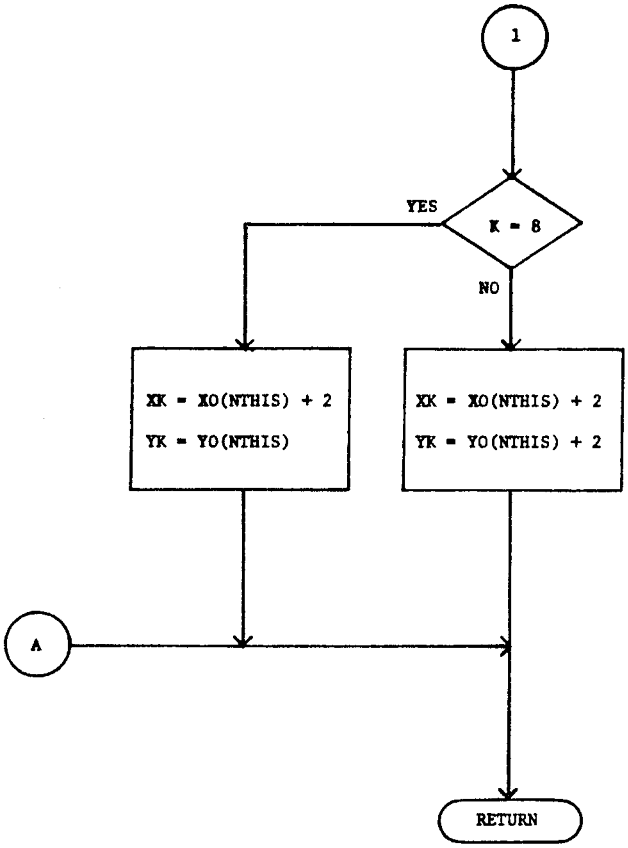
XK, YK = x and y coordinates of a new point which would be reached if vector k is selected;

XO, YO = current x and y coordinates describing occupant$_n$'s location;

c = a constant required to produce the actual locational shift.



Subroutine KTOXY



Subroutine KTOXY

```
C
C
C
C
C
C
C     SUBROUTINE KTOXY
C
C     THE PURPOSE OF KTOXY ('K TO X,Y') IS TO CONVERT SPATIAL LOCATIONS FROM
C     K-GRID DESIGNATIONS TO X,Y COORDINATES
C
      SUBROUTINE KTOXY(ITIME,NTHIS,IHAND1,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2  P,MOVE,XK,YK,K)
      INTEGER XO(20),YO(20),XK,YK
C     FOR THE VALUE OF K UNDER REVIEW, COMPUTE NEW X,Y COORDINATES (XK,YK)
C     AS A FUNCTION OF THE EXISTING ONES (XO,YO)
      GO TO (1,2,3,4,5,6,7,8,9),K
1     XK=XO(NTHIS)-2
      YK=YO(NTHIS)-2
      GO TO 10
2     XK=XO(NTHIS)-2
      YK=YO(NTHIS)
      GO TO 10
3     XK=XO(NTHIS)-2
      YK=YO(NTHIS)+2
      GO TO 10
4     XK=XO(NTHIS)
      YK=YO(NTHIS)-2
      GO TO 10
5     XK=XO(NTHIS)
      YK=YO(NTHIS)
      GO TO 10
6     XK=XO(NTHIS)
      YK=YO(NTHIS)+2
      GO TO 10
7     XK=XO(NTHIS)+2
      YK=YO(NTHIS)-2
      GO TO 10
8     XK=XO(NTHIS)+2
      YK=YO(NTHIS)
      GO TO 10

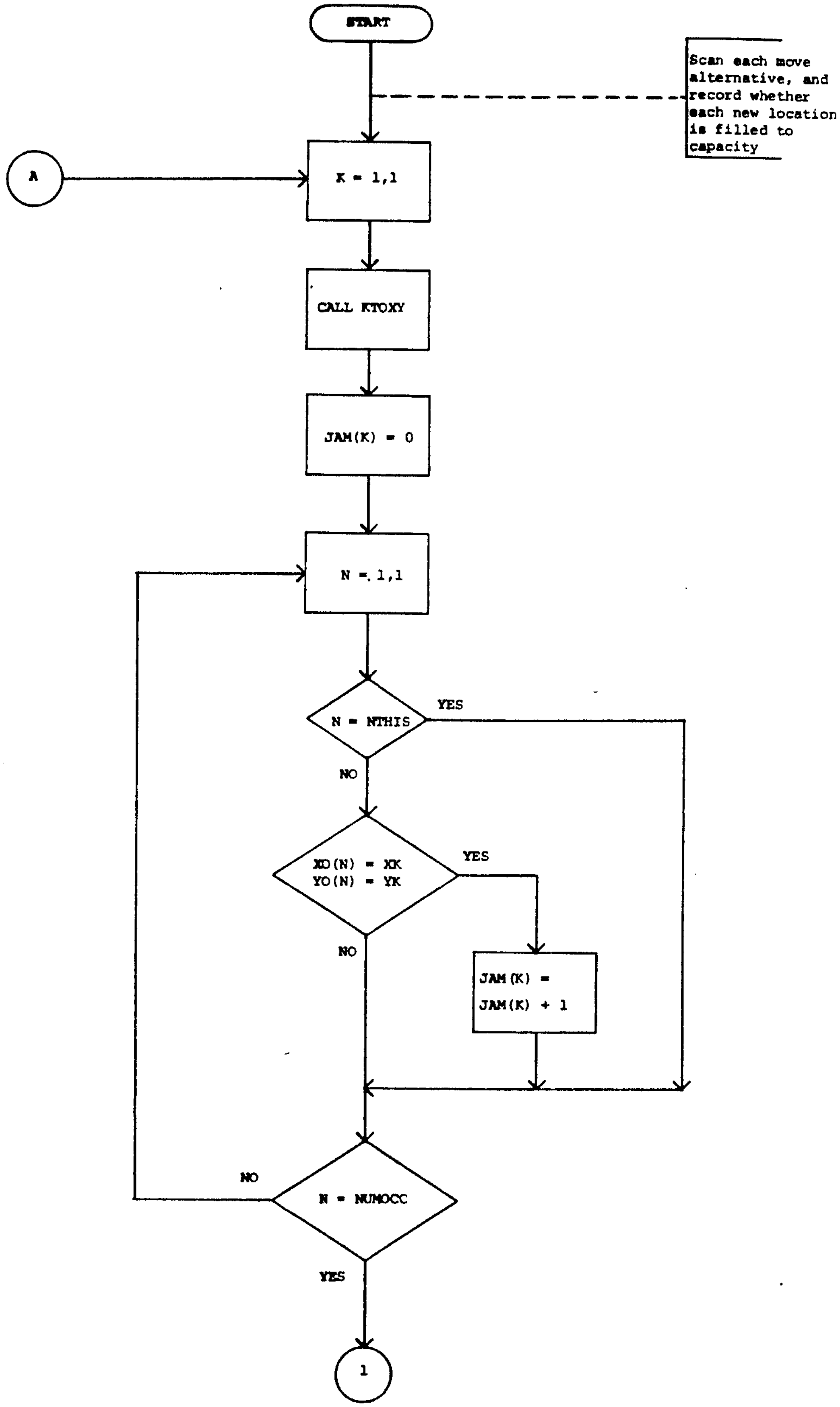
9     XK=XO(NTHIS)+2
      YK=YO(NTHIS)+2
10    RETURN
      END
```

Routine JAMMED

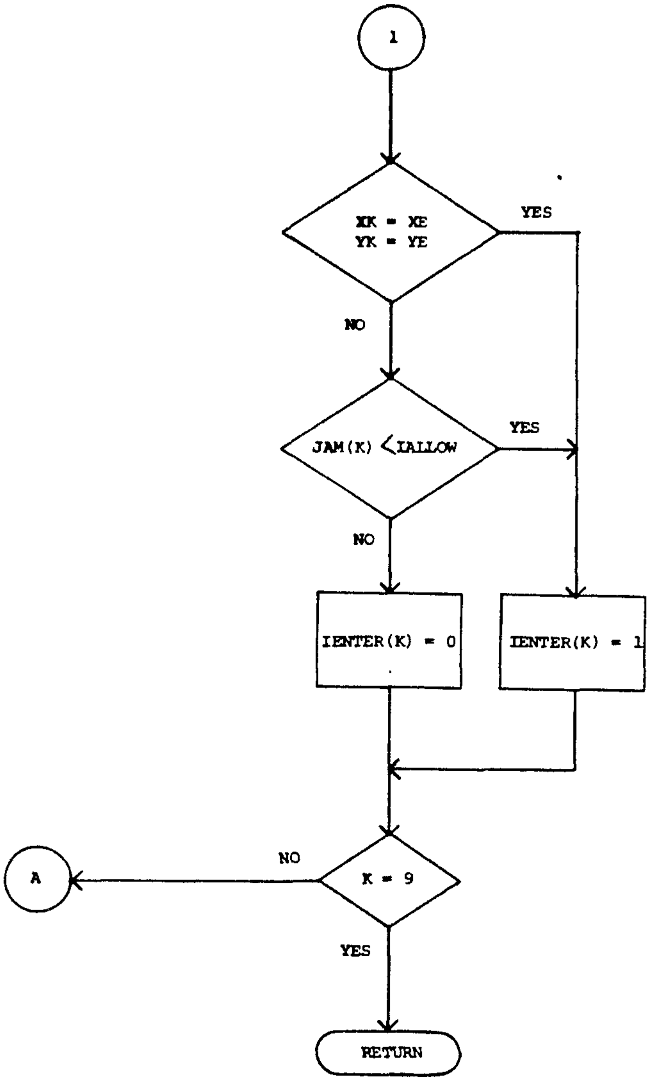
Loop Occupant

Purpose As occupants move about during a simulated fire, the population density of the different spatial locations varies. Some mechanism is necessary to enable an occupant to gather information about the density, or degree of physical crowding, of locations he may wish to enter. JAMMED satisfies this need. As an occupant looks ahead and scans target alternative locations available to him, he counts the number of other individuals already occupying each. If, for any given alternative location, this number is greater than his preset crowding tolerance, he rejects that alternative from his array of movement choices.

Formulas n/a



Subroutine JAMMED



Subroutine JAMMED

```
C
C
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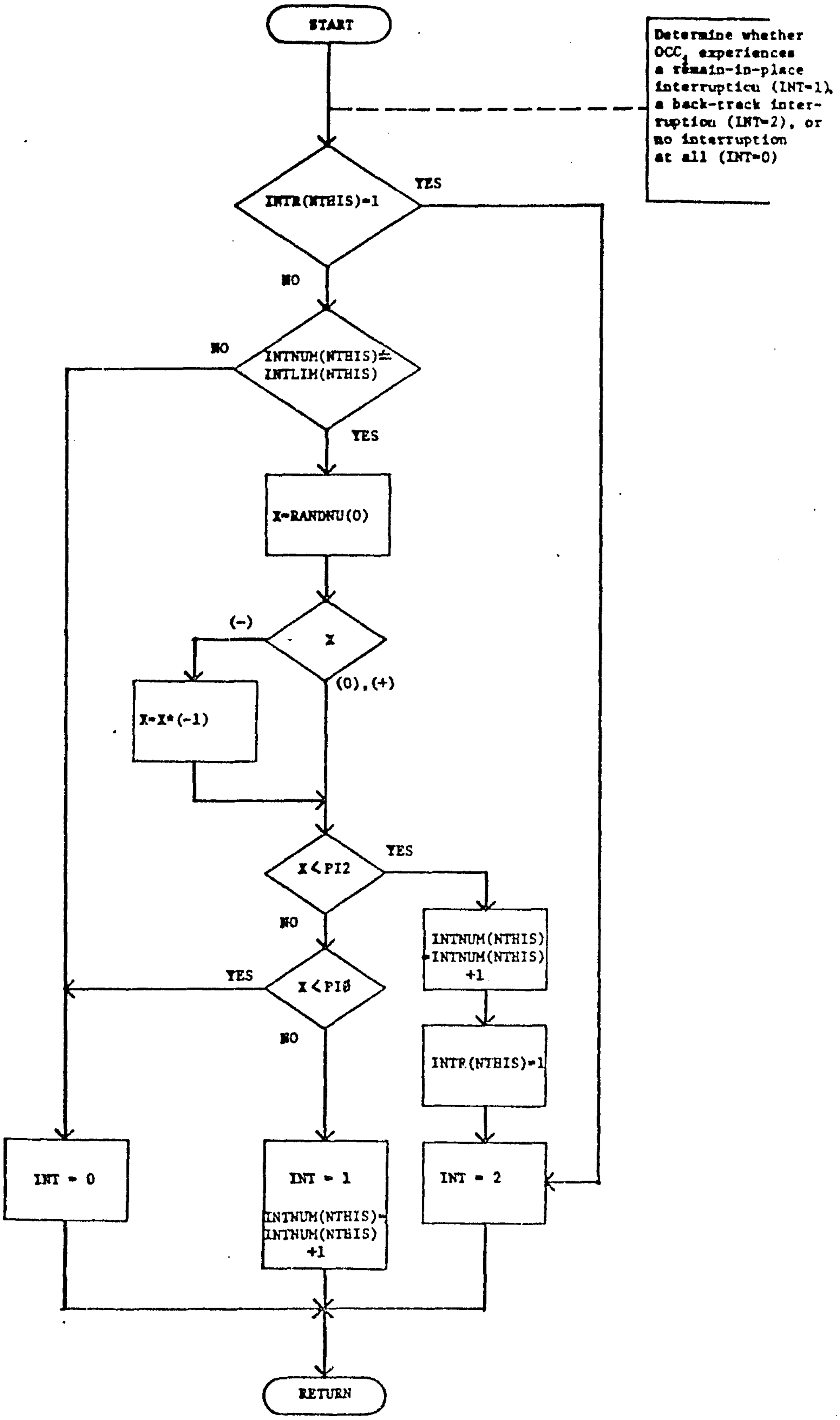
C
C    SUBROUTINE JAMMED
C
C    THE PURPOSE OF JAMMED IS TO ENABLE THE OCCUPANT TO GATHER INFORMATION ABOUT
C    THE DEGREE OF 'CROWDING' OF LOCATIONS HE MAY WISH TO ENTER...AS THE
C    OCCUPANT SCANS THE ALTERNATIVE TARGET LOCATIONS AVAILABLE TO HIM, HE
C    DETERMINES WHETHER EACH IS NON-ENTERABLE DUE TO OVERCROWDING
C
      SUBROUTINE JAMMED (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2   P,MOVE,XK,YK,K,IALLOW,NUMOCC,IENTER)
      INTEGER XD(20),YD(20),XK,YK,XE,YE
      DIMENSION JAM(9),IENTER(9)
C    SCAN EACH MOVE ALTERNATIVE, AND RECORD WHETHER EACH NEW LOCATION IS FILLED
C    TO CAPACITY
      DO 100 K=1,9
      CALL KTOXY (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2   P,MOVE,XK,YK,K)
      JAM(K)=0
      DO 200 N=1,NUMOCC
      IF (N.EQ.NTHIS) GO TO 200
      IF ((XD(N).EQ.XK).AND.(YD(N).EQ.YK)) GO TO 1
      GO TO 200
1     JAM(K)=JAM(K)+1
200   CONTINUE
      IF ((XK.EQ.XE).AND.(YK.EQ.YE)) GO TO 2
      IF (JAM(K).LT.IALLOW) GO TO 2
      GO TO 3
2     IENTER(K)=1
      GO TO 100
3     IENTER(K)=0
100   CONTINUE
      RETURN
      END
```

Routine INTRPT

Loop Occupant

Purpose This subroutine probabilistically determines whether an occupant's goal-directed behavior will be interrupted during time frame t. The two modes of interruption are remaining-in-place and backtracking. Occupants are assigned probabilities of encountering such interruptions. Each occupant is also assigned an interruption limit. If, during the course of a simulated event, an occupant has experienced a number of interruptions equal to his limit, he will not "tolerate" any more, and hence will ignore future interruptions.

Formulas n/a



Subroutine INTRPT

```
C
C
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C
C    SUBROUTINE INTRPT
C
C    THE PURPOSE OF INTRPT IS TO PROBABILISTICALLY DETERMINE WHETHER THE
C    OCCUPANT'S GOAL-DIRECTED BEHAVIOR WILL BE INTERRUPTED DURING TIME FRAME T.
C    TWO MODES OF INTERRUPTION ARE AVAILABLE, REMAINING-IN-PLACE AND
C    BACKTRACKING.  INTRPT DETERMINES WHETHER AN INTERRUPTION WILL OCCUR, AND
C    WHICH MODE WILL CONTROL.
C
      SUBROUTINE INTRPT (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X,INTLIM,INTR,INTNUM,P12,P10)
      DIMENSION INTNUM(20),INTLIM(20)
      DIMENSION INTR(20)

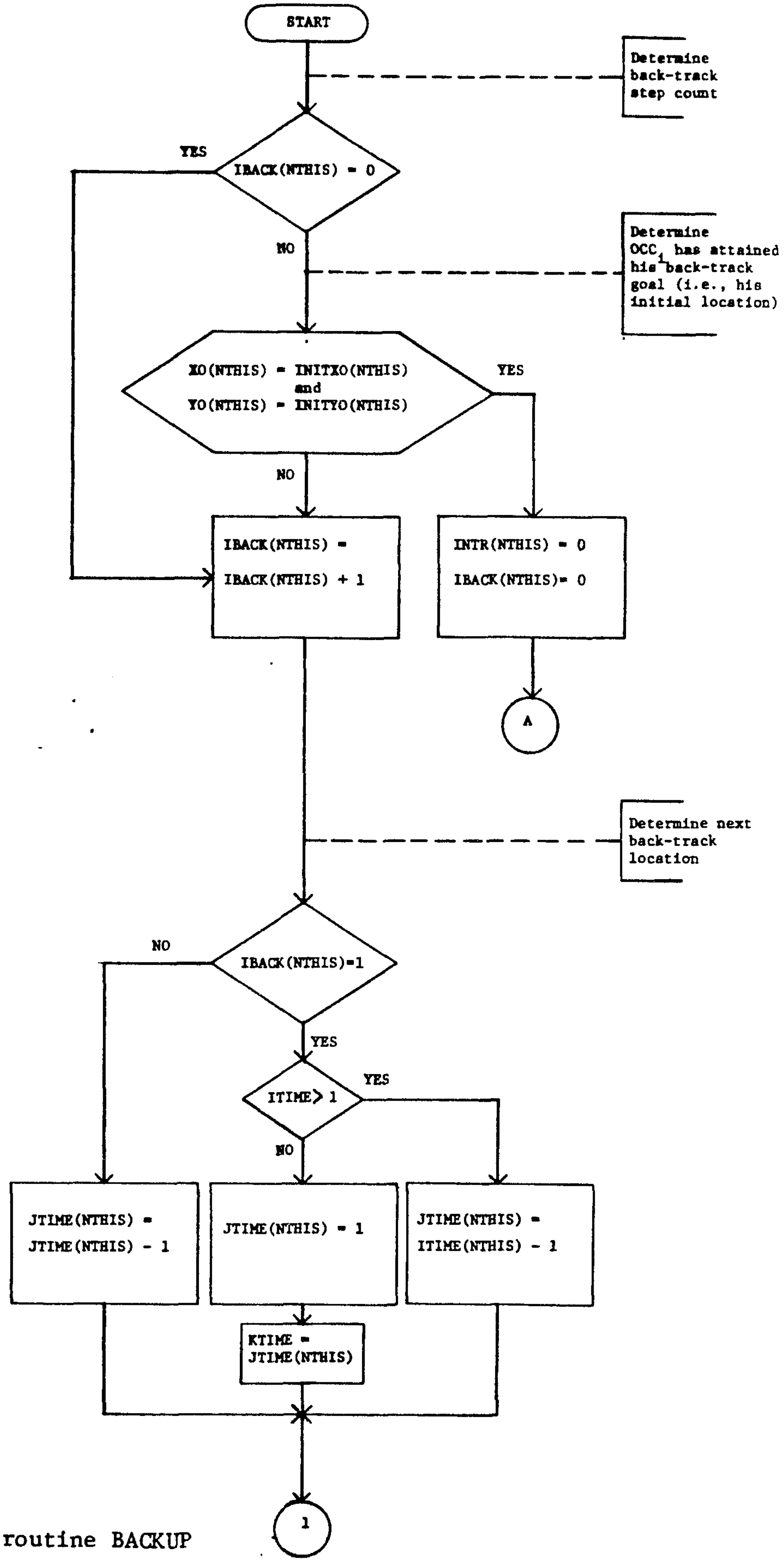

C    DETERMINE WHETHER THE OCCUPANT EXPERIENCES A REMAIN-IN-PLACE INTERRUPTION
C    (INT=1), A BACKTRACK INTERRUPTION (INT=2), OR NO INTERRUPTION AT ALL (INT=0)
      IF (INTR(NTHIS).EQ.1) GO TO 1
      IF (INTNUM(NTHIS).LE.INTLIM(NTHIS)) GO TO 2
      INT=0
      RETURN
1     INT=2
      RETURN
2     CALL RANDOM (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X)
      IF (X) 5,6,6
5     X=X*(-1)
6     CONTINUE
      IF (X.LT.P12) GO TO 3
      IF (X.LT.P10) GO TO 4
      INT=1
      INTNUM(NTHIS)=INTNUM(NTHIS)+1
      RETURN
3     INTNUM(NTHIS)=INTNUM(NTHIS)+1
      INTR(NTHIS)=1
      INT=2
      RETURN
4     INT=0
      RETURN
      END
```

Routine BACKUP

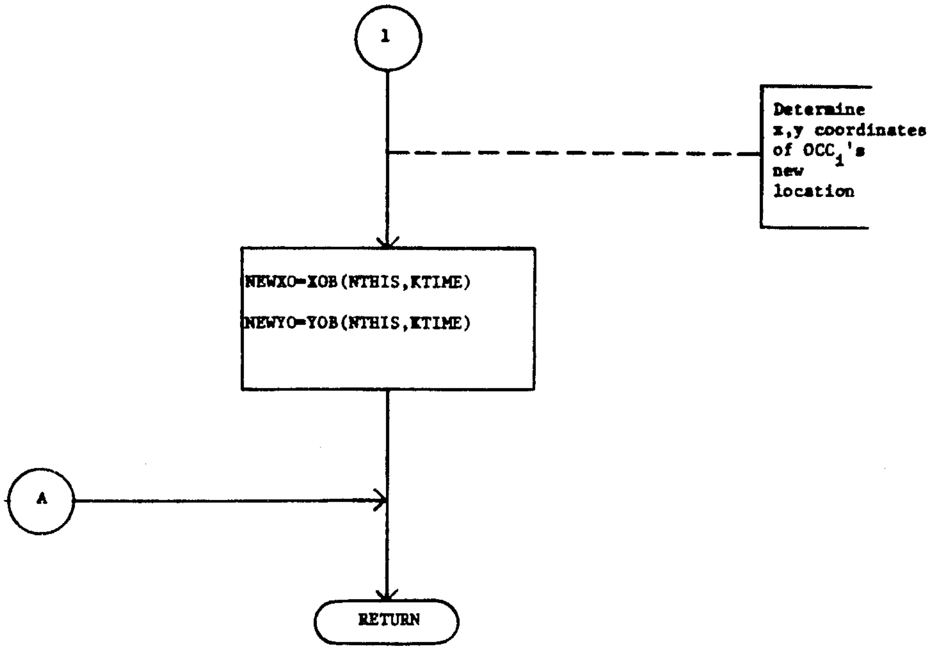
Loop Occupant

Purpose If a backtracking interruption is evoked by subroutine INTRPT, then BACKUP is called. BACKUP processes occupants who have entered into this mode by retracing their steps back toward their initial starting locations. Once an occupant has returned to his initial point, he is removed from the backtracking mode, and resumes the normal decisionmaking and goalseeking processes.

Formulas n/a



Subroutine BACKUP



Subroutine BACKUP

```
C
C
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C
C     SUBROUTINE BACKUP
C
C     THE PURPOSE OF BACKUP IS TO PROCESS OCCUPANTS THRUST INTO THE BACKTRACK
C     INTERRUPTION MODE.  BACKUP RETRACES THEIR STEPS BACK TOWARD THEIR INITIAL
C     STARTING LOCATIONS.  ONCE AT THIS LOCATION, OCCUPANTS REENTER THE NORMAL
C     GOAL-SEEKING MODE.
C
        SUBROUTINE BACKUP (IBACK,XO,YO,INITXO,INITYO,XOB,YOB,
       1   ITIME,NTHIS,NEWXO,NEWYO,INTR,JTIME)
        DIMENSION IBACK(20),INITXO(20),
       1   INITYO(20),JTIME(20),INTR(20)
        INTEGER XOB(20,100),YOB(20,100),XO(20),YO(20)
C     DETERMINE BACKTRACK STEP COUNT
        IF (IBACK(NTHIS).EQ.0) GO TO 1
C     DETERMINE WHETHER THE OCCUPANT HAS ATTAINED HIS BACKTRACK GOAL
        IF ((XO(NTHIS).EQ.INITXO(NTHIS)).AND.
       1   (YO(NTHIS).EQ.INITYO(NTHIS))) GO TO 3
1       IBACK(NTHIS)=IBACK(NTHIS)+1
C     DETERMINE THE NEXT BACKTRACK LOCATION
        IF (IBACK(NTHIS).EQ.1) GO TO 2
        JTIME(NTHIS)=JTIME(NTHIS)-1
        GO TO 4

2       IF (ITIME.GT.1) GO TO 21
        JTIME(NTHIS)=1
        GO TO 4
21       JTIME(NTHIS)=ITIME-1
4       KTIME=JTIME(NTHIS)
C     DETERMINE X,Y COORDINATES OF THE OCCUPANT'S NEW LOCATION
        NEWXO=XOB(NTHIS,KTIME)
        NEWYO=YOB(NTHIS,KTIME)
        RETURN
3       INTR(NTHIS)=0
        IBACK(NTHIS)=0
        RETURN
        END
```

<u>Routine</u> EQUALZ

<u>Loop</u> Occupant

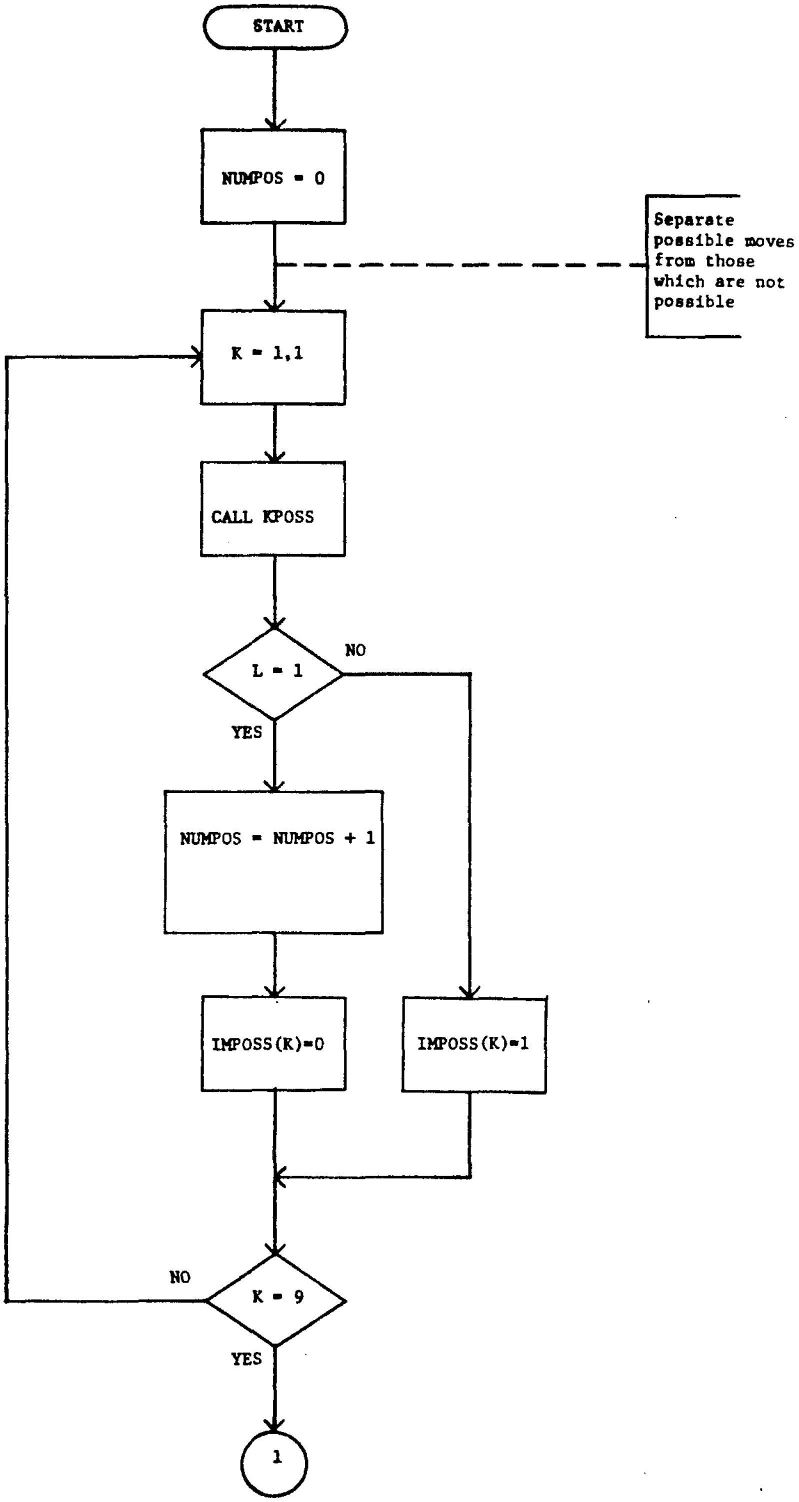
<u>Purpose</u> EQUALZ is one of the biasing routines available to subroutine ASSIGN. The function of EQUALZ is to satisfy the condition of <u>no bias</u>, that is, the situation in which the probability values of available move alternatives are equalized. An occupant enters a state of confusion whenever he is mobile and uninterrupted, makes a negative status evaluation, and is unable to discern an effective egress route. He will remain in this condition until he: (1) makes a positive safety status evaluation, or (2) learns of an effective route, or (3) decides to enter the backtracking interruption mode.

<u>Formulas</u> $P(K) = 1.0/NUMPOS$ (13)

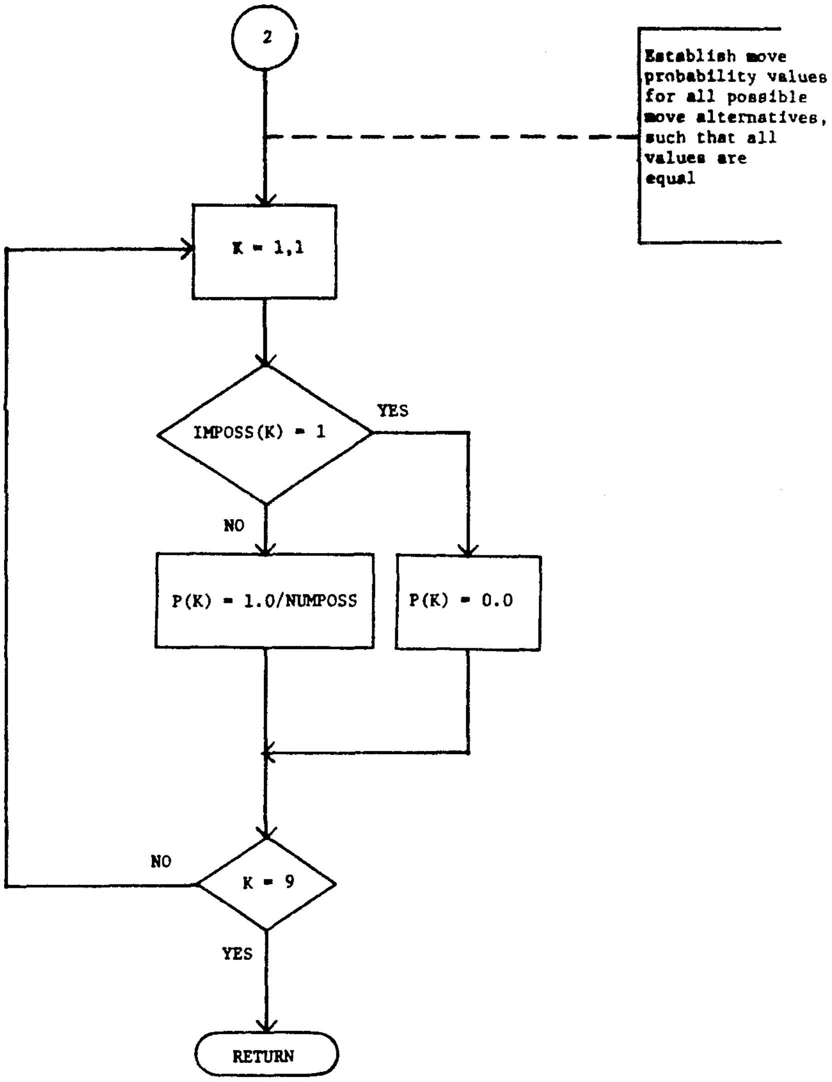
where:

$P(K)$ = the probability of selecting the kth move alternative;

$NUMPOS$ = the total number of possible alternatives available.



Subroutine EQUALZ



Subroutine EQUALZ

```
C
C
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C
C
C   SUBROUTINE EQUALZ
C
C   THE PURPOSE OF EQUALZ IS TO SATISFY THE CONDITION OF NO DECISION BIAS
C   (INDECISION), THAT IS, THE CONDITION UNDER WHICH THE PROBABILITY VALUES OF
C   AVAILABLE MOVE ALTERNATIVES ARE ALL EQUALIZED
C
      SUBROUTINE EQUALZ(ITIME,NTHIS,IHAND1,INT,IBYSTD,IEVAL,
     1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
      INTEGER XD(20),YD(20),XK,YK
      DIMENSION IMPOSS (9), P (9)
      NUMPOS=0
C   IDENTIFY ALL POSSIBLE MOVE ALTERNATIVES
      DO 1 K=1,9
      CALL KPOSS (ITIME,NTHIS,IHAND1,INT,IBYSTD,IEVAL,
     1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
      IF (L.EQ.1) GO TO 2
      GO TO 3
2     NUMPOS=NUMPOS+1
      IMPOSS(K)=0
      GO TO 1
3     IMPOSS(K)=1
1     CONTINUE
C   ESTABLISH MOVE PROBABILITY VALUES FOR ALL POSSIBLE MOVE ALTERNATIVES,
C   SUCH THAT ALL VALUES ARE EQUAL
      DO 4 K=1,9
      IF (IMPOSS(K).EQ.1) GO TO 5
      P(K)=1.0/FLOAT(NUMPOS)
      GO TO 4
5     P(K)=9.0
4     CONTINUE
      RETURN
      END
```

Routine TBIAS

Loop Occupant

Purpose Subroutine TBIAS effectuates "threat evasion" movement behavior. Whenever this biasing routine is assigned, it establishes move selection probabilities which "favor" moves maximizing the occupant's distance from the fire threat (threatened exit). TBIAS is assigned if the occupant: (1) is mobile and uninterrupted during the current time frame, (2) is operating under a positive status perception, (3) has no exit route in mind, and (4) knows the location of the threat.

Formulas

$$\mathrm{DIST}(K) = \mathrm{SQRT}((XT-XK)^2+(YT-YK)^2) \quad (14)$$

$$P(K) = \mathrm{DIST}(K)/\mathrm{TOTDST} \quad (15)$$

where:

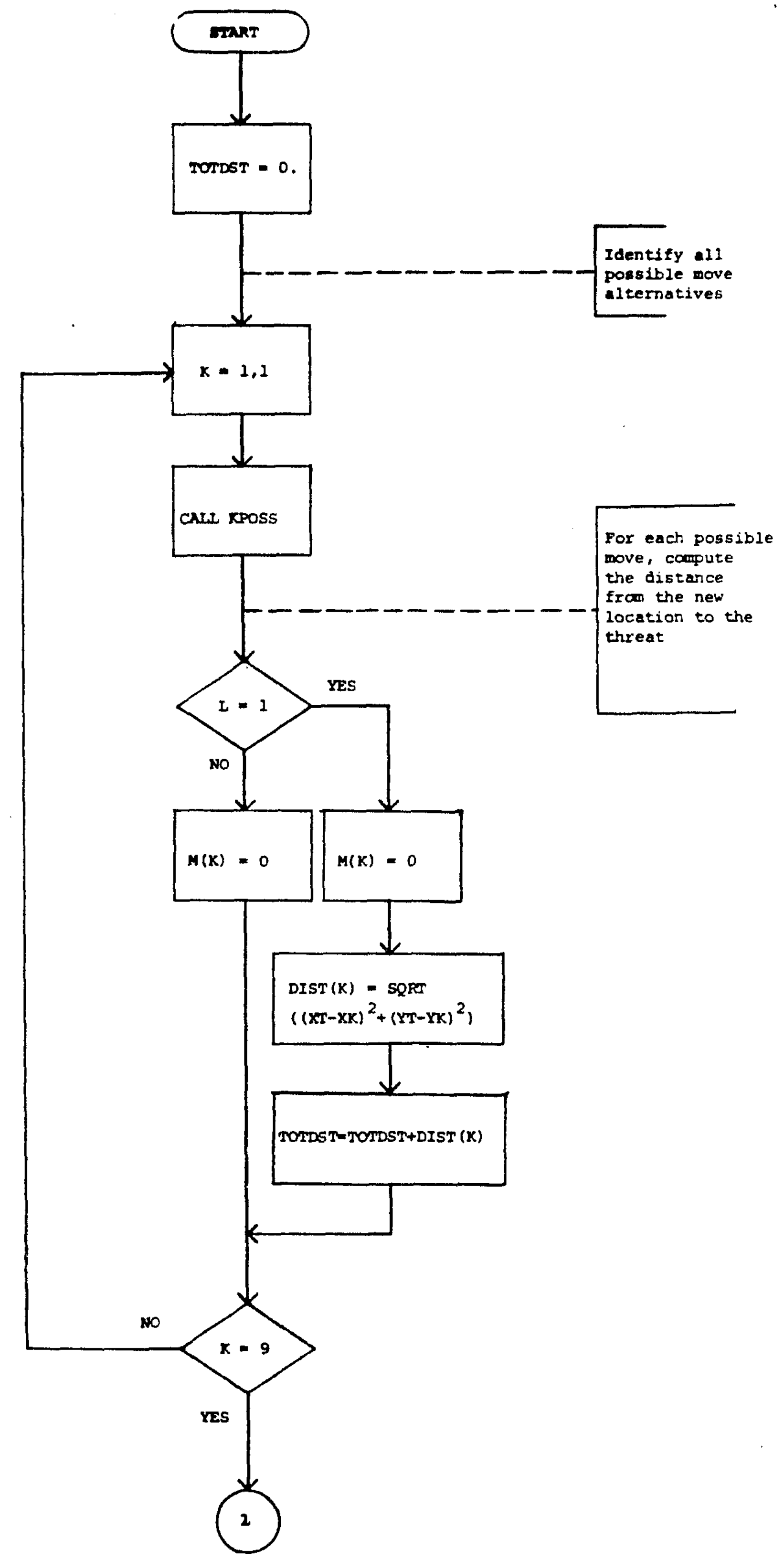
DIST(K) = linear distance between an alternative location and the threat location;

XT,YT = x,y coordinates of the threat location;

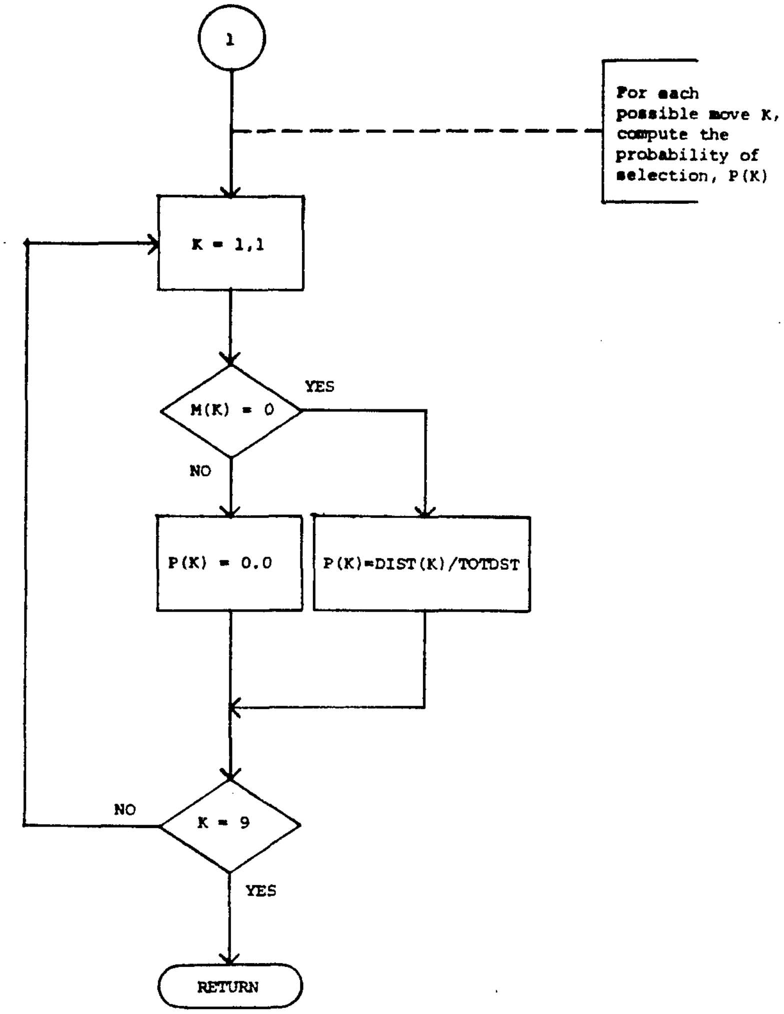
XK,YK = x,y coordinates of the kth alternative location;

P(K) = probability of selecting the kth alternative;

$$\mathrm{TOTDST} = \sum_{k=1}^{9} \mathrm{DIST}(K) \quad (16)$$



Subroutine TBIAS



Subroutine TBIAS

```
C
C
C
C
C
C     SUBROUTINE TBIAS
C
C     THE PURPOSE OF TBIAS IS TO EFFECTUATE 'THREAT EVASION' MOVEMENT BEHAVIOR.
C     WHENEVER TBIAS IS ASSIGNED, MOVE PROBABILITY VALUES ARE ESTABLISHED IN SUCH
C     A WAY AS TO 'FAVOR' MOVES WHICH MAXIMIZE THE OCCUPANT'S DISTANCE FROM
C     THREATENING STIMULI


C
        SUBROUTINE  TBIAS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       1  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
        INTEGER XD(20),YD(20),XT,YT,XK,YK
        DIMENSION M(9),DIST(9),P(9)
        TOTDST=0.
C     IDENTIFY ALL POSSIBLE MOVE ALTERNATIVES
        DO 10 K=1,9
        CALL KPOSS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
C     FOR EACH POSSIBLE MOVE, COMPUTE THE DISTANCE FROM THE NEW LOCATION TO THE
C     THREAT
        IF (L.EQ.1) GO TO 1
        M(K)=1
        GO TO 10
1       M(K)=0
        DIST(K)=SQRT(FLOAT((XT-XK)**2+(YT-YK)**2))
        TOTDST=TOTDST+DIST(K)
10      CONTINUE
C
C: FOR EACH POSSIBLE MOVE, COMPUTE THE MOVE-PROB., P(K):
C
C     FOR EACH POSSIBLE MOVE, COMPUTE THE PROBABILITY OF SELECTION, P(K)
        DO 15 K=1,9
        IF (M(K).EQ.0) GO TO 2
        P(K)=0.
        GO TO 15
2       P(K)=DIST(K)/TOTDST
15      CONTINUE
        RETURN
        END
```

Routine EBIAS

Loop Occupant

Purpose For all move alternatives available to an occupant at a given point in time, subroutine EBIAS weights move selection probabilities to favor moves which minimize the occupant's distance from an exit goal point. An occupant's decisionmaking strategy is routed through EBIAS if he: (1) is mobile and uninterrupted during the current time frame, (2) is operating under a positive status perception, and (3) has a specific egress routine in mind.

Formulas

$$\text{DIST(K)} = \text{SQRT((IGOALX-XK)}^2\text{+(IGOALY-YK)}^2\text{)} \qquad (17)$$

$$\text{P(K)} = \text{A(K)/SUMA} \qquad (18)$$

$$\text{A(K)} = \text{TOTDST/DIST(K)} \qquad (19)$$

$$\text{P(K)}^* = \text{1.0/ZERO} \qquad (20)$$

where:

DIST(K) = linear distance from new location designated by k, to the agreed-upon exit from space i;

IGOALX, IGOALY = x,y coordinates of the agreed-upon exit from space i;

XK,YK = x,y coordinates of the spatial location denoted by k;

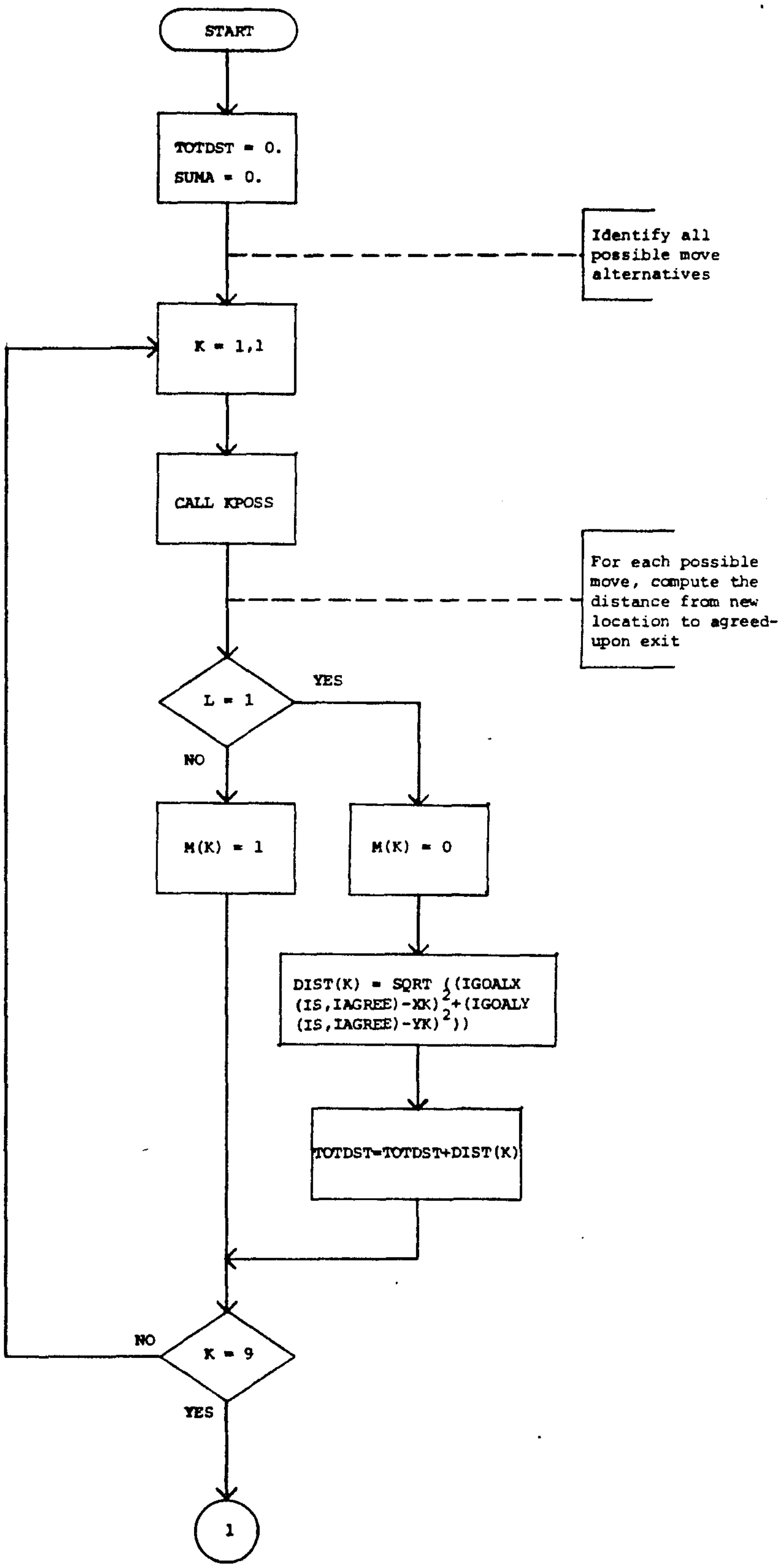
P(K) = the probability of selecting the kth move alternative, under the condition that not more than one alternative leads directly through an exit from space i, durint t;

$$\mathrm{TOTST} = \sum_{k=1}^{9} \mathrm{DIST}(K) \tag{21}$$

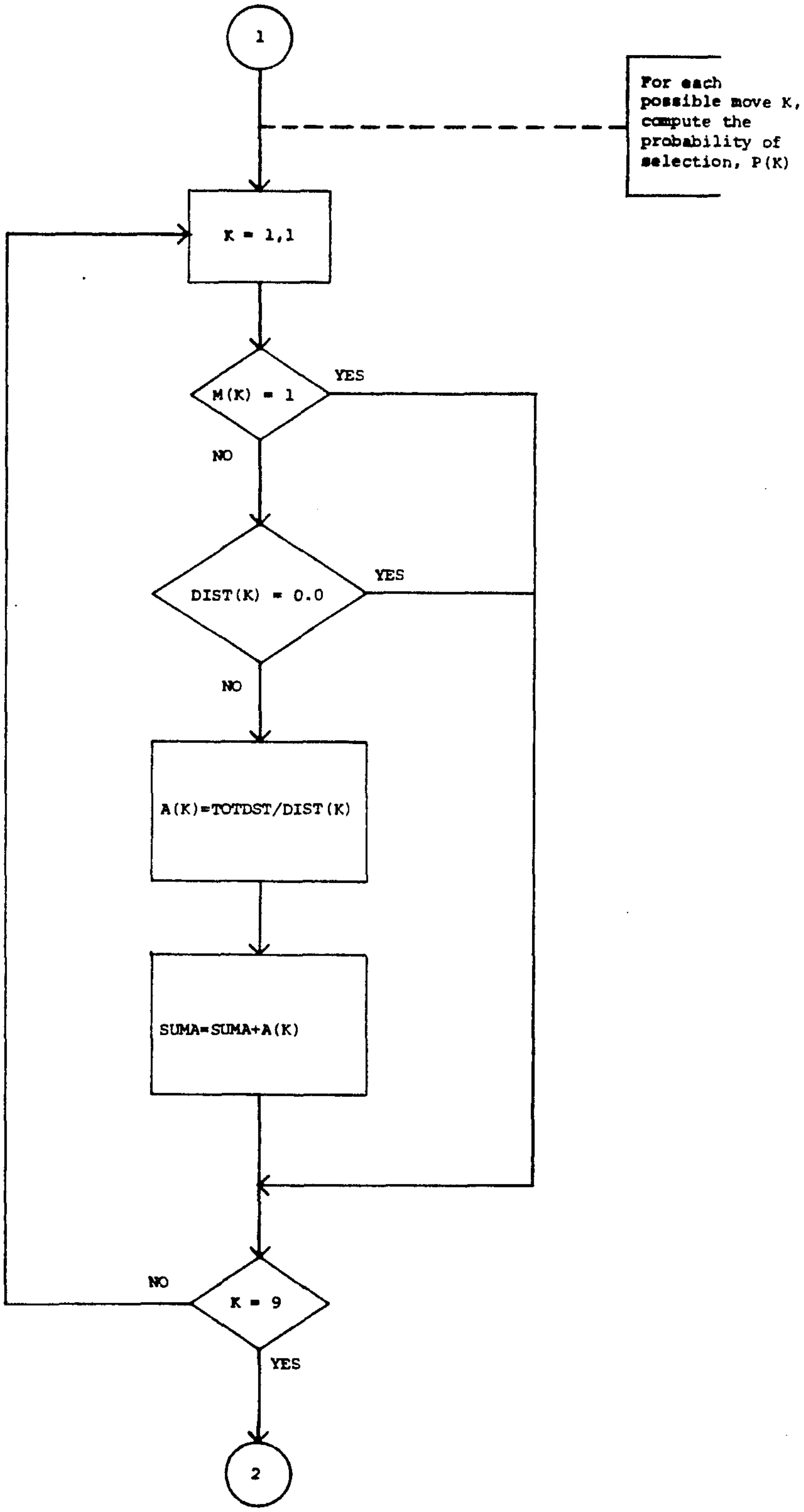
$$\mathrm{SUMA} = \sum_{k=1}^{9} A(K) \tag{22}$$

P(K)* = the probability of selecting an alternative which leads directly through an exit from space i, only under the condition that more than one alternative leads through such an exit;

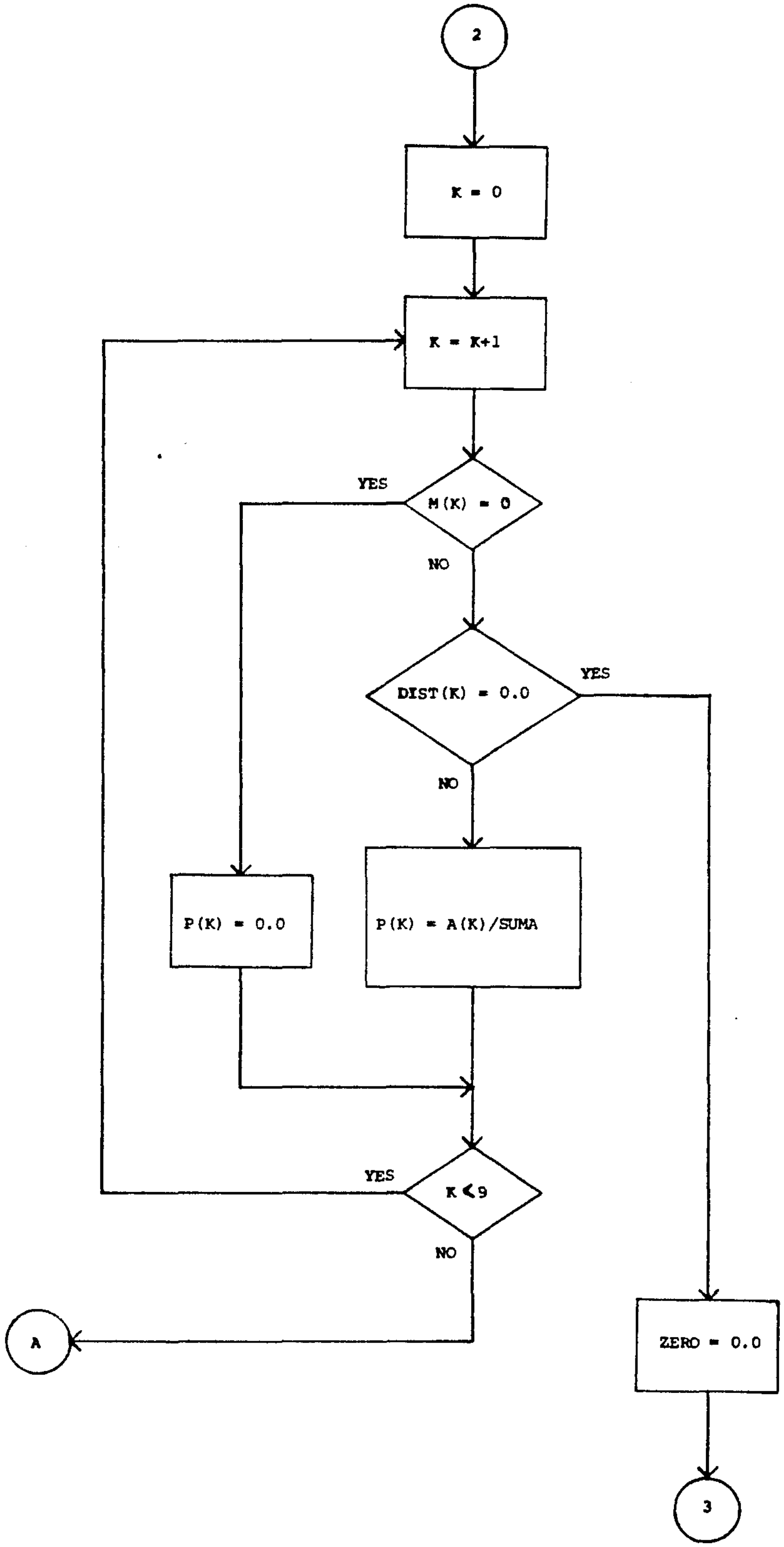
ZERO = the total number of alternatives leading directly through an exit from space i, during t.



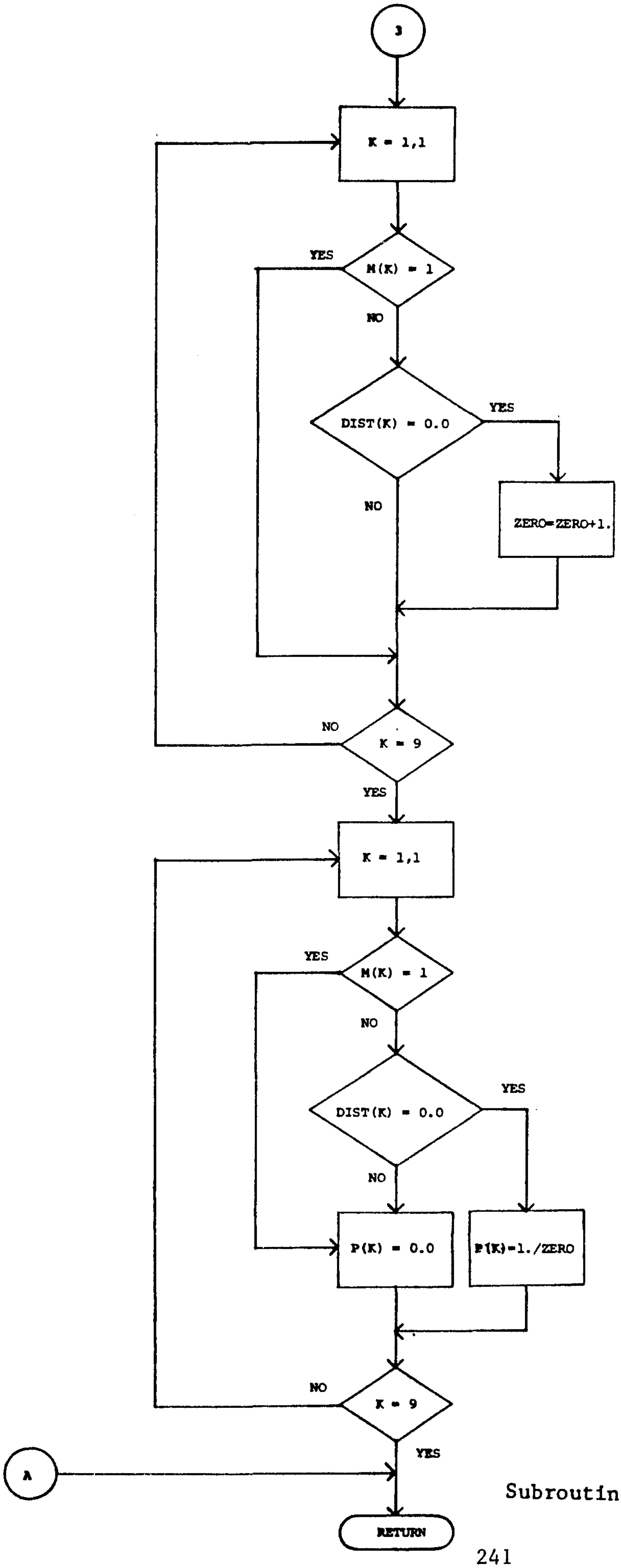
Subroutine EBIAS



Subroutine EBIAS



Subroutine EBIAS



Subroutine EBIAS

```
C
C
C
C
C
C    SUBROUTINE EBIAS
C
C    THE PURPOSE OF EBIAS IS TO EFFECTUATE GOAL SEEKING MOVEMENT BEHAVIOR.
C    EBIAS WEIGHTS MOVE SELECTION PROBABILITIES TO 'FAVOR' MOVES WHICH
C    MINIMIZE THE OCCUPANT'S DISTANCE TO AN EXIT GOAL
C
      SUBROUTINE EBIAS(ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
      INTEGER XO(20),YO(20),XE(10),YE(10),XK,YK
      DIMENSION M(9),DIST(9),A(9),P(9)
      DIMENSION IGOALX(20,10),IGOALY(20,10)
      TOTDST=0.
      SUMA=0.
C    IDENTIFY ALL POSSIBLE MOVE ALTERNATIVES
      DO 10 K=1,9


      CALL KPOSS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
C    FOR EACH POSSIBLE MOVE, COMPUTE THE DISTANCE FROM THE NEW LOCATION TO THE
C    AGREED-UPON-EXIT
      IF (L.EQ.1) GO TO 1
      M(K)=1
      GO TO 10
1     M(K)=0
      DIST(K)=SQRT(FLOAT((IGOALX(IS,IAGREE)-XK)**2+
     1    (IGOALY(IS,IAGREE)-YK)**2))
      TOTDST=TOTDST+DIST(K)
10    CONTINUE
C    FOR EACH POSSIBLE MOVE, COMPUTE THE PROBABILITY OF SELECTION, P(K)
      DO 15 K=1,9
      IF (M(K).EQ.1) GO TO 15
      IF (DIST(K).EQ.0.) GO TO 15
      A(K)=TOTDST/DIST(K)
      SUMA=SUMA+A(K)
15    CONTINUE
C
      K=0
2     K=K+1
      IF (M(K).EQ.1) GO TO 3
      IF (DIST(K).EQ.0.) GO TO 5
      P(K)=A(K)/SUMA
      GO TO 4
3     P(K)=0.
4     IF (K.LT.9) GO TO 2
      RETURN
5     ZERO=0.
      DO 20 K=1,9
      IF(M(K).EQ.1) GO TO 20
      IF (DIST (K).EQ.0.) GO TO 6
      GO TO 20
6     ZERO=ZERO+1.
20    CONTINUE
      DO 25 K=1,9
      IF (M(K).EQ.1) GO TO 707
      IF (DIST(K).EQ.0.) GO TO 7
707   P(K)=0.0
      GO TO 25
7     P(K)=1./ZERO
25    CONTINUE
      RETURN
      END
```

Routines DOORS1 and DOORS2

Loop Occupant

Purpose As part of its move selection function, subroutine ASSIGN controls the manipulation of doors by occupants. For example, when an individual encounters a closed door, there is some probability that he will open it, and some chance that he will not. If he chooses not to open the door, the through-door move alternative is deleted, and the probability values of remaining alternatives are adjusted so as to maintain a sum of unity. This function is controlled by subroutine DOORS1. Moreover, if the occupant indeed passes through an open door, he may or may not close it behind him. Subroutine DOORS2 controls this behavior.

Formulas

$$SUM = SUM+P(K) \tag{23}$$

$$DIFF = 1.0-SUM \tag{24}$$

$$SHARE = DIFF/NPOSS \tag{25}$$

$$P(K)^* = P(K)+SHARE \tag{26}$$

where:

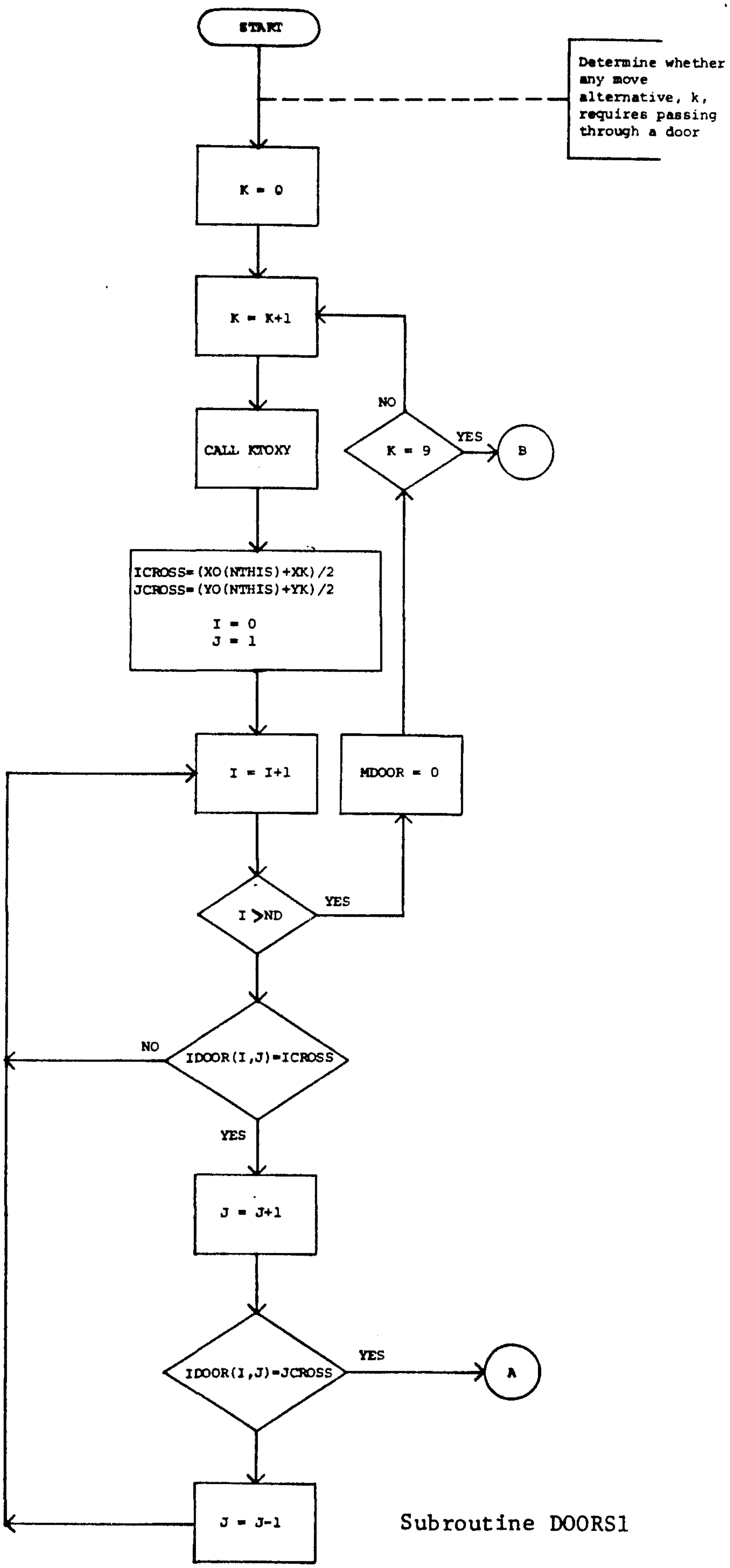
SUM = cumulative sum of probability values for all k vectors;

P(K) = likelihood of selecting move k;

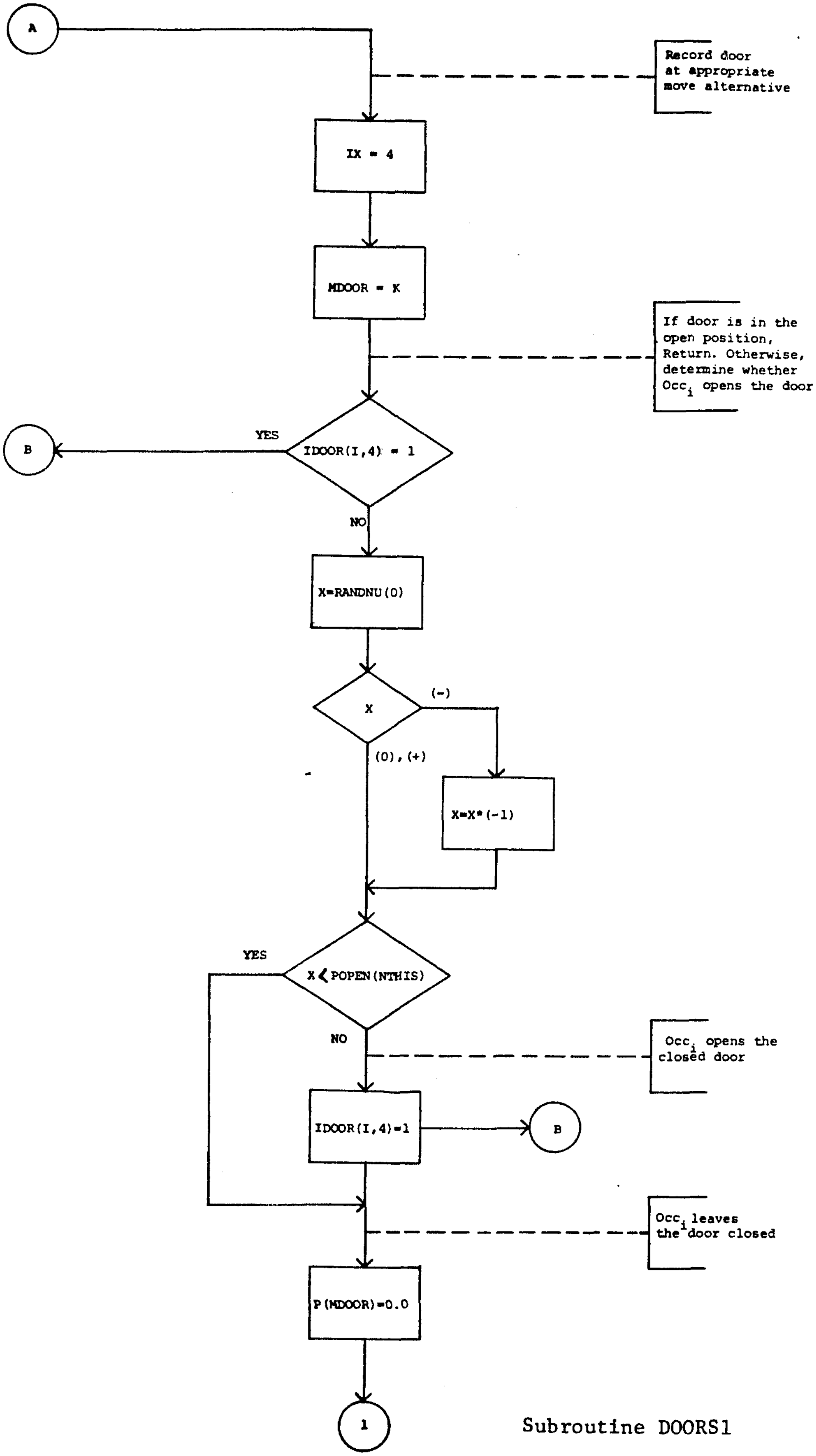
SHARE = proportion of cumulative probability which must be redistributed under the condition that the through-door alternative has been deleted;

NPOSS = total number of possible moves available during t;

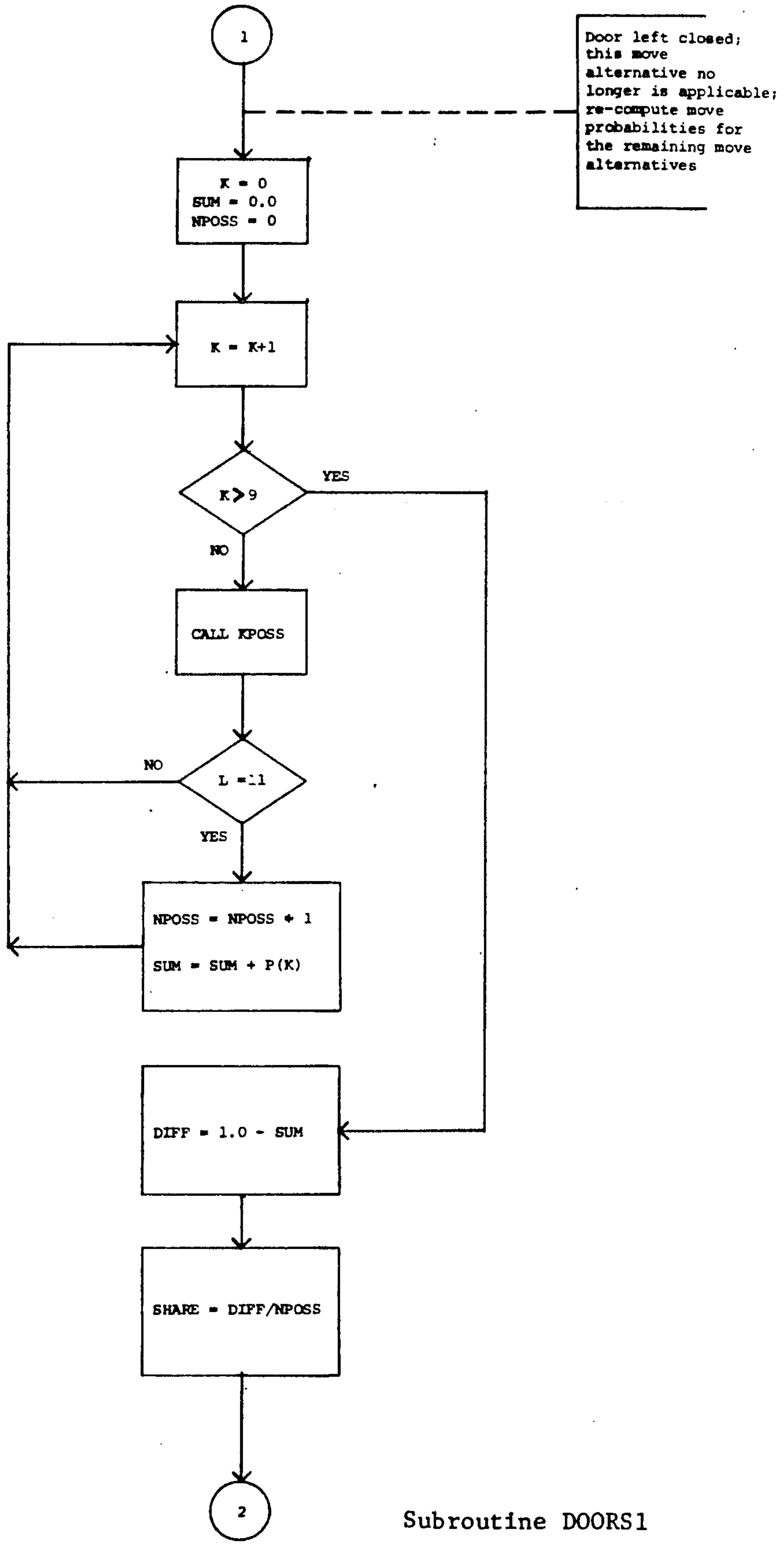
P(K)* = new value of P(K), after cumulative probability has been redistributed.



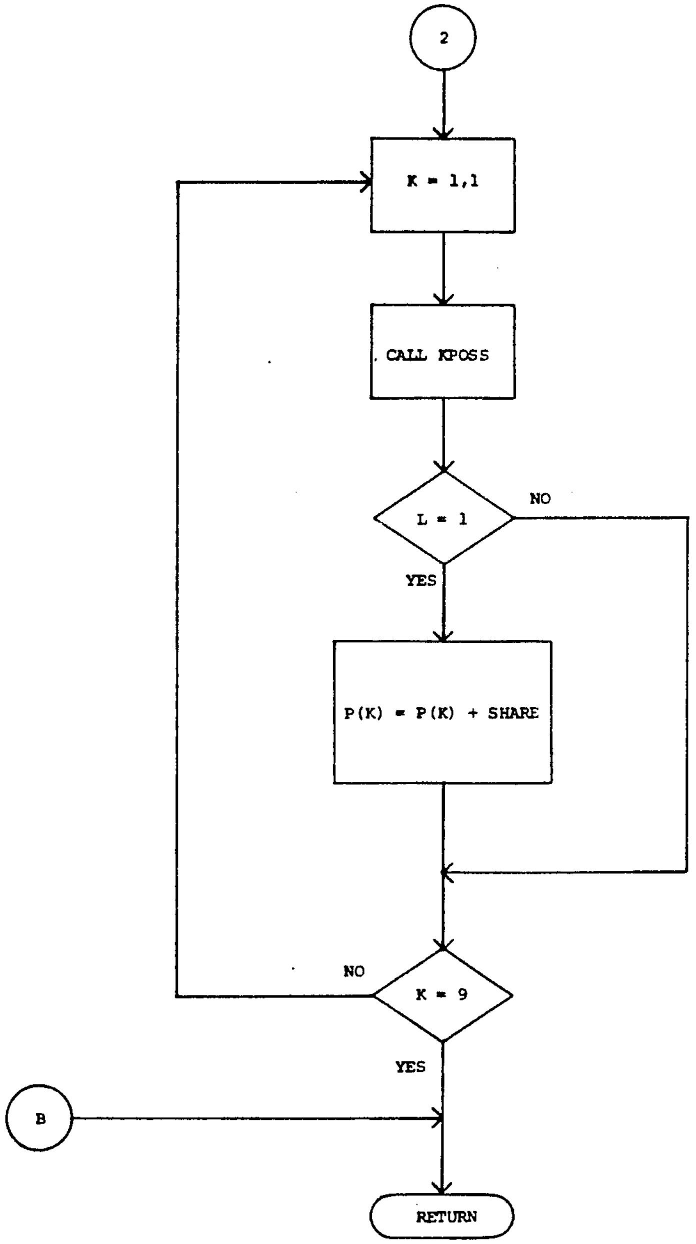
Subroutine DOORS1



Subroutine DOORS1



Subroutine DOORS1

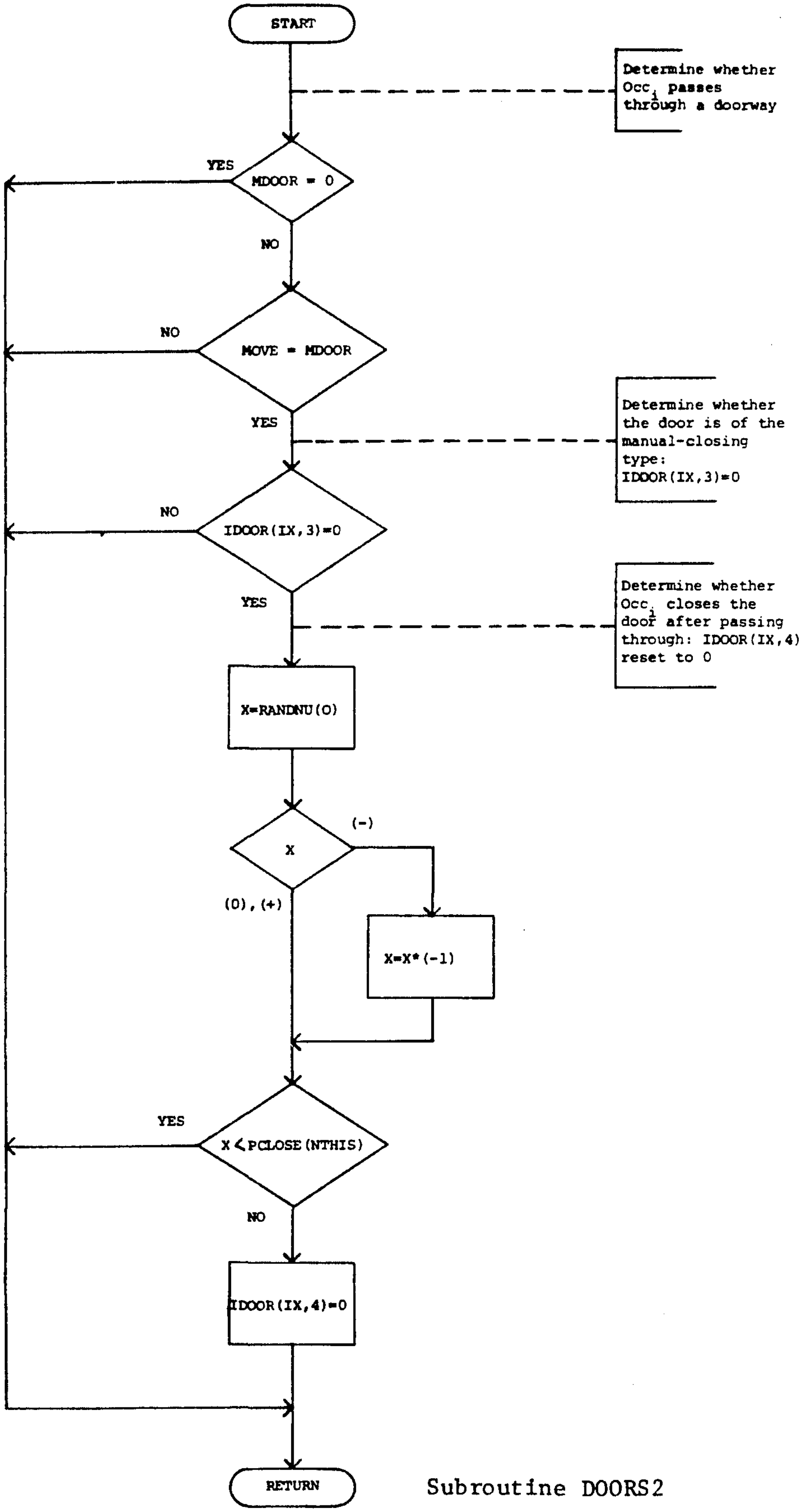


Subroutine DOORS1

```
C
C
C
C
C
C     SUBROUTINE DOORS1
C
C     THE PURPOSE OF DOORS1 IS TO DETERMINE WHETHER THE OCCUPANT WILL OPEN A
C     CLOSED DOOR WHICH IS ALONG AN ALTERNATIVE MOVEMENT PATH AVAILABLE TO HIM...


C     OPENING THE DOOR DOES NOT GUARANTEE THAT THE OCCUPANT WILL PASS THROUGH IT
C     ...IF HE DECIDES TO LEAVE THE DOOR CLOSED, HOWEVER, THE THRU-DOOR MOVE
C     ALTERNATIVE WILL BE CANCELED, AND THE MOVE PROBABILITIES WILL BE
C     RECOMPUTED
C
        SUBROUTINE DOORS1 (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
       3   X,IDOOR,POPEN,ND,MDOOR,PCLOSE,IX)
        DIMENSION P(9),IDOOR(30,4),POPEN(20)
        INTEGER XD(20),YD(20),XK,YK,TOTBAR
C     DETERMINE WHETHER ANY MOVE ALTERNATIVE REQUIRES PASSING THROUGH A DOOR
        K=0
5       K=K+1
6        CALL KTOXY (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K)
        ICROSS=(XD(NTHIS)+XK)/2
        JCROSS=(YD(NTHIS)+YK)/2
        I=0
        J=0
        J=1
3       I=I+1
        IF (I.GT.ND) GO TO 1
        IF (IDOOR(I,J).EQ.ICROSS) GO TO 2
        GO TO 3
2       J=J+1
        IF (IDOOR(I,J).EQ.JCROSS) GO TO 4
        J=J-1
        GO TO 3
1       MDOOR=0
        IF (K.EQ.9) GO TO 999
        GO TO 5
C     RECORD DOOR AT APPROPRIATE MOVE ALTERNATIVE
4       IX=I
        MDOOR=K
C     IF DOOR IS IN THE OPEN POSITION (IDOOR(I,4)=1)), RETURN...OTHERWISE,
C     DETERMINE WHETHER THE OCCUPANT OPENS THE DOOR
        IF (IDOOR(I,4).EQ.1) GO TO 999
        CALL RANDOM (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,X)
        IF (X) 55,56,56
55      X=X*(-1)
56      IF (X.LT.POPEN(NTHIS)) GO TO 6
C     THE OCCUPANT OPENS THE DOOR
        IDOOR(I,4)=1
        RETURN
        GO TO 999
C     THE OCCUPANT LEAVES THE DOOR CLOSED
6       P(MDOOR)=0.0
C     THE DOOR HAS BEEN LEFT CLOSED...THIS MOVE ALTERNATIVE IS NO LONGER
C     APPLICABLE...RECOMPUTE MOVE PROBABILITIES FOR THE REMAINING MOVE
C     ALTERNATIVES


        K=0
        SUM=0.0
        NPOSS=0
7       K=K+1
        IF (K.GT.9) GO TO 9
        CALL KPOSS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
        IF (L.EQ.1) GO TO 8
        GO TO 7
8       NPOSS=NPOSS+1
        SUM=SUM+P(K)
        GO TO 7
9       DIFF=1.0-SUM
        SHARE=DIFF/FLOAT(NPOSS)
        DO 25 K=1,9
        CALL KPOSS (ITIME,NTHIS,IHANDI,INT,IBYSTD, IEVAL,
       1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
        IF (L.EQ.1) GO TO 10
        GO TO 25
10      P(K)=P(K)+SHARE
25      CONTINUE
999     RETURN
        END
```



Subroutine DOORS2

```
C
C
C
C
C
C     SUBROUTINE DOORS2
C
C     THE PURPOSE OF DOORS2 IS TO DETERMINE WHETHER THE OCCUPANT CLOSES A DOOR
C     BEHIND HIM, ONCE HE HAS PASSED THROUGH (ONLY APPLICABLE FOR THE CASE OF
C     MANUALLY-OPERATED DOORS)
C
        SUBROUTINE DOORS2 (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
       3   X,IDOOR,POPEN,ND,MDOOR,PCLOSE,IXO
        DIMENSION IDOOR(30,4),PCLOSE(20)
        IF (MDOOR.EQ.0) GO TO 999
        IF (MOVE.EQ.MDOOR) GO TO 1
        GO TO 999
C     DETERMINE WHETHER THE DOOR IS OF THE MANUALLY-OPERATING TYPE, I.E.,
C     IDOOR(IX,3)=0
1       IF (IDOOR(IX,3).EQ.0) GO TO 2
        GO TO 999
C     DETERMINE WHETHER THE OCCUPANT CLOSES THE DOOR AFTER PASSING THROUGH,
C     IN WHICH CASE, IDOOR(IX,4) IS RESET TO 0, DENOTING THE CLOSED POSITION
2       CALL RANDOM (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
       1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
       2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,
       3   IENTER,XO

        IF (X) 55,56,56
55      X=X*(-1)
56      IF (X.LT.PCLOSE(NTHIS)) GO TO 999
        IDOOR(IX,4)=0
999     RETURN
        END
```

Routines EVAL8 and EVAL20

Loop Occupant

Purpose The direction of move probability biasing frequently depends upon an occupant's current evaluation of his own safety status (his spatial location with respect to those of the exit goal and the threat). Evaluations may be positive or negative: a positive evaluation results whenever an occupant perceives his status to have improved between time t-1 and time t. BFIRES provides two user-called options for the evaluation of safety status: EVAL8 and EVAL20.

EVAL8 constructs evaluations purely on the basis of straight-line distance measurements between an occupant's current location and those of threats and exits. A positive evaluation results whenever the occupant's perceived status at time t is better than at time t-1 (i.e., he is nearer to an exit goal, and/or farther from the treat).

EVAL20, on the other hand, evaluates egress progress relative to the total elapsed time an occupant has spent in the threatening environment. A move in a seemingly threatening direction may not be perceived as negative, if the occupant thinks (on the whole) he still has ample time left to escape safely.

Formulas EVAL8:

$$\text{TDIST} = \text{SQRT}((\text{XO}-\text{XT})^2+(\text{YO}-\text{YT})^2) \qquad (27)$$

$$\text{PTDIST} = \text{TDIST} \qquad (28)$$

$$TCHANG = TDIST-PTDIST \quad (29)$$

$$EDIST = SQRT((XO-IGOALX)^2+(YO-IGOALY)^2) \quad (30)$$

$$PEDIST = EDIST \quad (31)$$

$$ECHANG = EDIST-PEDIST \quad (32)$$

where:

TDIST = distance between occupant n and the threat at t;

XO,YO = x,y coordinates of occupant n's current location;

XT,YT = x,y coordinates of the threat location;

PTDIST = distance between occupant n and the threat at t-1;

TCHANG = change in distance between occupant n and the threat, between time frames t-1 and t;

EDIST = distance between occupant n and the agreed-upon exit from space i;

IGOALX,IGOALY = x,y coordinates of the agreed-upon exit from space i;

PEDIST = the distance between occupant n and the agreed-upon exit, at t-1;

ECHANG = change in distance between occupant n and the agreed-upon exit from space i, between time frames t-1 and t.

Formulas EVAL20:

$$TEST = SQRT((XO-XE)^2+(YO-YE)^2) \quad (33)$$

$$TDIST = TTIME-TIME \quad (34)$$

$$TDIST^{*} = TTIME-MXTIME \tag{35}$$

$$QDIST = SQRT((XO-XT)^{2}+(YO-YT)^{2}) \tag{36}$$

$$TDIST^{**} = TIME \tag{37}$$

where:

TEST = distance between occupant n's current location and the agreed-upon exit from the floor;

XO,YO = x,y coordinates of occupant n's current location;

XE,YE = x,y coordinates of agreed-upon exit from the floor;

TDIST = time distance factor with respect to the exit location, under the condition that the elapsed time is greater than the critical time;

TTIME = total number of time frames in the event;

TIME = elapsed time;

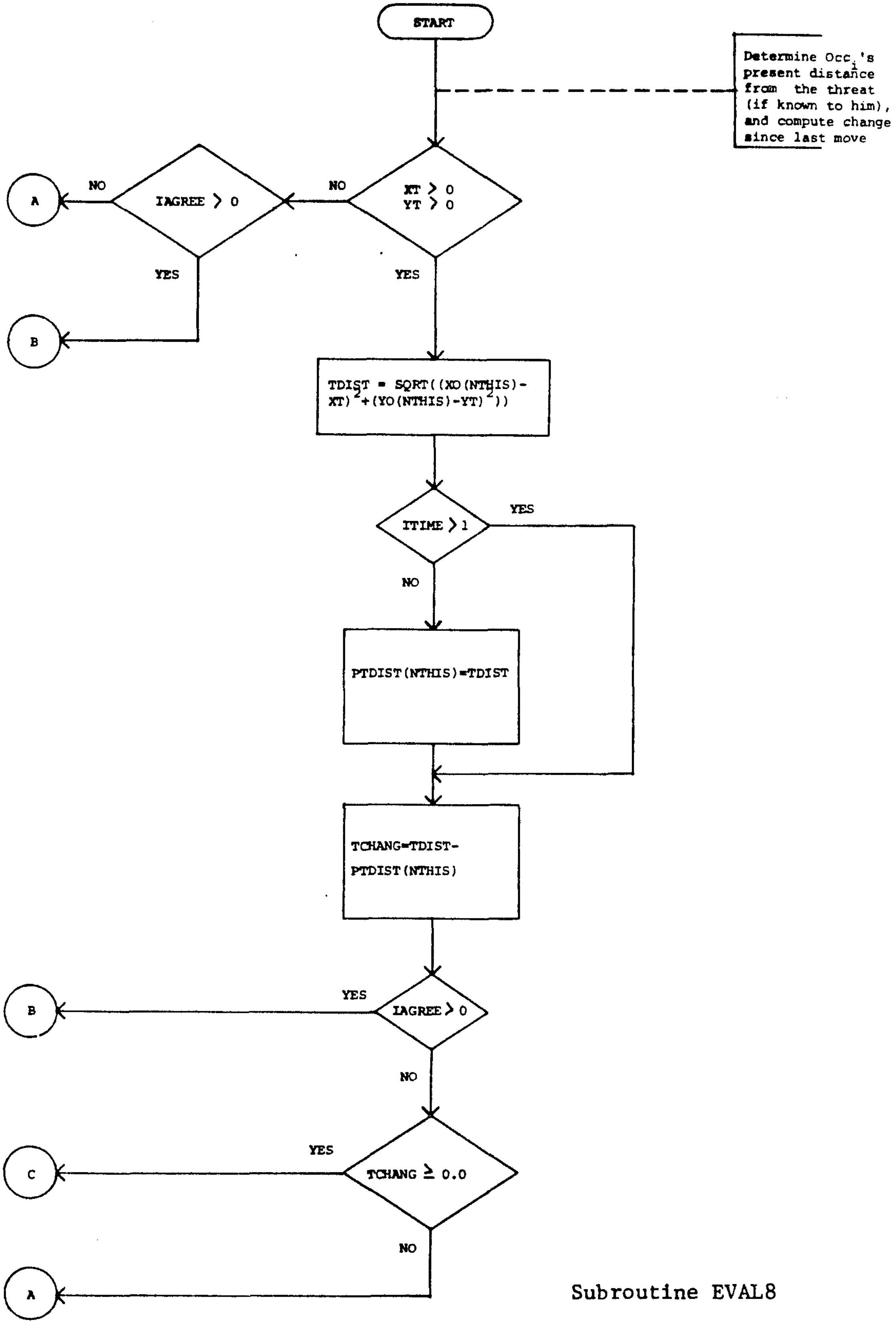
TDIST* = time distance factor with respect to the exit location under the condition that the elapsed time is less than the critical time;

MXTIME = critical time;

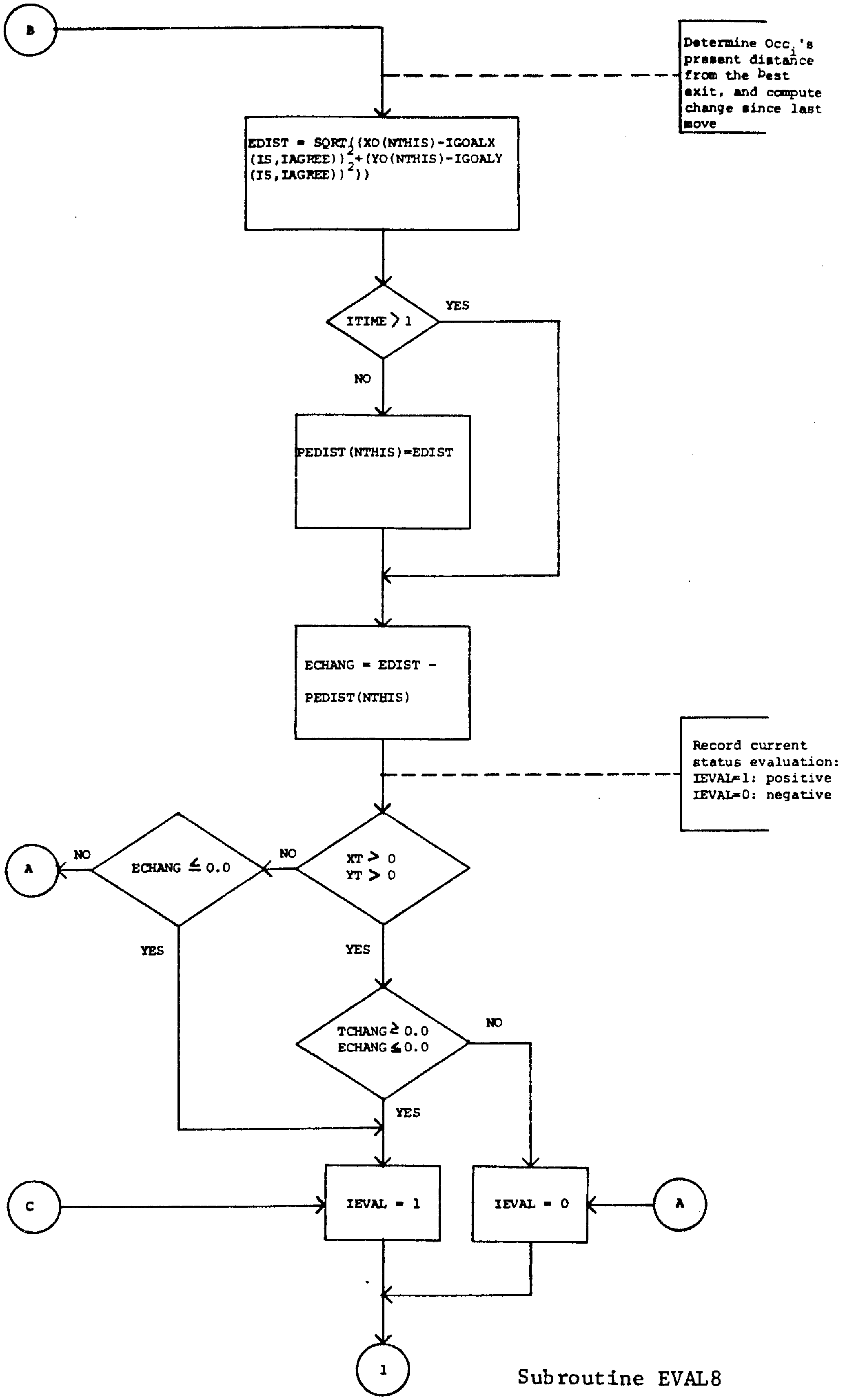
QDIST = distance between occupant n's current location and the threat location;

XT,YT = x,y coordinates of the threat location;

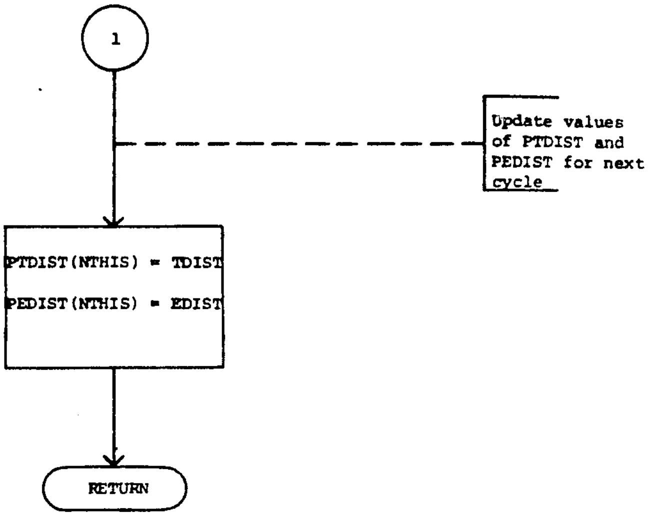
TDIST** = time distance factor with respect to the threat location, under the condition that the elapsed time is less than the critical time.



Subroutine EVAL8



Subroutine EVAL8

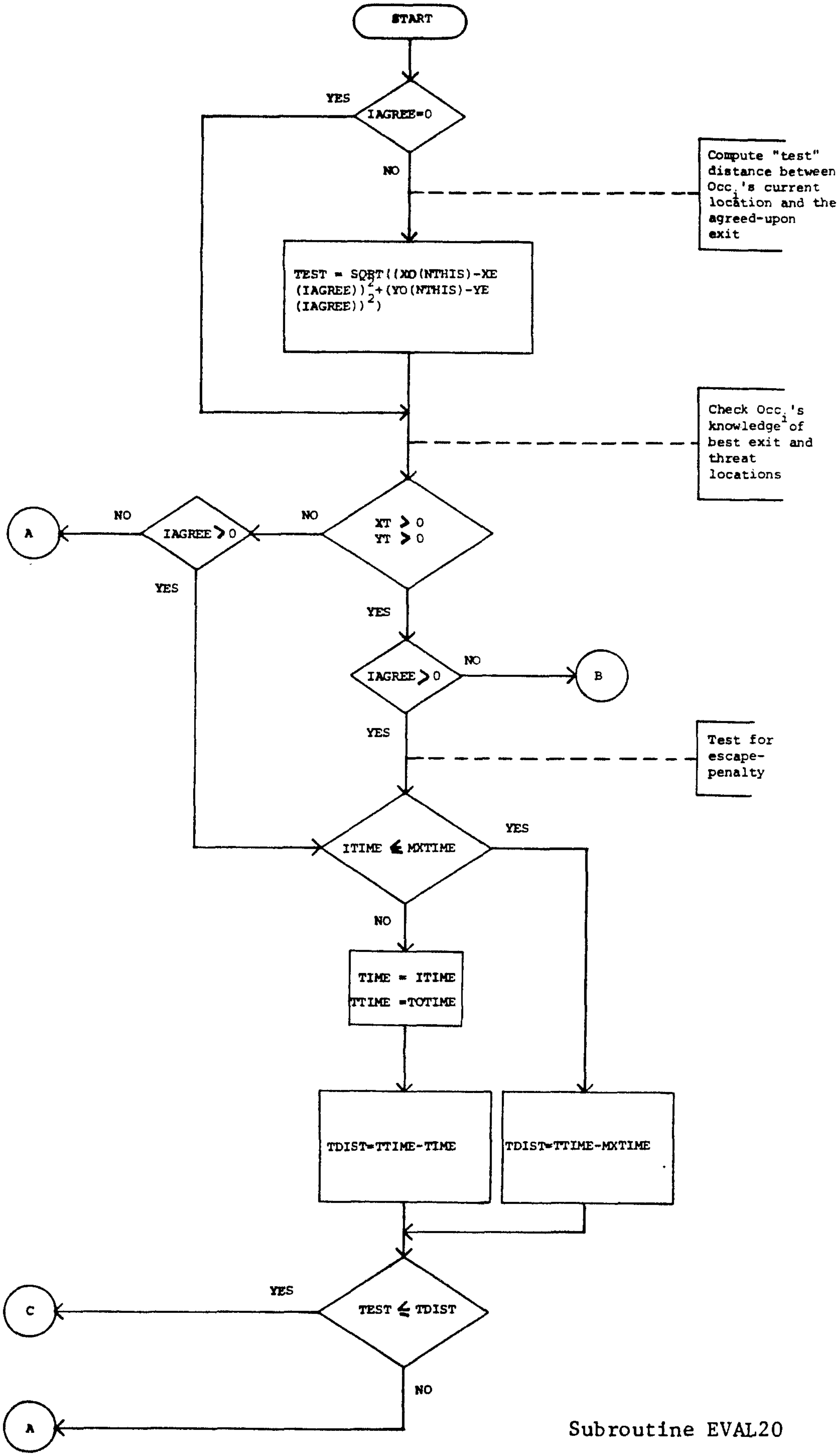


Subroutine EVAL8

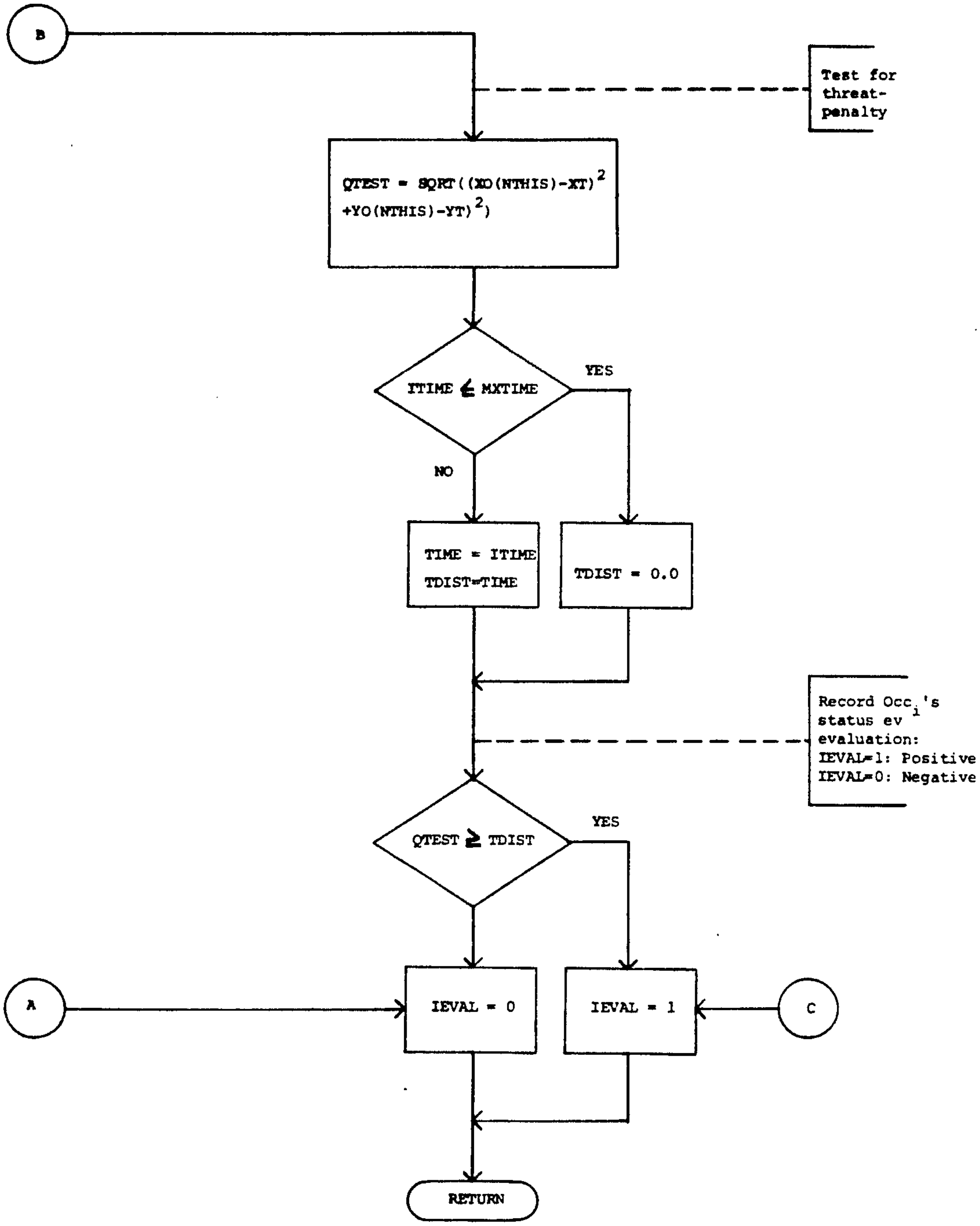
```
C
C
C
C
C
C    SUBROUTINE EVAL0
C



C    THE PURPOSE OF EVAL0 IS TO ENABLE THE OCCUPANT TO PROCESS DISTANCE
C    INFORMATION, AND THEREBY DETERMINE HIS CURRENT  'SAFETY STATUS'...EVAL0
C    CONDUCTS STATUS EVALUATIONS PURELY ON THE BASIS OF STRAIGHT-LINE DISTANCE
C    MEASUREMENTS BETWEEN THE OCCUPANT'S CURRENT LOCATION, AND THE LOCATIONS OF
C    THREATS AND EXITS...A POSITIVE STATUS EVALUATION RESULTS WHENEVER THE
C    OCCUPANT'S PERCEIVED STATUS AT TIME T IS 'BETTER' THAN IT WAS AT TIME T-1...
C    OTHERWISE, HIS EVALUATION IS NEGATIVE
C
      SUBROUTINE EVAL0 (XO,YO,XT,YT,XE,YE,NTHIS,
     1   IAGREE,ITIME,IEVAL,PTDIST,TDIST,PEDIST,
     1   EDIST,IS,IGOALX,IGOALY)
      INTEGER XO(20),YO(20),XE(10),YE(10),XT,YT
      DIMENSION PTDIST(20),IGOALX(20,10),IGOALY(20,10)
      DIMENSION PEDIST(20)
C    DETERMINE THE OCCUPANT'S PRESENT DISTANCE FROM THE THREAT (IF KNOWN TO HIM),
C    AND COMPUTE CHANGE SINCE LAST MOVE
      IF ((XT.GT.0).AND.(YT.GT.0)) GO TO 1
      IF (IAGREE.GT.0) GO TO 2
      GO TO 6
1     TDIST=SQRT(FLOAT((XO(NTHIS)-XT)**2+
     1   (YO(NTHIS)-YT)**2))
      IF (ITIME.GT.1) GO TO 50
      PTDIST(NTHIS)=TDIST
50    TCHANG=TDIST-PTDIST(NTHIS)
      IF (IAGREE.GT.0) GO TO 2
      IF (TCHANG.GE.0.) GO TO 5
      GO TO 6
C    DETERMINE THE OCCUPANT'S PRESENT DISTANCE FROM THE BEST EXIT, AND COMPUTE
C    CHANGE SINCE LAST MOVE
2     EDIST=SQRT(FLOAT((XO(NTHIS)-IGOALX(IS,IAGREE))**2
     1   +(YO(NTHIS)-IGOALY(IS,IAGREE))**2))
      IF (ITIME.GT.1) GO TO 55
      PEDIST(NTHIS)=EDIST
55    ECHANG=EDIST-PEDIST(NTHIS)
C    RECORD CURRENT STATUS EVALUATION, IEVAL=1 (POSITIVE), IEVAL=0 (NEGATIVE)
      IF ((XT.GT.0).AND.(YT.GT.0)) GO TO 3
      IF (ECHANG.LE.0.) GO TO 5
      GO TO 6
3     IF ((TCHANG.GE.0.).AND.(ECHANG.LE.0.)) GO TO 5
      GO TO 6
5     IEVAL=1
      GO TO 7
6     IEVAL=0
C    UPDATE VALUES OF PTDIST AND PEDIST FOR THE NEXT CYCLE
7     PTDIST(NTHIS)=TDIST
      PEDIST(NTHIS)=EDIST
      RETURN
      END
```



Subroutine EVAL20



Subroutine EVAL20

```
C
C
C
C
C
C   SUBROUTINE EVAL20


C
C   THE PURPOSE OF EVAL20 IS TO ENABLE THE OCCUPANT TO EVALUATE HIS
C   'SAFETY STATUS' BY COMPARING EGRESS PROGRESS AGAINST TOTAL ELAPSED TIME
C   SPENT IN THE DANGER ZONE
C
      SUBROUTINE EVAL20 (MXTIME,MK,XD,YD,XE,YE,NTHIS,IAGREE,
     1   ITIME,C,IEVAL,TDTIME)
      INTEGER XD(20),YD(20),XE(10),YE(10),XT,YT,TDTIME
      IF (IAGREE.EQ.0) GO TO 5
C   COMPUTE TEST DISTANCE BETWEEN THE OCCUPANT'S CURRENT LOCATION AND THE
C   AGREED-UPON EXIT
      TEST=SQRT(FLOAT((XD(NTHIS)-XE(IAGREE))**2+
     1   (YD(NTHIS)-YE(IAGREE))**2))
5     CONTINUE
C   CHECK THE OCCUPANT'S KNOWLEDGE OF BEST EXIT AND THREAT LOCATIONS
      IF ((XT.GT.0).AND.(YT.GT.0)) GO TO 10
      IF (IAGREE.GT.0) GO TO 20
      GO TO 50
10    IF (IAGREE.GT.0) GO TO 20
      GO TO 30
C   TEST FOR ESCAPE PENALTY
20    IF (ITIME.LE.MXTIME) GO TO 21
      TIME=ITIME
      TTIME=TDTIME
      TDIST=TTIME-TIME
      GO TO 22
21    TDIST=TTIME-(FLOAT(MXTIME))
22    IF (TEST.LE.TDIST) GO TO 51
      GO TO 50
C   TEST FOR THREAT PENALTY
30    QTEST=SQRT(FLOAT((XD(NTHIS)-XT)**2+
     1   (YD(NTHIS)-YT)**2))
      IF (ITIME.LE.MXTIME) GO TO 31
      TIME=ITIME
      TDIST=TIME
      GO TO 32
31    TDIST=0.0
C   RECORD THE OCCUPANT'S STATUS EVALUATION, IEVAL=1 (POSITIVE), IEVAL=0
C   (NEGATIVE)
32    IF (QTEST.GE.TDIST) GO TO 51
50    IEVAL=0
      RETURN
51    IEVAL=1
      RETURN
      END
```

Routine ASSIGN

Loop Occupant

Purpose BFIRES assumes that an individual's decisionmaking behavior will be biased, and that the direction of bias will be determined by his immediate perception of the fire situation. The primary function of ASSIGN is to "recall" for each occupant all those factors which comprise his current perception (e.g., current evaluation of success, knowledge of exit and threat locations, interruption status, etc.). It then assigns his decisionmaking task to an appropriate biasing subroutine, as follows: (1) threat evasion via TBIAS, (2) exit goalseeking via EBIAS, (3) interruption mode fulfillment via INTRPT and/or BACKUP, and confusion, i.e., no specific bias, via EQUALZ.

Formulas

$$\mathrm{CUM}(K) = P(K) \tag{38}$$

$$\mathrm{CUM}(K)^{*} = P(K)+\mathrm{CUM}(K-1) \tag{39}$$

$$\mathrm{RAND} = \mathrm{CUM}(K)-X \tag{40}$$

where:

$\mathrm{CUM}(K)$ = the cumulative probability of selecting the move designated by $k=1$;

$\mathrm{CUM}(K)^{*}$ = the cumulative probability of selecting moves designated by $k=2$ through $k=9$;

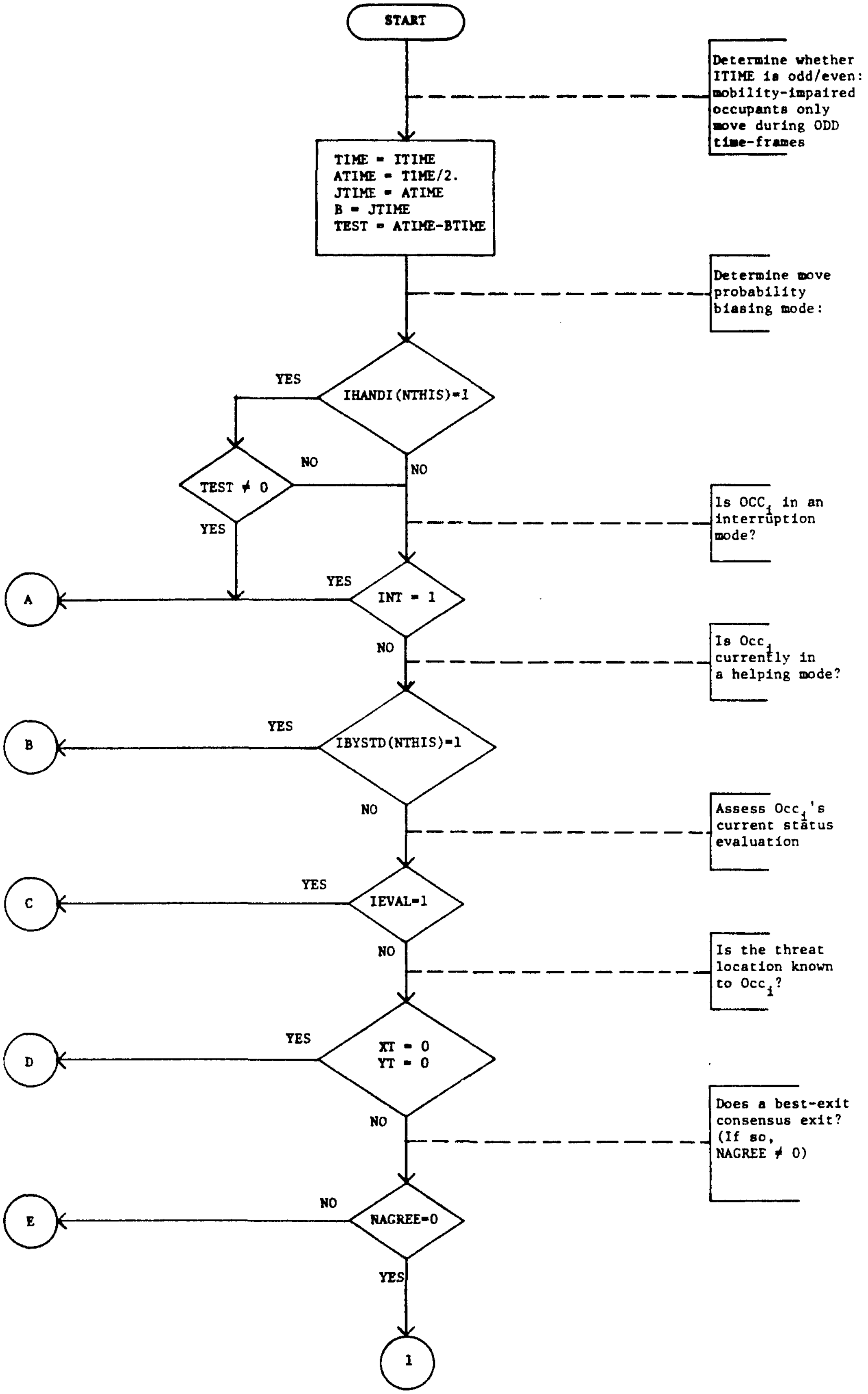
P(K) = the computed probability of selecting the kth move;

K = move identifier;

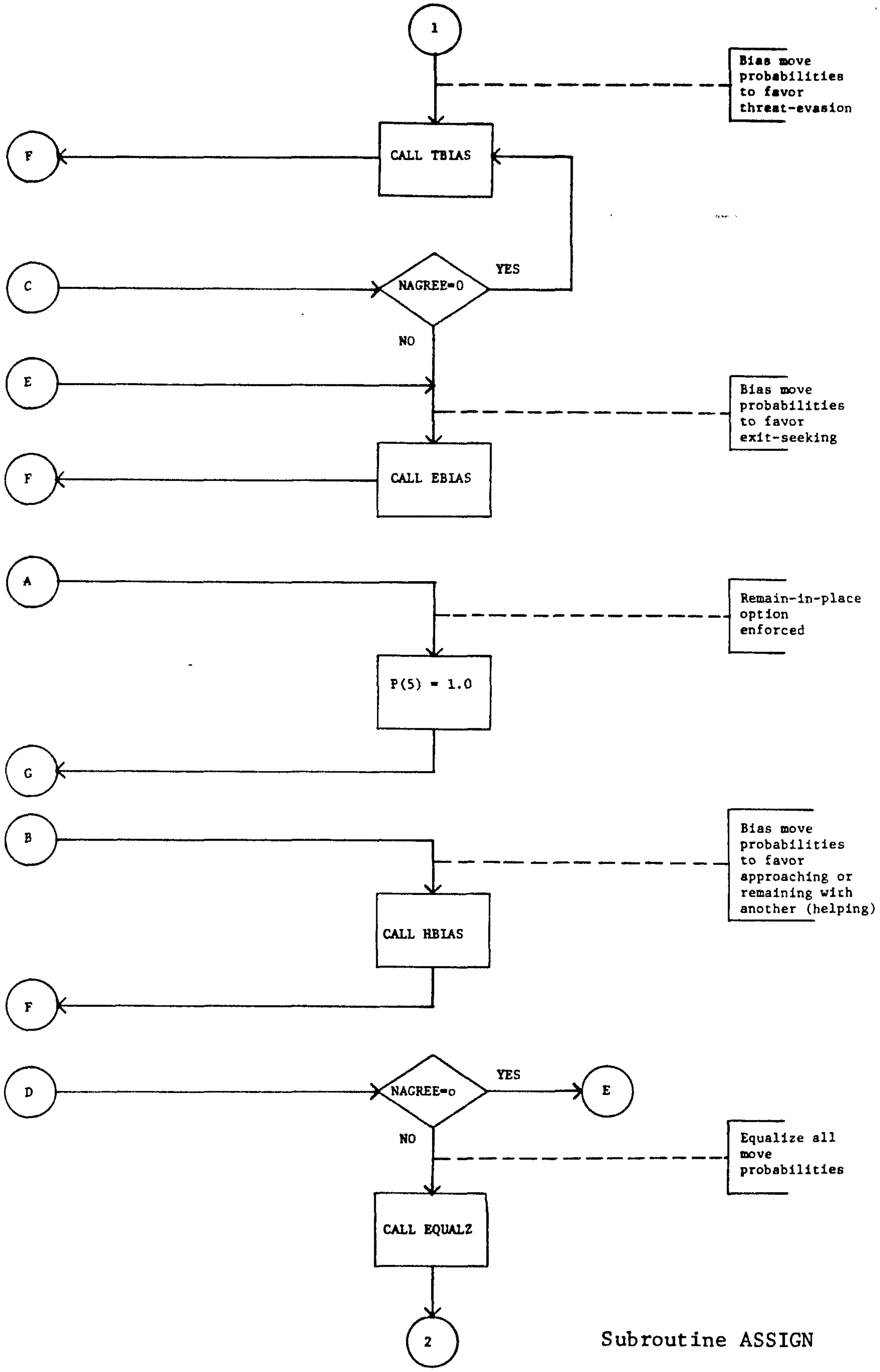
X = a uniformly distributed random number between 0 and 1;

RAND = Test number for stochastic selection process

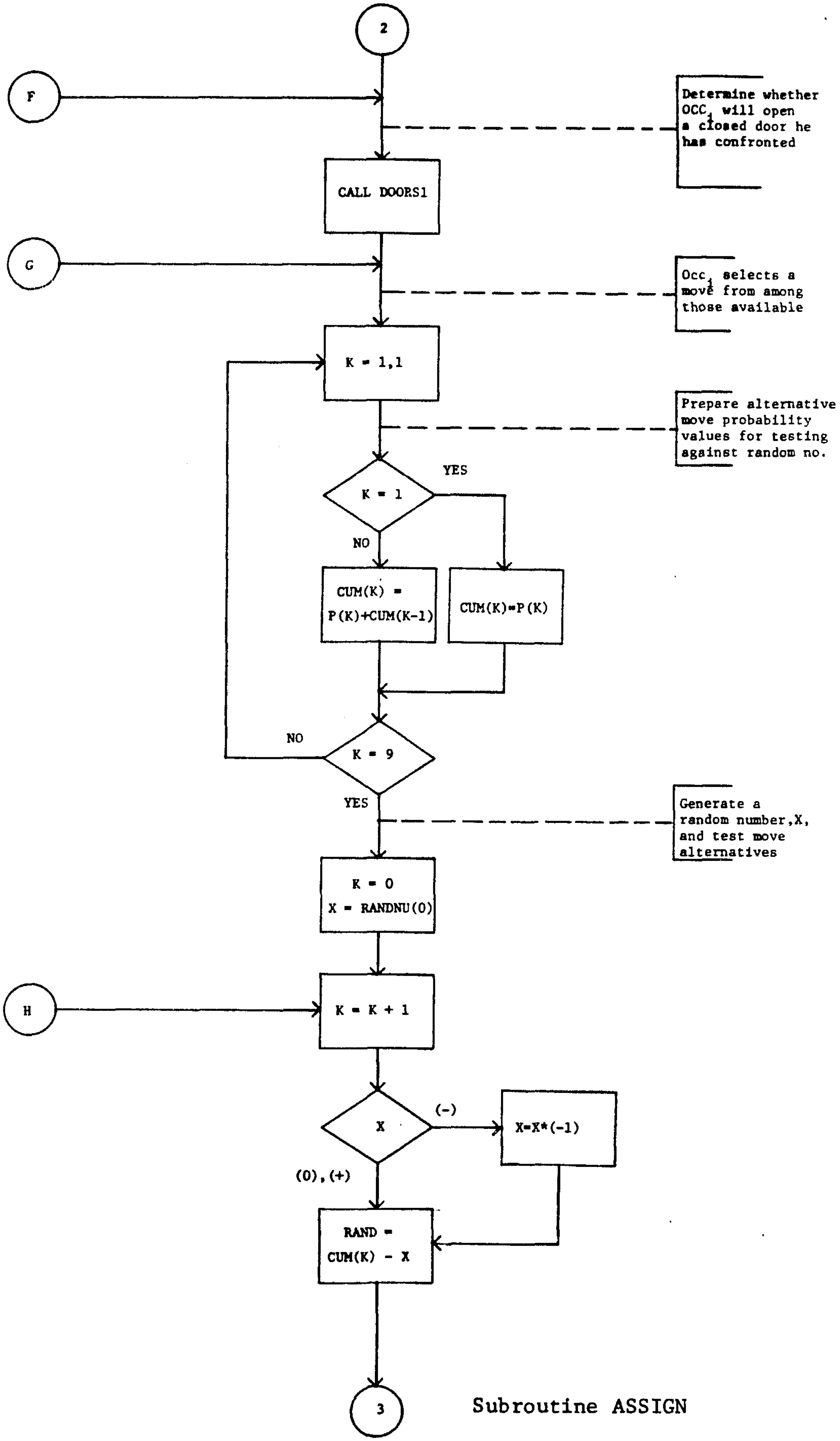
$$= CUM(K)-X \tag{41}$$



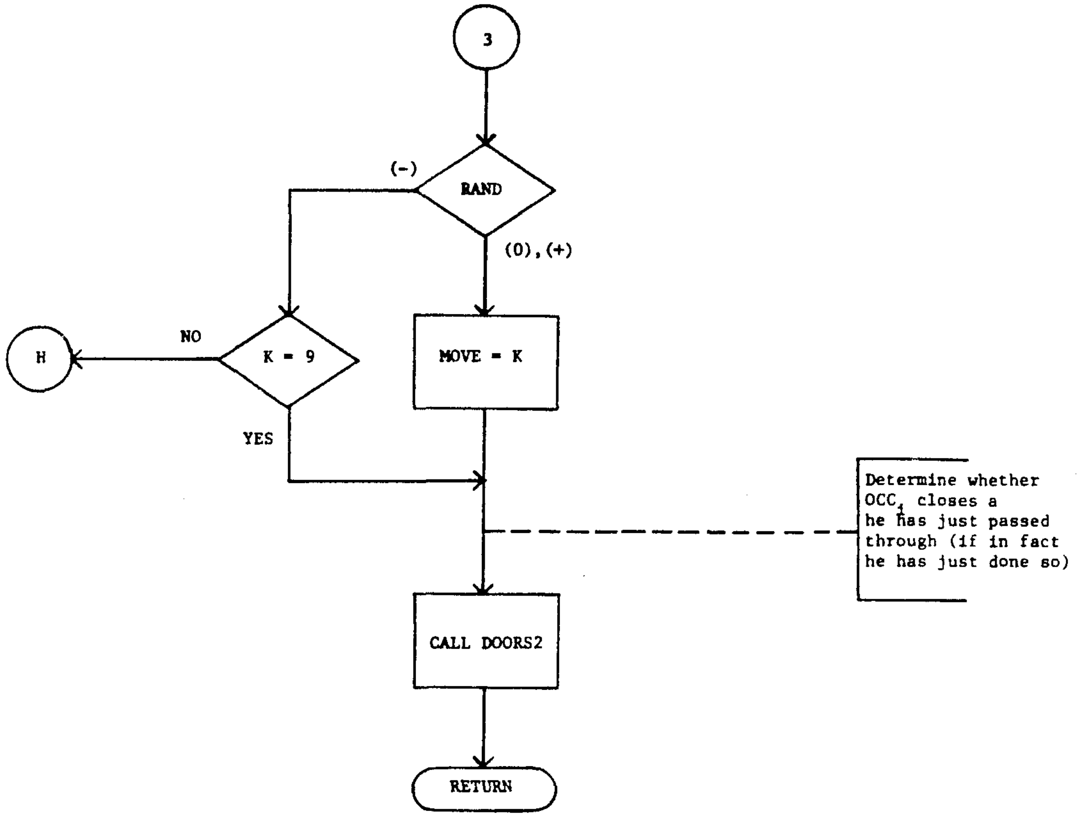
Subroutine ASSIGN



Subroutine ASSIGN



Subroutine ASSIGN



Determine whether OCC_i closes a
he has just passed
through (if in fact
he has just done so)

Subroutine ASSIGN

```
C
C
C
C
C
C    SUBROUTINE ASSIGN
C
C    THE PURPOSE OF ASSIGN IS TO CONSIDER ALL FACTORS COMPRISING THE OCCUPANT'S
C    CURRENT PERCEPTION OF HIS SITUATION, AND THEN TO SWITCH CONTROL FOR
C    DECISION-MAKING TO THE APPROPRIATE BIASING ROUTINE.
C
      SUBROUTINE ASSIGN (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X,IDOOR,POPEN,ND,MDOOR,PCLOSE)
      DIMENSION IHANDI(20),IBYSTD(20),P(9),CUM(9)
      INTEGER XO(20),YO(20),XE(10),YE(10),XT,YT
C    DETERMINE WHETHER ITIME, THE CURRENT TIME-FRAME, IS ODD OR EVEN...
C    MOBILITY-IMPAIRED OCCUPANTS ONLY MOVE DURING ODD TIME-FRAMES
      TIME=ITIME
      ATIME=TIME/2.
      JTIME=ATIME
      BTIME=JTIME
      TEST=ATIME-BTIME
C    DETERMINE MOVE PROBABILITY BIASING MODE
      IF (IHANDI(NTHIS).EQ.1) GO TO 1
      GO TO 11


1     IF (TEST.NE.0.) GO TO 2
C    IS THE OCCUPANT IN AN INTERRUPTION MODE
11    IF (INT.EQ.1) GO TO 2
C    IS THE OCCUPANT CURRENTLY IN A HELPING MODE
      IF (IBYSTD(NTHIS).EQ.1) GO TO 3
C    ASSESS THE OCCUPANT'S CURRENT STATUS EVALUATION
      IF (IEVAL.EQ.1) GO TO 4
C    IS THE THREAT LOCATION KNOWN TO THE OCCUPANT
      IF ((XT.EQ.0).AND.(YT.EQ.0)) GO TO 5
C    DOES A BEST-EXIT CONSENSUS EXIST (IF SO, NAGREE.NE.0)
      IF (NAGREE.EQ.0) GO TO 404
      GO TO 504
C    BIAS MOVE PROBABILITIES TO FAVOR THREAT-EVASION
404   CALL TBIAS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
      GO TO 6
4     IF (NAGREE.EQ.0) GO TO 404
C    BIAS MOVE PROBABILITIES TO FAVOR EXIT-SEEKING
504   CALL EBIAS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
      GO TO 6
C    REMAIN-IN-PLACE OPTION ENFORCED
2     P(5)=1.0
      DO 50 K=1,4
50    P(K)=0.0
      DO 51 K=6,9
51    P(K)=0.0
      GO TO 601
C    BIAS MOVE PROBABILITIES TO FAVOR APPROACHING OR REMAINING WITH A MOBILITY-
C    IMPAIRED OTHER
3     CALL HBIAS (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P)
      GO TO 6
5     IF (NAGREE.NE.0) GO TO 504
C    EQUALIZE ALL MOVE PROBABILITIES
      CALL EQUALZ (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER)
C    DETERMINE WHETHER THE OCCUPANT WILL OPEN A CLOSED DOOR HE HAS CONTRONTED
6     CALL DOORS1 (ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XO,YO,IBAR,TOTBAR,XT,YT, NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X,IDOOR,POPEN,ND,MDOOR,PCLOSE,IXO
601   CONTINUE
C    THE OCCUPANT SELECTS A MOVE FROM AMONG THE ALTERNATIVES AVAILABLE
      DO 100 K=1,9
C    PREPARE ALTERNATIVE MOVE PROBABILITY VALUES FOR TESTING AGAINST A RANDOM
C    NUMBER
      IF (K.EQ.1) GO TO 200
      CUM(K)=P(K)+CUM(K-1)
      GO TO 100
```

```
200   CUM(K)=P(K)
100   CONTINUE
C   GENERATE A RANDOM NUMBER, X, AND THEST THE MOVE ALTERNATIVES
      K=0
      CALL RANDOM (ITIME,NTHIS,IHANDI,INT, IBYSTD,IEVAL,
     1  XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2  P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,X)
7     K=K+1
      IF (X) 71,72,72
71    X=X*(-1)
72    RAND=CUM(K)-X
      IF (RAND) 52,53,53
53    MOVE=K
      GO TO 8
52    IF (K.LT.9) GO TO 7
C   DETERMINE WHETHER THE OCCUPANT CLOSES A DOOR JUST PASSED THROUGH (IF IN
C   FACT HE HAS JUST DONE SO)
8     CALL DOORS2(ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1   XD,YD,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2   IRAND,P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,
     3   X,IDOOR,POPEN,ND,MDOOR,PCLOSE,IX)
12    RETURN
      END
```

Routines UPDATE, NEWXY, XSCORE, STEPS, PASSG (Utility Programs)

Loops Occupant and Replication

Purposes UPDATE: This program changes the x,y coordinates denoting occupant locations to reflect movement actions of each during the just-completed time frame.

NEWXY: This program converts spatial locations from k-grid designators to x,y coordinates, using subroutine KTOXY, in those cases where KTOXY is not called directly.

XSCORE: this program computes each occupant's escape score for the entire event.

STEPS: This program keeps track of the total number of spatial displacements ("steps") actually made by each occupant during the fire event. Remaining-in-place is not recorded as a step.

PASSG: This program keeps track of door-passage behavior.

Formulas XSCORE:

$$SCORE = (SUMTIM-E)/SUMTIM \qquad (42)$$

where:

SCORE = occupant n's overall escape score;

SUMTIM = total number of time frames available;

E = time frame at which escape occurred (if the occupant never escapes, E = SUMTIM).

```
C
C
C
C
C
C   SUBROUTINE UPDATE
C
C   THE PURPOSE OF UPDATE IS TO CHANGE THE X,Y COORDINATES OF OCCUPANT LOCATIONS
C   TO REFLECT MOVEMENT ACTIONS OF EACH DURING THE JUST-COMPLETED TIME FRAME
C
      SUBROUTINE UPDATE (XO,YO,NTHIS,NEWXO,NEWYO)
      INTEGER XO(28),YO(28)
      XO(NTHIS)=NEWXO
      YO(NTHIS)=NEWYO
      RETURN
      END
```

```
C
C
C
C
C
C    SUBROUTINE NEWXY
C
C    THE PURPOSE OF NEWXY IS TO CONVERT SPATIAL LOCATIONS FROM K-GRID
C    DESIGNATORS TO X,Y COORDINATES. USING SUBROUTINE KTOXY. IN THOSE
C    CASES WHERE KTOXY IS NOT CALLED DIRECTLY
C
      SUBROUTINE NEWXY (ITIME,NTHIS.IHANDI.INT.IBYSTD.IEVAL,
     1   XO,YO.IBAR.TOTBAR.XT.YT.NAGREE.XE.YE.IAGREE,
     2.  IRAND.P,MOVE,XK.YK,K,NEWXO.NEWYO)
      INTEGER XK,YK
      CALL KTOXY (ITIME.NTHIS.IHANDI.INT.IBYSTD.IEVAL.
     1   XO,YO.IBAR.TOTBAR.XT.YT.NAGREE.XE.YE.IAGREE.
     2   IRAND.P,MOVE,XK.YK,K)
      NEWXO=XK
      NEWYO=YK
      RETURN
      END
```

```
C
C
C
C
C
C
C     SUBROUTINE XSCORE
C
C     THE PURPOSE OF XSCORE IS TO COMPUTE EACH OCCUPANT'S ESCAPE SCORE FOR THE
C     ENTIRE EVENT, I.E., SCORE=(TOTAL TIME AVAILABLE - CURRENT TIME FRAME)
C     DIVIDED BY THE TOTAL TIME AVAILABLE
C
        SUBROUTINE XSCORE (TOTIME,ISCORE,NUMOCC,SCORE)
        DIMENSION ISCORE(20),SCORE(20)


        INTEGER TOTIME
        SUMTIM=TOTIME
        DO 10 NTHIS=1,NUMOCC
        E=ISCORE(NTHIS)
C     COMPUTE THE OCCUPANT'S ESCAPE SCORE FOR THE ENTIRE EVENT
10      SCORE(NTHIS)=(SUMTIM-E)/SUMTIM
        RETURN
        END
```

```
C
C
C
C
C
C   SUBROUTINE STEPS
C
C   THE PURPOSE OF STEPS IS TO KEEP TRACK OF THE TOTAL NUMBER OF SPATIAL
C   RELOCATIONS ('STEPS') ACTUALLY MADE BY EACH OCCUPANT DURING THE FIRE EVENT
C   ...A STEP IS DEFINED AS A SPATIAL RELOCATION, AND THEREFORE, REMAINING-IN-
C   PLACE IS NOT RECORDED AS A STEP
C
      SUBROUTINE STEPS (XPRIOR,YPRIOR,XD,YD,NUMSTP,NTHIS)
      INTEGER XPRIOR(20),YPRIOR(20),XD(20),YD(20)
      DIMENSION NUMSTP(20)
C   RECORD WHETHER THE OCCUPANT MOVED DURING THE TIME FRAME JUST ENDED, THAT IS,
C   WHETHER (YPRIOR.NE.XD).AND.(YPRIOR.NE.YD)
      IF ((XPRIOR(NTHIS).EQ.XD(NTHIS)).AND.(YPRIOR(NTHIS).EQ.YD(NTHIS)))
     1  GO TO 999
C   UPDATE THE TOTAL NUMBER OF STEPS TAKEN BY THE OCCUPANT DURING THE EVENT
      NUMSTP(NTHIS)=NUMSTP(NTHIS)+1
999   RETURN
      END
```

```
C
C
C
C
C
C   SUBROUTINE PASSG
C
C   THE PURPOSE OF PASSG IS TO KEEP TRACK OF DOOR-PASSAGE BEHAVIOR EXHIBITED BY
C   OCCUPANTS
C


      SUBROUTINE PASSG (IDPASS,IDOOR,XD,YD,NTHIS,
     1   ND,NEWXD,NEWYD)
      DIMENSION IDPASS(20),IDOOR(30,4)
      INTEGER XD(20),YD(20)
C   DETERMINE WHETHER THE OCCUPANT PASSED THROUGH A DOORWAY DURING THE TIME-
C   FRAME JUST ENDED
      IXPASS=(NEWXD+XD(NTHIS))/2
      IYPASS=(NEWYD+YD(NTHIS))/2
      DO 10 I=1,ND
      IF ((IDOOR(I,1).EQ.IXPASS).AND.
     1   (IDOOR(I,2).EQ.IYPASS)) GO TO 5
      GO TO 10
C   UPDATE THE TOTAL NUMBER OF DOOR PASSAGES MADE BY THE OCCUPANT DURING THE
C   FIRE EVENT
5     IDPASS(NTHIS)=IDPASS(NTHIS)+1
10    CONTINUE
      RETURN
      END
```

Routines SUMMRY, REPORT, TRACE, TOTALS (Input/Output Programs)

Loops Occupant and Replication

Purposes SUMMRY: This program prints a summary table for each replication. Output are values for various dependent measures computed by BFIRES. These values are "grand means" taken across occupants and time frames, and report aggregated scores and final status at the end of the last time frame for each replication. Initial conditions are also printed, for comparison against final states.

REPORT: This program prints a summary table for each time frame within a given replication. Each table reports results of the decision process for each occupant in the run. Data include move probability values, and x,y coordinates for occupants' locations at times t-1 and t.

TRACE: This program prints a summary table for each occupant in a given replication. Each table traces the spacial displacement of the occupant across the entire simulated event (in terms of changes in x,y coordinates).

TOTALS: This program prints summary tables reporting total numbers of door passages and interruptions for each occupant in the event. Door passages are also reported by subroutine SUMMRY.

Formulas n/a

```
C
C
C
C
C
C     SUBROUTINE SUMMRY
C
C     THE PURPOSE OF SUMMRY IS TO PRINT-OUT A SUMMARY TABLE FOR EACH REPLICATION
C     RUN...OUTPUT VALUES ARE 'GRAND MEANS' TAKEN ACROSS OCCUPANTS AND TIME-
C     FRAMES, AND REPORT AGGREGATED SCORES AND FINAL STATUS AT THE END OF THE
C     LAST TIME FRAME FOR EACH REPLICATION
C
       SUBROUTINE SUMMRY (INITXO,INITYO,INTLIM,LBYSTD,IHANDI,KNOWAY,
      1   POPEN,PCLOSE,SCORE,NUMSTP,IPS,III,NUMREP,NUMOCC,TOTIME,
      2   XO,YO,XE,YE,TITLE)
       DIMENSION INITXO(20),INITYO(20),INTLIM(20),LBYSTD(20),IHANDI(20),
      1  KNOWAY(20),POPEN(20),PCLOSE(20),SCORE(20),NUMSTP(20),IPS(20)
       DIMENSION NUMBER(20),SMEAN(20),DMEAN(20),DIST(20),DEINIT(20),
      1   DIFF(20),DFMEAN(20),TITLE(20)
       REAL NMEAN(20),IMEAN(20)
       INTEGER TOTIME,XO(20),YO(20),XE(10),YE(10)
       DIFTOT=0.0
       DTOTAL=0.0
       STOTAL=0.0
       NTOTAL=0
       ITOTAL=0
       NSUM=NUMOCC*NUMREP
       SUM=NSUM
       AN=NUMOCC
       WRITE (6,100)
       WRITE (6,134) TITLE
       WRITE (6,119)
       WRITE (6,102)
       WRITE (6,103)
       WRITE (6,119)
       WRITE (6,104) III,NUMREP,TOTIME
       WRITE (6,102)
       WRITE (6,119)
       WRITE (6,105)
       WRITE (6,119)
       WRITE (6,106)
       DO 200 N=1,20
       NUMBER(N)=N
200    CONTINUE
       WRITE (6,107) (NUMBER(N),N=1,20)
       WRITE (6,101)


       DO 55 K=1,NUMOCC
55     DEINIT(K)=SQRT(((INITXO(K)-XE(1))**2)+((INITYO(K)-YE(1))**2))
       WRITE (6,131) (DEINIT(K),K=1,NUMOCC)
       WRITE (6,108) (INITXO(K),K=1,NUMOCC)
       WRITE (6,109) (INITYO(K),K=1,NUMOCC)
       WRITE (6,110) (INTLIM(K),K=1,NUMOCC)
       WRITE (6,111) (LBYSTD(K),K=1,NUMOCC)
       WRITE (6,112) (IHANDI(K),K=1,NUMOCC)
       WRITE (6,113) (KNOWAY(K),K=1,NUMOCC)
       WRITE (6,114) (POPEN(K),K=1,NUMOCC)
       WRITE (6,115) (PCLOSE(K),K=1,NUMOCC)
       WRITE (6,102)
       WRITE (6,119)
       WRITE (6,116)
       WRITE (6,119)
       WRITE (6,106)
       WRITE (6,107) (NUMBER(N),N=1,20)
       WRITE (6,101)
C..COMPUTE REPLICATION MEANS...
       DO 20 K=1,NUMOCC
       DIST(K)=SQRT(((XE(1)-XO(K)) **2)+((YE(1)-YO(K))**2))
       DTOTAL=DTOTAL+DIST(K)
       STOTAL=STOTAL+SCORE(K)
       NTOTAL=NTOTAL+NUMSTP(K)
20     ITOTAL=ITOTAL+IPS(K)
       SMEAN(III)=STOTAL/AN
       NMEAN(III)=FLOAT(NTOTAL)/AN
       IMEAN(III)=FLOAT(ITOTAL)/AN
       DMEAN(III)=DTOTAL/AN
C
       DO 201 K=1,NUMOCC
       DIFF(K)=DEINIT(K)-DIST(K)
       DIFTOT=DIFTOT+DIFF(K)
201    NUMSTP(K)=NUMSTP(K)+1
       WRITE (6,127) (XO(K),K=1,NUMOCC)
       WRITE (6,128) (YO(K),K=1,NUMOCC)
       WRITE (6,129) (DIST(K),K=1,NUMOCC)
       WRITE (6,132) (DIFF(K),K=1,NUMOCC)
       WRITE (6,117) (SCORE(K),K=1,NUMOCC)
       WRITE (6,118) (NUMSTP(K),K=1,NUMOCC)
       WRITE (6,120) (IPS(K),K=1,NUMOCC)
C. COMPUTE NESCAP...
       NESCAP=NUMOCC
       DO 300 L=1,NUMOCC
       IF (SCORE(L).LE.0.001) GO TO 301
       GO TO 300
301    NESCAP=NESCAP-1
300    CONTINUE
       WRITE (6,126) NESCAP
       WRITE (6,102)
       WRITE (6,122) NUMOCC
       WRITE (6,130) DMEAN(III)
       DFMEAN(III)=DIFTOT/AN
       WRITE (6,133) DFMEAN(III)
```

```
      WRITE (6,123) SMEAN(III)
      WRITE (6,124) NMEAN(III)
      WRITE (6,125) IMEAN(III)
      WRITE (6,102)
      WRITE (6,121)
      WRITE (6,102)
100   FORMAT ('1')
101   FORMAT (130('*'))
102   FORMAT (130('*'),/,130('*'))
103   FORMAT (57X,'SIMULATION SUMMARY')
104   FORMAT (3X,'REPLICATION',I5,'   OF',I5,70X,'RUN FOR',I4,
     1   ' TIME FRAMES')
105   FORMAT (57X,'INITIAL CONDITIONS')
106   FORMAT (63X,'OCCUPANT NUMBER')
107   FORMAT (11X,20(I2,3X))
108   FORMAT (3X,'INITXO',1X,29(I3,2X),I3)
109   FORMAT (3X,'INITYO',1X,29(I3,2X),I3)
110   FORMAT (3X,'INTLIM',1X,29(I3,2X),I3)
111   FORMAT (3X,'LBYSTD',1X,29(I3,2X),I3)
112   FORMAT (3X,'IHANDI',1X,29(I3,2X),I3)
113   FORMAT (3X,'KNOWAY',1X,29(I3,2X),I3)
114   FORMAT (3X,'POPEN ',1X,29(F3.2,2X),F3.2)
115   FORMAT (3X,'PCLOSE',1X,29(F3.2,2X),F3.2)
116   FORMAT (58X,'OUTCOMES')
117   FORMAT (3X,'SCORE ',1X,20(F4.2,1X))
118   FORMAT (3X,'STEPS ',1X,20(I3,2X))
120   FORMAT (3X,'PASSES',1X,20(I3,2X))
119   FORMAT (' ')
121   FORMAT (57X,'END OF REPLICATION')
122   FORMAT (9X,'MEANS COMPUTED ACROSS',I3,' OCCUPANTS...')
123   FORMAT (20X,'MEAN SCORE = ',F4.2)
124   FORMAT (20X,'MEAN STEPS = ',F6.2)
125   FORMAT (20X,'MEAN PASSES =',F6.2)
126   FORMAT (3X,'NUMBER ESCAPED',5X,I3)
127   FORMAT (3X,'FIN X ',1X,20(I3,2X))
128   FORMAT (3X,'FIN Y ',1X,20(I3,2X))
129   FORMAT (3X,'DIST  ',1X,20(F4.1,1X))
130   FORMAT (20X,'MEAN DIST  = ',F4.1)
131   FORMAT (3X,'INIT D',1X,20(F4.1,1X))
132   FORMAT (3X,'DIFF D',   20(F5.1))
133   FORMAT (20X,'MEAN DIFF D =',F4.1)
134   FORMAT (1X,'RUN TITLE/  ',20A4)
      RETURN
      END
```

```
C
C
C
C
C
C     SUBROUTINE REPORT
C
C     THE PURPOSE OF REPORT IS TO PRINT-OUT A SUMMARY TABLE FOR EACH TIME-FRAME
C     OF A GIVEN REPLICATION...EACH TABLE REPORTS RESULTS OF THE DECISION
C     PROCESS FOR EACH OCCUPANT IN THE TIME FRAME, PARTICULARLY MOVE PROBABILITY


C     VALUES ASSIGNED TO EACH AVAILABLE MOVE ALTERNATIVE AT THAT POINT IN TIME
C     ...X,Y COORDINATES ARE ALSO SHOWN FOR BOTH TIMES T AND T+1, FOR EACH
C     OCCUPANT IN THE TIME FRAME
C
       SUBROUTINE REPORT(ITIME,NTHIS,IHANDI,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,
     2  IRAND,P,MOVE,XK,YK,K,NUMEXT,NUMOCC,TOTIME,INTLIM,
     3  LBYSTD,KNOWAY,PTDIST,TDIST,PEDIST,EDIST,NEWXO,NEWYO,
     4   EVLOPT,IDOOR,IDOPEN,ND,INTR)
       DIMENSION IBAR (20,75,2),INTLIM(20),LBYSTD(20),IHANDI
     1  (20),KNOWAY(20),IBYSTD(20),P(9),INTR(20)
       DIMENSION IDOOR(30,4),IDOPEN(30,100)
       INTEGER XE(10),YE(10),XO(20),YO(20),XT,YT,TOTIME,
     1  XK,YK,EVLOPT
C
       IF ((ITIME.GT.1).OR.(NTHIS.GT.1)) GO TO 1
C
C: ECHO:CHECK INPUT PARAMETERS*
C:  (1) ENVIRONMENTAL:
C
       WRITE (6,100)
       WRITE (6,101) XT,YT
       WRITE (6,102) NUMEXT
       WRITE (6,104)
       WRITE (6,105) (XE(I),I=1,NUMEXT)
       WRITE (6,106) (YE(I),I=1,NUMEXT)
C
C:  (2) SYSTEM:
C
       WRITE (6,109) NUMOCC
       WRITE (6,110) TOTIME
       WRITE (6,111) IRAND
C
C:  (3) OCCUPANT:
C
       WRITE (6,112)
       WRITE (6,113) (INTLIM(I),I=1,NUMOCC)
       WRITE (6,114) (LBYSTD(I),I=1,NUMOCC)
       WRITE (6,115) (IHANDI(I),I=1,NUMOCC)
       WRITE (6,116) (KNOWAY(I),I=1,NUMOCC)
       WRITE (6,117)
C
1      CONTINUE
C
       IF (NTHIS.NE.1) GO TO 2
C
C: IF NTHIS=1, PRINT CURRENT TIME MARKER AND COLUMN HEADINGS:
C
       WRITE (6,118)
       WRITE (6,119) ITIME
       WRITE (6,118)
       WRITE (6,120)
       WRITE (6,118)
C


C
2      IF (INTR(NTHIS).EQ.1) GO TO 22
C
C: WRITE OUTPUT MATRIX:
       IF (EVLOPT-1) 20,20,21
20     CONTINUE
       WRITE (6,121) NTHIS,XO(NTHIS),YO(NTHIS),INT,IBYSTD(NTHIS),IAGREE,
     1 TDIST,EDIST,(P(K),K=1,9),NEWXO,NEWYO
       GO TO 23
21     WRITE (6,123) NTHIS,XO(NTHIS),YO(NTHIS),INT,IBYSTD(NTHIS),
     1    IAGREE,(P(K),K=1,9),NEWXO,NEWYO
       GO TO 23
22     WRITE (6,127) NTHIS,XO(NTHIS),YO(NTHIS),INT,
     1    NEWXO,NEWYO
23     CONTINUE
       IF (NTHIS.EQ.NUMOCC) GO TO 3
       GO TO 4
3      WRITE (6,118)
4      IF ((ITIME.EQ.TOTIME).AND.(NTHIS.EQ.NUMOCC)) GO TO 5
       GO TO 6
5      WRITE (6,118)
       WRITE (6,124)
       WRITE (6,118)
       WRITE (6,125)
       WRITE (6,118)
       DO 30 I=1,ND
       WRITE (6,126) I,IDOOR(I,1),IDOOR(I,2),IDOOR(I,3),
     1    (IDOPEN(I,ITM),ITM=1,TOTIME)
```

```
30     CONTINUE
       WRITE (6,110)
       WRITE (6,122)
       WRITE (6,110)
       GO TO 6
C
C: OUTPUT FORMATING:
C
100    FORMAT (1X,120('*'),//,55X,'ECHO-CHECK INPUT PARAMETERS',//,120
      1 ('*'),//,1X,'(1) ENVIRONMENTAL:',/)
101    FORMAT (24X,'THREATENED EXIT: X= ',I2,4X,'Y=',I2)
102    FORMAT (24X,'NUMBER OF EXITS:  = ',I2)
103    FORMAT (24X,'NO. OF BARRIER PTS=',I3,/)
104    FORMAT (24X,'COORDINATES OF EXITS:  1  2  3  4  5  6  7  8  9 10',
      1 /)
105    FORMAT (43X,'X: ',10(I2,1X))
106    FORMAT (43X,'Y: ',10(I2,1X),/)
107    FORMAT (1X,'BARRIER-POINT MATRIX:',/)
108    FORMAT (2X,'X:',30(I2,1X),/,2X,'Y:',30(I2,1X),/)
109    FORMAT (1X,'(2) SYSTEM',/,24X,'NUMBER OF OCCUPANTS IN THE SPACE ='
      1 ,I3)
110    FORMAT (24X,'TOTAL NO. OF TIME INCREMENTS =',I3)
111    FORMAT   (24X,'RANDOM NUMBER STARTER         =',I3,/)
112    FORMAT (1X,'(3) OCCUPANT:',/,12X,'PARAMETER',5X,'OCC NO  1  2  3
      1 4  5  6  7  8  9 10 11 12 13 1 4 15 16 17 18 19 20',/)
113    FORMAT (12X,'INTLIM',15X,20(I2,1X))


114    FORMAT (12X,'LBYSTD',15X,20(I2,1X))
115    FORMAT (12X,'IHANDI',15X,20(I2,1X))
116    FORMAT (12X,'KNOWAY',15X,20(I2,1X),/)
117    FORMAT (2(1X,120('*'),/))
118    FORMAT (1X,120('*'),/)
119    FORMAT (1X,'TIME = ',I3,/)
120    FORMAT (6X,'PRIOR',18X,'EXIT',89X,'NEW',/,1X,'OCC',2X,'LOCAT',17X,
      1'AGREED',87X,'LOCAT',/,1X,'NUM',2X,'XO YO  INT     IBYSTD   UPON
      2  PTDIST TDIST   PEDIST EDIST   P(1)  P(2)  P(3)  P(4)  P(5)  P(6)
      3 P(7)  P(8)  P(9)',6X,'XO YO',/)
121    FORMAT (1X,I2,3X,I2,1X,I2,4X,I1,6X,I1,6X,I2,3X,2(7X,F6.3,2X),
      1 9(F5.3,1X),4X,I2,1X,I2)
122    FORMAT (50X,'END OF SIMULATION',/)
123    FORMAT (1X,I2,3X,I2,1X,I2,4X,I1,6X,I1,6X,
      1    I2,33X,9(F5.3,1X),4X,I2,1X,I2)
124    FORMAT (50X,'DOOR STATUS SUMMARY',/)
125    FORMAT (1X,'DOOR',4X,'X  Y',5X,'TYPE',5X,'T= 1  2  3  4  5
      1  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
      2  24 25 26 27 28 29 30',/)
126    FORMAT (2X,I2,5X,I2,1X,I2,7X,I1,8X,30(I2,1X))
127    FORMAT (1X,I2,3X,I2,1X,I2,4X,I1,106X,I2,1X,I2)
6      RETURN
       END
```

```
C
C
C
C
C
C    SUBROUTINE TRACE
C
C    THE PURPOSE OF TRACE IS TO PRINT-OUT A SUMMARY TABLE FOR EACH OCCUPANT IN
C    A GIVEN REPLICATION...EACH SUCH TABLE TRACES THE SPATIAL DISPLACEMENT
C    (CHANGE IN X,Y COORDINATES) OF EACH OCCUPANT ACROSS THE ENTIRE SIMULATED
C    EVENT
C
      SUBROUTINE TRACE (IXTRCE,IYTRCE,NTHIS,ITIME,NUMOCC,
     1   TOTIME)
      DIMENSION IXTRCE(20,100),IYTRCE(20,100)
      INTEGER TOTIME
      WRITE (6,1)
      DO 25 I=1,NUMOCC
      WRITE (6,2) I
      DO 24 J=1,TOTIME
      WRITE (6,3) J,IXTRCE(I,J),IYTRCE(I,J)
24    CONTINUE
      WRITE (6,4)
25    CONTINUE
      WRITE (6,5)
1     FORMAT (1X,120('*'),//,40X,
     1   'OCCUPANT MOVEMENT TRACES',//,1X,120('*'))
2     FORMAT (1X,120('*'),//,1X,'OCCUPANT NUMBER:',I4,/,
     1   10X,'TIME',/,10X,'FRAME',10X,'X',5X,'Y',/,
     2   1X,120('*'))
3     FORMAT (12X,I2,10X,I2,4X,I2)


4     FORMAT (1X,120('*'))
5     FORMAT (1X,120('*'),//,55X,'END OF TRACES',//,
     1   1X,120('*'))
      RETURN
      END
```

```
C
C
C
C
C
C     SUBROUTINE TOTALS
C
C     THE PURPOSE OF TOTALS IS TO PRINT-OUT SUMMARY TABLES REPORTING TOTAL
C     NUMBERS OF DOOR PASSAGES AND INTERRUPTIONS (OF EACH TYPE) FOR EACH
C     OCCUPANT IN THE EVENT
C
      SUBROUTINE TOTALS (IDPASS,ITYPE1,ITYPE2,NTHIS,NUMOCC)
      DIMENSION IDPASS(20),ITYPE1(20),ITYPE2(20)
      DIMENSION IOCC(20)
      DO 25 I=1,NUMOCC
25    IOCC(I)=I
      WRITE (6,1)
      WRITE (6,2) (IOCC(I),I=1,NUMOCC)
      WRITE (6,3) (ITYPE1(NTHIS),NTHIS=1,NUMOCC)
      WRITE (6,31) (ITYPE2(NTHIS),NTHIS=1,NUMOCC)
      WRITE (6,4)
      WRITE (6,5) (IOCC(I),I=1,NUMOCC)
      WRITE (6,6) (IDPASS(NTHIS),NTHIS=1,NUMOCC)
      WRITE (6,7)
      WRITE (6,8)
1     FORMAT (1X,120('*'),//,45X,
     1   'OCCUPANTS INTERRUPTION TOTALS:',//,38X,
     2   'REPORTS TOTAL NUMBER OF FRAMES SPENT IN MODES',
     3   //,1X,120('*'))
2     FORMAT (1X,'INTRPT',28X,'OCCUPANT',/,2X,'TYPE',
     1   10X,20(I3))
3     FORMAT (1X,120('*'),/,4X,'1',11X,20(I3))
31    FORMAT (4X,'2',11X,20(I3),/,1X,120('*'))
4     FORMAT (1X,120('*'),//,50X,'DOOR PASSAGE TOTALS',
     1   //,1X,120('*'),/,55X,'OCCUPANT')
5     FORMAT (30X,20(I3),/,1X,120('*'))
6     FORMAT (30X,20(I3),/,1X,120('*'))
7     FORMAT (1X,120('*'),//,52X,'END OF TOTALS',//,1X,
     1   120('*'))
8     FORMAT (1X,120('*'),//,55X,'END OF RUN',//,1X,120('*'))
      RETURN
      END
```

```
C
C
C
C
C
C: IBM UNIFORMLY DISTRIBUTED RANDOM NUMBER GENERATOR:
C: SUBROUTINE *RANDU* (FROM SSP-2 PACKAGE). BASED ON THE


C: POWER-RESIDUE METHOD.
C
      SUBROUTINE RANDOM(ITIME,NTHIS,IHAND1,INT,IBYSTD,IEVAL,
     1  XO,YO,IBAR,TOTBAR,XT,YT,NAGREE,XE,YE,IAGREE,IRAND,
     2  P,MOVE,XK,YK,K,L,IS,IGOALX,IGOALY,IENTER,X)
      IY=IRAND*65539
      IF (IY) 5,6,6
5     IY=IY+2147483647+1
6     X=IY
      X=X*.4656613E-9
      IRAND=IY
      RETURN
      END
```

REFERENCES

Appleton, I. and Quiggen, P. Hackney hospital fire precautions project; an evacuation model. Boreham Wood, UK: Building Research Establishment, Fire Research Station, Operations Research and Systems Study Section, 1976.

Apter, M. J. The computer simulation of behavior. New York: Harper - Colophon, 1970.

Baer, A. E. A simulation model of multidirectional pedestrian movement within physically bounded environments. Pittsburgh, Pa.: Carnegie-Mellon Univ., Inst. of Physical Planning, Report #47, June 1974.

Breaux, J., Canter, D. V. and Sime, J. Psychological aspects of behavior of people in fire situations. Surrey, UK: University of Surrey, Fire Research Unit, 1976.

Brunswik, E. Perception and the representative design of psychological experiments. Berkeley and Los Angeles: Univ. of California Press, 1956.

Bryan, J. L. Smoke as a determinant of human behavior in fire situations: project people. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, NBS GCR 77-94, 1977.

Canter, D. Roles, rules and human behavior in fires. In Canter, D. (ed.), Human behavior and fires. London: John Wiley & Sons, in press.

Canter, D., Breaux, J. and Sime, J. Human behavior in fires. Borehamwood, U.K.: Building Research Establishment, Fire Research Station, PD 124/78, 1978.

Caravaty, R. D. and Haviland, D. S. Life safety from fire: a guide for housing the elderly. Troy, N.Y.: Rensselaer Polytechnic Institute, Center for Architectural Research, 1967.

Cohen, S. Environmental load and the allocation of attention. Univ. of Oregon, unpul. ms., 1975.

Downs, R. M. and Stea, D. (eds.). Image and environment: cognitive mapping and spatial behavior. Chicago: Aldine, 1973.

Dutton, J. M. and Starbuck, W. H. Computer simulation of human behavior. New York: John Wiley & Sons, 1971.

Edelman, P., Herz, E., and Bickman, L. Applications of a model of human behavior in a fire emergency to the case study of a nursing home fire. In Canter D. (ed.), Human behavior in fires. London: John Wiley & Sons, in press.

Edmundo, P. M., Hahin, R. and Sinay, J. P. Emergency egress from ships' compartments; Phase II: a systems analysis. Annapolis, Md.: Naval Ship R & D Laboratory, Report #3203, November, 1969.

Edwards, A. L. Experimental design in psychological research. New York: Holt, Rinehart and Winston, 1972.

Feldman, J. Computer simulation of cognitive processes. In Borko, H. (ed.), Computer applications in the behavioral sciences. Englewood Cliffs, N.J.: Prentice-Hall, 1962.

Fruin, J. J. Traffic and space characteristics of pedestrians. In Fruin, J. J., Pedestrian planning and design. New York: Metro. Ass'n. of Urban Designers and Environmental Planners, Inc., 1971.

Glaser, B. G. and Strauss, A. L. Discovery of substantive theory: a basic strategy underlying qualitative research. American behavioral scientist, 1965, 8, 6, 5-12.

Gordon, C. Occupancy analysis and the assessment of fire safety. Paper presented at the Second International Seminar on Behavior in Fire, National Bureau of Standards, Gaithersburg, Maryland, October 29, 1978.

Haber, G. M. Fire as environment: a study of human interaction with fire as environment, in health-care institutions. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, Center for Fire Research, unpubl. ms., 1977.

Herz, E., Edelman, P. and Bickman, L. The impact of fire emergency training on knowledge of appropriate behavior in fires. Washington, D.C.: National Bureau of Standards, NBS GCR 78-137.

Ittelson, W. H. Some issues facing a theory of environment and behavior. In Proshansky, H. M., Ittelson, W. H. and Rivlin, L. G. Environmental psychology: 2nd edition. New York: Holt, Rinehart and Winston, 1976, 51-59.

Ittelson, W. H., Proshansky, H. M., Rivlin, L. G. and Winkel, G. H. An introduction to environmental psychology. New York: Holt, Rinehart and Winston, 1974.

Keating, J. P. and Loftus, E. F. Vocal emergency alarms in hospitals and nursing facilities: practices and potential. Washington, D.C.: National Bureau of Standards, NBS GCR 77-102.

Kerlinger, F. Foundations of behavioral research. New York: Holt, Rinehart, and Winston, 1973.

Kleinjnen, J. P. C. Statistical techniques in simulation. New York: Marcel Dekker, 1974.

Korkemaz, P. N. A discrete event simulation of a burning occupied building. South Bend, In.: Univ. of Notre Dame, unpubl. masters thesis, May, 1977.

Krystiniak, J. A. A stochastic simulation of horizontal pedestrian circulation in buildings. State College, Pa.: The Penn. State Univ., punpubl. masters thesis, Sept., 1972.

Latane, B. and Darley, J. M. Unresponsive bystander: why desn't he help? Englewood Cliffs, N.J.: Prentice-Hall, 1970.

London Transport Board. Second report of the operational research team on the capacity of footways. London: London Transport Bd. Research Report #95, August, 1958.

Lozar, R. C. A methodology for the computer simulation of behavior-environment interactions in dining halls. In Carson, D. (gen. ed.) and Bazjanac, V. (ed.), Man-environment interactions, Part 10: computers and architecture. Proceedings of EKDA-5, 1974, 211-34.

Luce, R. D. and Raiffa, H. Games and decisions. In Shubik, M. (ed.), Game theory and related approaches to social behavior. New York: John Wiley and Sons, 1964.

Melinek, S. J. and Booth, S. An analysis of evacuation times and the movement of crowds in buildings. Boreham Wood, U.K.: Building Research Establishment, Fire Research Station, CP 96/75, October, 1975.

Meyers, W. T. Room arrangements and fire safety: an anlysis of relationships between dwelling unit spatial characteristics and fire losses in multifamily residential occupancies. Princeton: School of Architecture and Urban Planning, Princeton Univ., Unpubl. ms., 1977.

Moore, G. T. and Golledge, R. G. (eds.). Environmental knowing: theories, research and methods. Stroudsburg, Pa.: Dowden, Hutchinson, and Ross.

National Bureau of Standards. Design and construction of building exits. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, Misc. Pub. M151, 1935.

National Fire Data Center. Highlights of Fire in the United States. Washington, D.C.: U.S. Dept. of Commerce, National Fire Prevention and Control Administration, 1978.

Neisser, U. The imitation of man by machine. Science, 1963, 139, 193-7.

Nelson, H. E. Personal communications. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, Center for Fire Research, 1975.

Newell, A., Shaw, J. C. and Simon, H. A. Elements of a theory of human problem solving. *Psych. review*, 1965, *65*, 3, 151-66.

Pauls, J. L. Movement of people in buildings. Presented at the Symposium on Human Response to Tall Buildings. Chicago, July, 1975. Ottawa: National Research Council of Canada, Division of Building Research, June, 1975.

Peschl, I. Passage capacity of door openings in panic situations. *Bowen* (Construction), January 9, 1971, *2*, 62, 7.

Proshansky, H. M. Environmental psychology: a methodological orientation. In Proshansky, H. M., Ittelson, W. H. and Rivlin, L. G. *Environmental psychology: 2nd edition*. New York: Holt, Rinehart and Winston, 1976, 59-69.

Raser, J. R. *Simulation and society*. Boston: Allyn & Bacon, 1969.

Rubin, A. and Cohen, A. Human behavior in building fires. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, TN #818, 1974.

Saegert, S. Stress inducing and reducing qualities of environments. In Proshansky, H. M., Ittelson, W. H. and Rivlin, L. G. *Environmental psychology: 2nd edition*. New York: Holt, Rinehart and Winston, 1976, 218-223.

Schultz, R. L. The use of simulation for decision making. *Behavioral science*, 1974, *19*, 5, 344-50.

Simon H. A. Motivational and emotional controls of cognition. *Psych. review*, 1967, *74*, 1, 29-39.

Simon, H. A. *The sciences of the artificial*. Cambridge, Mass.: MIT Press, 1969.

Sinay, J. P. Unpubl. computer programming list.

Stahl, F. I. Simulating human behavior in high-rise building fires. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, NBS-GCR 77-92, 1975 (a).

Stahl, F. I. Performance-based fire safety provisions for tall buildings. Presented at the 6th Annual Conference of the Environmental Design Research Ass'n., Lawrence, Kansas, April, 1975 (b).

Stahl, F. I. Some factors influencing human responses in building fires: exploratory and experimental approaches. New York: Environmental Psychology Program, the City Univ. of New York, unpubl. ms., May, 1975 (c).

Stahl, F. I. Some prospects for simulating human behavior in high-rise building fires. In Suedfeld, P. and Russell, J. (eds.), The behavioral basis of design, Book 1. Stroudsburg, Pa.: Dowden, Hutchinson and Ross, 1976, 211-18.

Stahl, F. I. Human response to fire: three designs for research. Washington, D.C.: National Bureau of Standards, NBSIR 78-1508, 1978.

Stahl, F. I. and Archea, J. An assessment of the technical literature on emergency egress from buildings. Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards, NBSIR 77-1313, 1977.

Studer, R. G. and Hobson, R. H. Simulation of human learning in urban movement systems. In Preiser, W. (ed.), Environmental design research, Vol. 2. Stroudsburg, Pa.: Dowden, Hutchinson, and Ross, 1973.

Swartz, J. A. The importance of role identification in the behavior of people in fires. Paper presented at the Second International Seminar on Behavior in Fire, National Bureau of Standards, Gaithersburg, Maryland, October 29, 1978.

Togawa, K. Study on fire escapes based on the observation of multitude currents. Tokyo: Ministry of Construction, Building Research Inst., 1955.

Wolpert, J. and Zillmann, D. The sequential expansion of a decision model in a spatial context. Environment and planning, 1969, 1, 91-104.

Wood, P. G. The behavior of people in fires. London: Dept. of the Environment and Fire Officers' Committee, Joint Fire Research Organization, November, 1972.