LIFESAFETY ANALYSIS IN THE BUILDING FIRESAFETY ENGINEERING METHOD

by

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1.0 Introduction

The purpose of this thesis is to demonstrate and enhance the technical basis of the procedure for evaluating lifesafety within the Building Firesafety Engineering Method (BFSEM). A framework for the analysis has been documented, but not extensively tested in a building situation.[16] Hence, procedures to obtain the necessary input data and to evaluate that data needed to be developed. In addition, the general framework had to be tested rigorously enough to identify weaknesses.

Evaluating lifesafety in the BFSEM combines both people movement and smoke movement analyses. The lifesafety analysis in the BFSEM is quite different from traditional code approaches. Codes typically deal with designing exits for the building occupants. Time is implicit in the code approach. The BFSEM, on the other hand, attempts to identify the performance of the egress system for expected fires in the building. The method attempts to predict whether egressing people and hazardous conditions will occupy the same space at the same time.

One of the goals of this thesis is to define "hazardous conditions." Visibility conditions are most easily used for performance expectations because they can be easily understood by the general public and visibility obscuration often precedes the toxic gas or heat effects on an occupant. The method does not attempt to predict injury or death. It identifies the performance of a building's egress system relative to the time of tenability limits. People movement in fire situations is a very complex phenomena. Human behavior is difficult to characterize and it is often omitted from analyses due to its unpredictability. Research from the available sources is presented in this thesis, and some of the commonly recognized behaviors and social aspects are incorporated into the analysis. Another objective in this document is to demonstrate the way in which computer models can be integrated into the lifesafety analysis. HAZARDI and CFAST are used to predict smoke movement and visibility in a target space. EVACNET+ is to simulate people movement. These computer models are used in this project but are not a requirement of the analysis because the major objective was to test and evaluate the procedures of the BFSEM. There are a number of other available models that could have been used to obtain the data.

The aspects of the analysis are presented in this thesis and demonstrated in an example. The example case is the test building used in the CIB/W14 firesafety symposium sponsored by the University of Ulster, Northern Ireland in September 1993.

2.0 Lifesafety Analysis

Lifesafety is devoted to the preservation of life and the avoidance of long term injuries. There are a number of aspects that constitute lifesafety. These include the effects of fire, smoke, toxic gas and heat on people; the design of egress systems; and an understanding of human behavior in fires.

This chapter will focus on the traditional concepts of lifesafety including the description of means of egress and the design of means of egress from a building code point of view. Sources that will be used are NFPA 101, *Life Safety Code* [38] and an example model building code.[11] Concepts of lifesafety will be expanded in the Section 2.1. Following that, the components of the means of egress will be defined and egress design will then be discussed. Finally, an example of the code approach to egress analysis will be provided using the *Life Safety Code* [38] and the BOCA National Building Code.[11] The study of human behavior is an important aspect of lifesafety. Chapter 3 will discuss this topic in greater detail.

Defend in place also should be identified as an aspect of lifesafety, because this is a possible solution for many occupancies. Defend in place is most appropriate for buildings housing the physically or mentally handicapped, the incarcerated and, to some extent, the occupants of very large buildings. Areas of refuge are protected areas where people can wait in relative safety for fire extinguishment and rescue. This is an important issue to the handicapped, especially with the adoption of the Americans with Disabilities Act, also known as ADA. ADA extends comprehensive civil rights to over 43 million individuals with physical disabilities. It does have, and will continue to have, a major impact on the design and operation of buildings. However, this is a very complex issue that on its own would be a challenging thesis topic. Instead of devoting a small section to the handicapped and not giving this problem the attention it deserves, it is not included in this analysis, but is recommended for further work.

2.1 Introduction to the Principles of Lifesafety

Lifesafety pertains to the overall protection of people, which encompasses much more than means of egress. Topics in lifesafety include the physical and physiological effects of fire, smoke, toxic gas and heat on people, as well as defending the occupants in place or enabling them safe egress out of the building. As a means of giving a general overview of lifesafety, some of the general concepts included in NFPA 101, *Life Safety Code*, are described. NFPA 101 was first introduced in 1927 and has undergone numerous revisions since the first edition. The NFPA Committee on Safety to Life has assembled some of the primary objectives concerning occupant safety from fire. Unlike the building codes, which are concerned with both the loss of property and life, NFPA 101 is devoted solely to the preservation of life. The *Life Safety Code* is the basis for many local laws and regulations as well as a guide to good practice. NFPA 101 is versatile in that it is intended to be applied to both new and existing buildings. Another difference is that NFPA 101 makes little distinction between occupancies of buildings, except where limitations of the occupants require that it be given consideration.

Means of egress are not the only consideration in lifesafety. There are many other factors that enter into the picture. Smoke, toxic gases, fire and heat can have a profound effect on occupants attempting to egress. The effects can classified into three categories: narcotic, irritant and thermal. [5] Narcotic effects refer to the gases interfering with the body's intake of oxygen and utilization by the body's cells. [5] For example, the carbon monoxide molecule attaches to red blood cells more proficiently than oxygen thereby preventing cells from absorbing vital oxygen. It has been shown that small doses of carbon monoxide can cloud judgment. Other gases, such as CO_2 and HCL, have irritant effects on humans. These gases cause irritation of the eyes and respiratory tract. [5] Flame and heat cause skin and lung damage as well as systemic overheating. [5] Damage to the skin may be caused by radiative heating and may occur without contact with flame or products of combustion. This will be covered more in depth in Chapter 6.

The *Life Safety Code* addresses these and other special situations and gives guidance in providing extra safety measures. These include materials for interior finish that have low flame spread rates and reduced smoke producing properties. Other safety measures that are discussed are the use of automatic sprinkler and smoke control systems. The last two provisions are key applications in protecting occupants in areas of refuge until exits become passable, the fire is extinguished or the people are rescued.

The preceding paragraph mentions just a few of the guidelines and requirements set forth in NFPA 101. [38] A more complete list is shown below:

1. Properly designed and unobstructed means of egress
2. Protection of the means of egress from fire, smoke and heat for the total egress time
3. Provisions for alternate means of egress
4. Use of areas of refuge where total evacuation is not a consideration

5. Protection of vertical openings to limit smoke and fire spread as well a limiting the operation of fire protection devices
6. Use of detection or alarm system to warn occupants
7. Sufficient use of lighting in means of egress
8. Proper marking of exits
9. Protection of areas of higher hazard that are capable of producing large fires and endangering egressing occupants
10. Effective and proper use of fire drills
11. Use of instructional materials where deemed necessary
12. Use of low flame spread rate and reduced smoke producing materials for interior finish

The list above covers a number of topics including manual suppression, barriers, fire growth, smoke movement and egress. The list below organizes the topics with regard to functional firesafety, and identifies guidelines and requirements that correspond to each.

- Fire growth - 5, 9, 12
- Manual suppression - 3
- Barriers - 5, 9
- Smoke movement - 5, 9, 12
- Egress - 1, 2, 3, 4, 6, 7, 8, 9, 10, 11

The reason for the multiple lifesafety features is that the writers of the *Life Safety Code* realize that systems occasionally do not function because of either human or mechanical failure. Thus, NFPA 101 recognizes the importance of redundant systems, all of which are capable of providing a minimum level of lifesafety.[15] Therefore, in the case of failure of one system, the occupant is afforded a level of protection from the other systems.

The provisions addressed in NFPA 101, *Life Safety Code,* address the types of considerations that must be contemplated in lifesafety. Egress is only one component.

However, an egress analysis provides a sense of comparison for different architectural circulation designs. The following sections will discuss general aspects of egress and the building code.

2.2 A General Look at Egress

Although number of aspects that comprise lifesafety were discussed briefly in the previous section, the *means of egress* is given the greatest attention in the *Lifesafety Code*. One of the primary objectives in a fire situation is to get people out of the building. A means of egress is defined as a continuous path from any point within a building to a point of safety outside the building. The whole can be looked upon as an *egress system*. This system is comprised of three separate parts: the exit access, the exit and the exit discharge. Each portion of the egress system will discussed in depth.

The *exit access* is the part of the means of egress that leads an individual from any part of the building to the exit. A number of different components can act as an exit access. These include aisles, corridors, balconies, galleries, rooms, porches or roofs. The distance that one travels in order to reach to the entrance of exit is the travel distance that is described in building codes and standards. Travel distances are measured from the most remote point to the exit entrance. These requirements vary with the occupancy, and are affected by the presence of a sprinkler system. The components of the egress system should be designed to accommodate the maximum number of occupants. The provisions for calculating widths are given in the building code, along with the minimum allowed widths.

There are three main provisions that are typically studied when designing an exit access. First, it is important that the path be free and unobstructed at all times. This includes no doors that can be locked and no furnishings or protrusions to impede occupant flow. Next, the exit access should be level. Where this is not possible because of small changes in elevation, a ramp should be used instead of stairs, because people can trip on the stairs when the access is crowded. The other feature that is prominent in egress design is the presence of dead ends. These are exit access components that do not lead to an exit. In most cases, when a person is egressing and encounters a dead end, he has just passed an exit or made a wrong turn off the main corridor. Dead ends are not desirable elements, but are allowed in the code to provide the architect with design latitude for the effective utilization of space. Although dead ends are permitted, their length is limited in the code. For example, the BOCA Code limits dead end length to 6.1 meters (20 feet).[11]

The most commonly recognized portion of the means of egress is the *exit* itself. An exit is a separated path that provides a route to the exit discharge and eventually out of the building to safety. The term separated refers to a path that is protected. This means that the exit is enclosed by floors, walls, ceilings and doors having the required fire resistance that prevents products of combustion from entering the exit. In most cases, access to two exits is required from all interior points of the building. The building codes do allow buildings with one exit. These include buildings with no more than one floor below the level of exit discharge, provided they meet defined Use Group specific criteria. The criteria used to identify these structures are one or two stories above ground and either a maximum occupant load, a maximum travel distance or a specified number of dwelling units on these floors. Which criteria apply depends on the Use Group.

Width requirements for exits can be found in the code. Other important provisions that must be adhered to include: the path must not narrow moving toward the discharge, no protrusions or obstructions are permitted in the exit and doors must open in the direction of travel. There also are other guidelines stated in the code concerning specific hardware, such as handrails, handles, door hardware, panic bars and others that will not be discussed here because these details are too specific to the purpose of this document.

Exits may have both vertical and horizontal components, such as doorways, stairways, corridors, ramps and passageways. The types of exits that are permitted include doors leading directly outside or through a protected passageway to the outside, horizontal exits, smokeproof towers, inside stairs, outside stairs and ramps. Code provisions that apply to these components will be addressed in the next section. Escalators and moving walks may also be considered exits provided certain criteria are met. Note that elevators are not acceptable exits.

The last portion of the means of egress is the *exit discharge*. The discharge is the location that occupants go to upon leaving the exit. This would ideally be the exterior of the building, but may also be a lobby provided that it is located at street level, protected by sprinklers, separated from the floor below by, in most cases, construction with a 2 hour fire resistance rating, and has an unobstructed path to the outside. NFPA

101 allows a maximum of 50% of the exits to discharge onto the floor at street level, because a fire on that floor would force people to discharge into the fire area [38]. Also, it should be noted that discharging to the outside is not necessarily discharging to a safe place. If the areas are small and fenced or walled in, occupants may be exposed to radiant heat or falling debris. Discharge areas should provide room enough for the capacity of the exits they are serving. Another concern is stairways that continue to floors below the level of exit discharge. In their level of heightened anxiety, people may inadvertently pass by the discharge and become trapped on the floor(s) below. In this case, the code requires that some type of partition be installed to prevent an occupant from passing by the exit discharge to the floor below.

2.3 Code Approach to Egress

This section will present a more in-depth description of the code approach to egress, including illustrating an analysis for an example building. The code deals with *means of egress* as opposed to lifesafety. All building codes generally are similar except for some wording and slightly different requirements. For purposes of this description, the <u>1990 BOCA National Building Code</u> will be used. Here, it will simply be referred to as the code. Throughout this section examples of certain principles will be presented. All examples will be related to the building used at the CIB/W14 workshop held at the University of Ulster in September 1993. The building is a six story, multi-use facility with a total floor area of 2700 m^2. Floor plans can be found in Appendix A, Figures A-1 through A-5.

Building codes in the United States provide minimum requirements that are based primarily on defined standards and specifications, rather than on performance. The types of topics that the code section on means of egress discusses are [11]:

- General limitations
- Maintenance of exits
- Occupant design load for exits
- Type and location of exits
- Number of exits
- Requirements for exit accesses and corridors
- Doorways
- Horizontal exits
- Exit hardware (latches, handrails, guards, etc.)
- Special requirements for occupancies
- Revolving doors, ramps, stairs and fire escapes
- Signage and lighting
- Smokeproof enclosures

The section on general limitations notes some of the basic, good practice, do's and don'ts for a means of egress. These involve floor openings, protrusions, floor surface, open sides and elevation change. The next section on maintenance briefly addresses obstructions and exterior stairwell maintenance.

Following these introductory requirements is the section on occupant load. This is a primary quantity of exit design. The occupant load is the number of people for which exit facilities are designed. First, for a given building or part of a building the type of occupancy or Use Group should be determined. Buildings are classified into one of the following Use Groups [11]:

• Use Group A:	assembly
• Use Group B:	business
• Use Group E:	educational
• Use Group F:	factory and industrial

- Use Group H: high hazard
- Use Group I: institutional
- Use Group M: mercantile
- Use Group R: residential
- Use Group S: storage
- Use Group U: utility and miscellaneous

These occupancies are further separated into specific uses such as library, temporary or fixed seating assembly, courtrooms, classrooms, etc. From this information, the floor area (ft^2) per occupant can be found from a table in the code. The last piece of data needed is the floor area of the space. From this information, the number of occupants the exit shall be designed for can be found. As a example, take the office labeled "office 4" on Figure A-3. The room has an area of 1066 ft^2. In the code, Table 806.1.2 lists 100 ft^2 per occupant for office occupancies [11]. Assume that there are no adjacent spaces to this room. To find the total occupant load simply divide:

$$\frac{1066\,ft^2}{100\,ft^2/occupant} = 11\,occupants \tag{2.1}$$

In most areas, at least two exits are required. Each exit is permitted to serve half of the design occupant load, not the total occupant load.

The next requirements that are addressed involve the types and number of exits. This section deals with egress through adjoining spaces, requirements for assembly buildings, skating rinks, foyers and waiting spaces. Also, requirements are stated for exit discharges, including the protection of exits, the remoteness of exits and the length of travel. In a room, space or building that requires more than one exit, those exits shall be located as remotely as possible from each other.

The portion on length of travel is next in the section on egress. This indicates the maximum length of exit access travel. It is dependent on the Use Group of the building or area and whether a sprinkler system is installed. The presence of a sprinkler system will, in most cases, allow more lenient criteria, i.e. longer travel distances to be used. There are some exceptions to the requirements that are stated in this section.

The design basis for exits is the subject of the next section, Capacity of Egress Components. The code designs means of egress according to a minimum width based on the Use Group, the presence of a sprinkler system, the maximum number of occupants and possibly some additional requirements in the code. The Ulster building will be used to illustrate the process of calculating minimum stair and door widths. The fitness area on the fourth floor will be used for the example. The area can be seen in Figure A-5, labeled as "physical fitness suite".

$$\mathit{Stairs}: (0.3\,in./per)\,(200pp) = 60\,in. \qquad \mathit{Doors}: (0.2\,in./per)\,(200pp) = 40\,in. \tag{2.2}$$

Of course, there are minimum widths for each component that is required by the code. These requirements are stated in later sections on the individual egress components. Also note that where two egress components converge into one, the width shall be at least the sum of the two.

The next section gives information on the number of exits that are required. These guidelines are independent of the Use Group and are driven solely by the number of occupants. Criteria are also presented for buildings or areas with one exit. These are based on Use Group, the number of stories above grade, the number of occupants, and, in some cases, the travel distance. Some other provisions also are described concerning emergency escapes and open parking garages.

The rest of the chapter on means of egress goes into the requirements for the components of the system. The first components discussed are exit access passageways and corridors. The initial discussion involves the location at which exit accesses shall be provided. Then, some special requirements for specific Use Groups are identified. Of particular concern is the avoidance of long dead ends in any building or area. The code limits the length of dead end passageways or corridors to 6.1 meters (20 feet).[11] Next, the minimum width requirements are listed. Width restrictions are based on the occupant load with some special provisions for Use Groups I and E. For occupant loads greater than 50, the minimum corridor/passageway width is (112 cm) 44 inches.[11] This falls to 91.5 cm (36 inches) for occupant loads under 50 [11]. Of course, it should be noted that these are the minimum widths required. Any calculated width larger than these criteria becomes the design parameter. The remainder of this section goes into the fire resistance ratings required. These specifications are based on the same guidelines as most others, as well as the number of occupants, the Use Group and the presence of sprinklers. The maximum rating required in any Use Group is 1 hour.

Following the corridor fire resistance requirements, are some guidelines for assembly aisles and aisle accessways. This section applies specifically to Use Group A buildings. The requirements discuss all aspects of aisle design including, width, capacity, walking surface, handrails and others.

Next is a discussion of the requirements for means of egress doorways. Some of the requirements stated in the section on number of exits are reinforced here. Guidelines discussed include the number of doorways, location of doors, requirements for entrance and exit only doors, minimum widths of doors and detailed requirements for door hardware, such as locks, latches, bolts, special locking arrangements, panic hardware, power operated doors and sliding doors.

The last of the sections that will be discussed is the one on stairways. Minimum widths and capacities are included along with requirements for landings, headroom, vertical rise, treads and risers. Other provisions can be found for spiral and circular stairs, doors, direction of swing of doors, stairway construction, protection and requirements for exterior stairways. The code requires a width based on the minimum width or based on the number occupants, which ever is larger. Note that the earlier section on capacity of egress components allows the maximum number of occupants from any one floor to be used to compute the width, not the total number of occupants on all floors. Stairways, like corridors, should never decrease in width along their entire length.

These are some of the main, frequently used provisions in the code. They are given to provide a sense of the process of an egress analysis. Many other topics are included in the chapter on means of egress dealing with somewhat special components like revolving doors, horizontal exits, ramps, roof accesses, smokeproof enclosures, fire escapes, slidescapes, exit signs and lighting, guards and handrails. All of these are important to a good building design for egress.

The code is no more than a set of requirements. The chapter on egress is the only portion on lifesafety in the code. A number of aspects are missing from the code and that precludes it from dealing with lifesafety fully. Although, egress is the dominant part of lifesafety. Many of these requirements have no technical basis, although they can be recognized as good practice. There is really no way of objectively comparing an egress design. A design may be code compliant, but its performance may be less than satisfactory. The next section on the Engineering Method attempts to evaluate the performance of a building for egress so that different building designs can be compared.

3.0 Engineering Method and Lifesafety

The Building Firesafety Engineering Method contains the framework for a lifesafety analysis. The BFSEM lifesafety analysis describes the likelihood that occupants and untenable conditions will occupy the same space at the same time. The BFSEM is best applied to existing buildings or to compare different building design alternatives. Prior to this thesis, the approach to lifesafety had limited experience and was in need of more rigorous testing. The main focus of this thesis will be to apply the BFSEM for the lifesafety analysis using computer programs as a basis for quantification of the egress and smoke movement analyses. This proposed approach is quite different from the code approach that focuses on egress design requirements. The method takes a more in-depth look at the performance of the egress system as a whole and how it relates to the building and its occupants. The method does not deal with the specifications of egress design directly, although those components are a part of the building egress. It focuses on evaluating the *performance* of the system for a specific building or egress alternative. People movement and smoke movement are the two key analyses that must be performed in developing the lifesafety analysis. Human behavior is a major factor and needs to be incorporated into the egress analysis to obtain more meaningful, realistic results from the lifesafety analysis.

The BFSEM approach deals with the egressing occupants and identifies if those occupants are in any danger of occupying an untenable space during their egress. The principal threats to people from a fire as they are evacuating a structure are smoke and toxic gases. Heat and structural collapse are secondary hazards that occur relatively long after smoke and toxic gases affect the occupants. Toxic gases are more hazardous to the occupants than the smoke. However, visibility obscuration due to smoke normally occurs before toxic gases seriously affect the occupants. Therefore, the lifesafety analysis will be based on visibility obscuration. One of the goals of the thesis will be to identify criteria for visibility. One of the reasons that visibility obscuration is used is that it is more easily understood by the general public in addition to being easier to quantify than toxic products of combustion. It is also possible to base the analysis on products of combustion or heat. The overall goal of the lifesafety analysis of the Engineering Method is to evaluate building performance and to identify a relative level of risk to the occupants in the building design.

Figure 3.1 shows the possible outcomes for a complete lifesafety analysis. The network is intended to be a visual representation of all possible outcomes of an individual with regard to safety to life in a building.

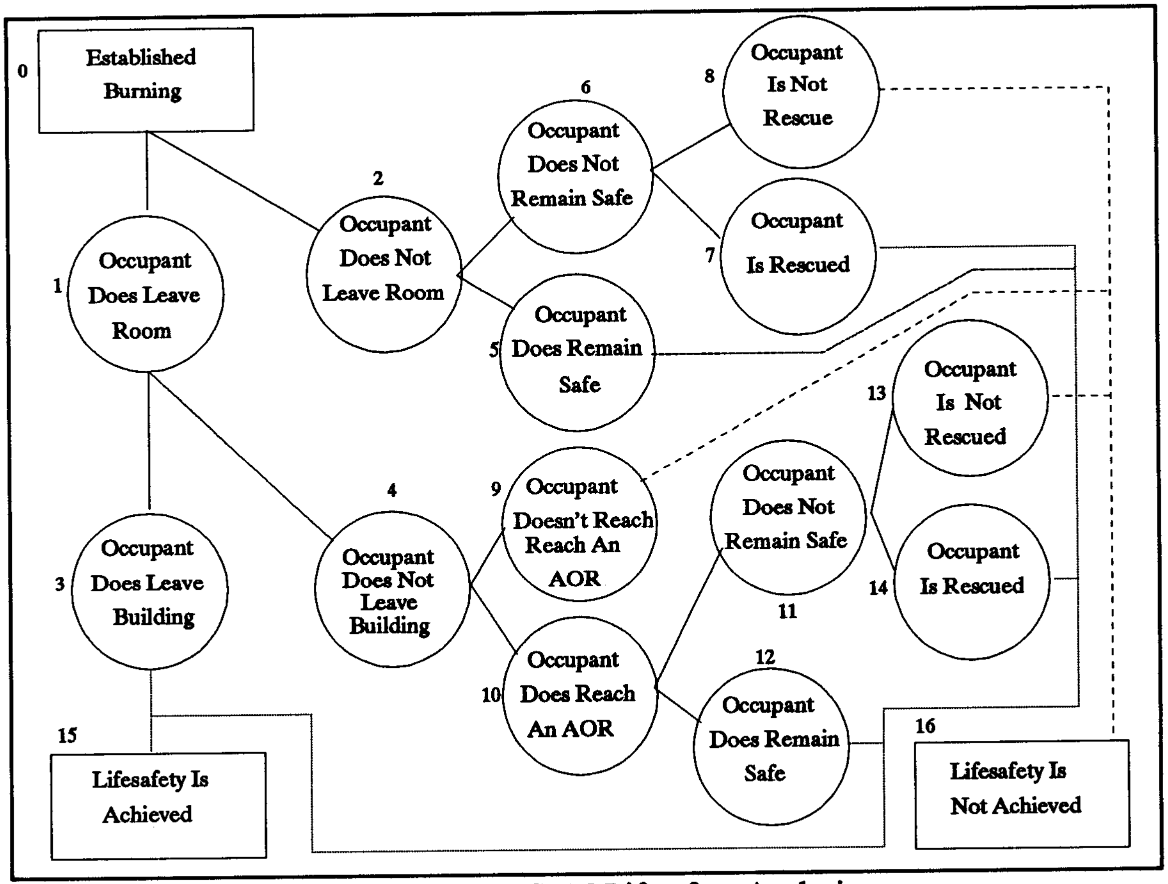


Figure 3.1 - BFSEM Lifesafety Analysis

In Figure 3.1, the usual successful evacuation from a building is identified by the Path 0 - 1 - 3- 15. A defend in place or remain in place situation is denoted by the Path 0 - 1 - 2 - 5 or 6. The occupants have chosen to remain in a place where products of combustion may or may not affect them. Beyond that, the occupant may or not be rescued, as shown by events 7 and 8. The lower path, events 0 - 1 - 4 - 9 or 10 - 11 or 12, describes the area of refuge scenario. Here the occupants reach a place that is designed for or accidently provides sufficient protection from the fire and the product of combustion. Whether or not the occupants are rescued is described by events 13 and 14.

The lifesafety analysis will be a combination of two sections of the Engineering Method. These involve people movement and smoke movement analyses. The principal goal will be to identify the likelihood that people and untenable conditions will occupy the same space at the same time. If the lifesafety analysis shows this to be true, the building performance is deemed unsatisfactory. Conversely, if people and untenable conditions do not occupy the same space at the same time, building performance is satisfactory. It should be noted that the likelihood of injury or death are not being evaluated. Science that relates dose rate and total dose that leads to death or hospitalization is not yet developed to the level of making rational decisions for design. Consequently, tenability based on visibility criteria is used as the basis for evaluation. When additional criteria are developed well enough to use for performance evaluation of buildings, they may follow the same format as this analysis. The lifesafety performance analysis is especially useful in identifying weaknesses that may be present in a code complying building design.

The type of information that is needed for the lifesafety analysis varies greatly from the code analysis. In fact, the code analysis is the first step done in the method. Even though it can be assumed that most buildings are code compliant, this step gives additional insight into the means of egress design. Following this stage, a number of specific events need to be characterized in order to begin evaluation of lifesafety.

The initial step in the analysis is to choose target spaces in the building. Target spaces are selected because the size and complexity of most buildings make performance analysis involving every room impractical at this time. Target spaces are usually the spaces that are important to the successful egress of the occupants.

Another step involves construction of the smoke movement curves for target spaces. The smoke movement curves and the egress timelines will have the same scale and, thus, may be compared to determine the likelihood that people and smoke will occupy the same space at the same time. However, this in no way attempts to predict death or injury. A computer program will be used as a basis for constructing the smoke curves. Computer results produce a deterministic evaluation. The BFSEM takes those computer results and evaluates the degree of belief that they are appropriate for the specific building and fire situation being studied. In this analysis, the identification and weighting of uncertainties is used to construct a probablistic curve. The probablistic curve is conveys the degree of belief that a room will maintain tenable conditions for a given length of time. The smoke movement analysis is discussed in depth in Chapter 7.

The other portion of the lifesafety analysis is the egress analysis. This includes the construction of the egress time line. The egress time line has two parts. The first segment is the time to start egress. This is the time duration from established burning until the occupant(s) decide to leave the room. A number of factors including fire size, fire detection, location, alerting the occupant, the occupant's state of mind, and others affect this part of the egress time line. The second part of the time line is the actual time to reach various target spaces along the egress path. This involves the time duration between the occupant deciding to leave the room and the occupant reaching the target space. Three different times to reach target spaces along the egress path should be developed. These are:

- the most optimistic reasonable time
- the most likely reasonable time
- the most pessimistic reasonable time

The time to egress may be based on results of a computer model. The two time durations of time to from established burning to leaving the room and time duration along the egress path are then combined into a total expected egress time line. The egress analysis process is described in depth in Chapter 8. The combination of the two analyses form the base of the lifesafety analysis, which is discussed with an example in Chapter 9.

The differences between the Engineering Method and building codes are apparent. The building code establishes criteria for the design of means of egress, but has no way of determining the ineffectiveness. The BFSEM is a tool that looks at the performance of the means of egress in relation to the building and its occupants. The BFSEM is capable of showing differences between different design alternatives. The two approaches are complimentary rather than comparable.

4.0 Human Behavior

People have many different reactions to a fire. A number of studies have attempted to identify the behaviors and behavioral tendencies associated with fires. The prominent researchers of human behavior are Bryan, Wood and Sime. Bryan and Wood identified human behaviors from interviews of people involved in fires conducted by fire department personnel.[10,60] These studies were comprised of a large number of people. Sime conducted a smaller scale experiment using only five fires, along with other experimental methods to arrive at conclusions about human behavior. Other studies have been performed that characterize what might be termed behavioral tendencies.

This chapter will the more significant aspects of human behavior from a building design viewpoint. The findings of these researchers will be described in this chapter. This information is important in the development of a lifesafety analysis in the Engineering Method. First, the processes that are involved in making decisions will be examined. Following that, will be a discussion of panic and the appropriateness of the use of this term. Next, some of the common behavioral tendencies will be discussed. Lastly, the behaviors of people in fires that have been reported in the studies of Bryan, Wood and Sime will be examined.

4.1 Individual Decision Processes

What goes into an individual making a decision? There are seven processes that may be used in trying to structure and evaluate threat cues [59]. This section will discuss those processes that are active in fire situations. Of the seven, the six that have been identified as active processes are [15]:

- Recognition
- Validation
- Definition
- Evaluation
- Commitment
- Reassessment

The relationship between these processes is shown below in Figure 3.1. [15]

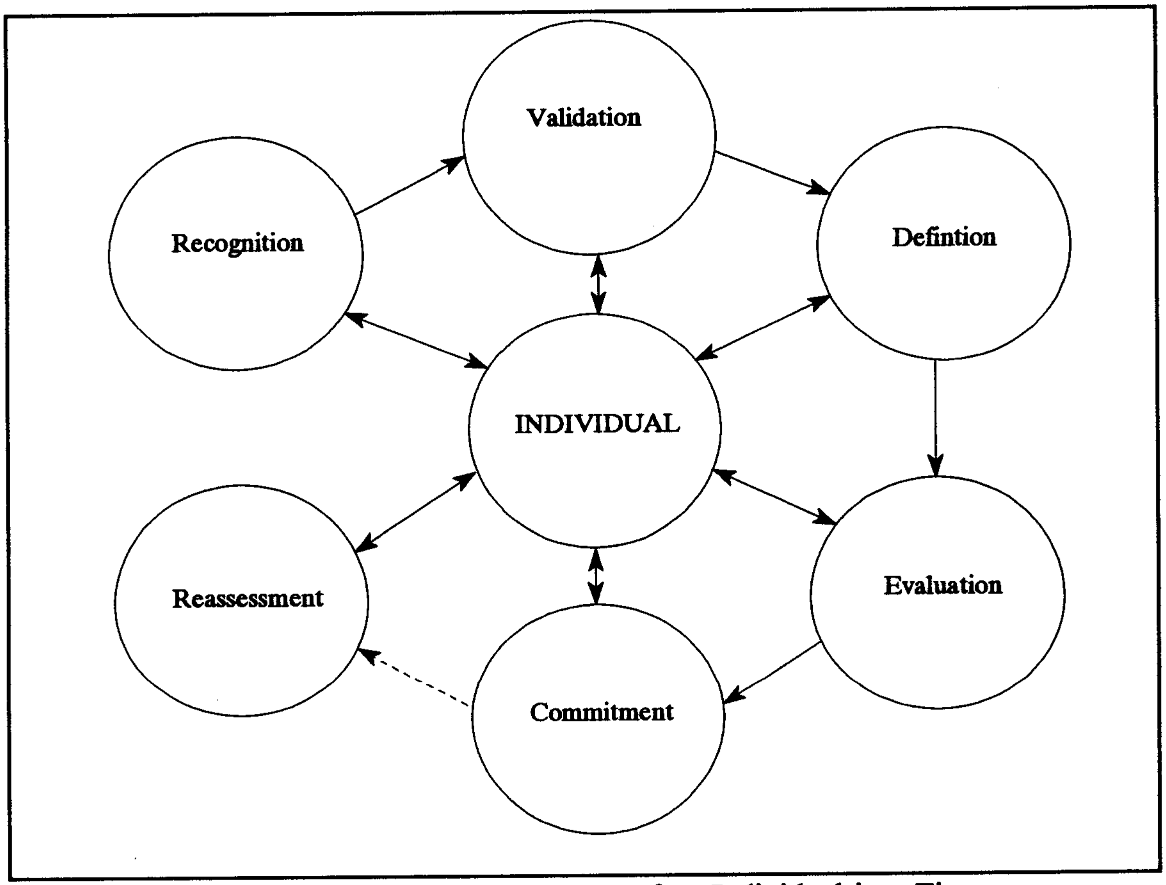


Figure 4.1 - Decision Processes of an Individual in a Fire

The process that occurs when the individual first perceives signs of a fire is called recognition. Far before the obvious sign of fire such as flame and heavy smoke appear, slight cues are received by the individual. These cues are not always indicative of a fire, but are usually continuous and steadily intensifying as the fire grows. These cues are initially processed as a more likely scenario from a past experience, such as a smoker or burning food. Bryan refers to it as an "optimistic wish." [15] The wish is possibly a direct result of an individual's sense of invulnerability.

The recognition process is very important in fire protection. Warning others, pulling alarms and evacuating the building are all actions that take place after the recognition of the fire. The smaller the number of cues that are needed for recognition of the fire, the quicker an action may be taken. This concept is also particularly important in the Engineering Method's approach to lifesafety. One of the problems is characterizing the initial part of the egress curve for the time it takes for the occupants to leave the room and start the egress action.

Validation is the process following recognition where an individual attempts to assess the seriousness of the signals. Usually the individual tries to reassure himself by rationalizing the mild nature of the cues and the improbability of the fire. During the processing of initial signs, the individual may attempt to obtain more information by questioning others in the area. The presence of others during the recognition and validation stages has been suspected of inhibiting or influencing the responses of the individual. [15]

The individual now attempts to relate the information received to some of the variables. These include the nature of the threat, the magnitude of deprivation of the threat and the time context. This is known as the definition stage. The stress of an individual is most often at its highest before the meaning of the situation is established. In other words, the worst aspect in a fire is not knowing what is happening. The role of the individual is significant in how the threat is perceived on a personal level.

The next process is known as evaluation. This can best be described as the cognitive and psychological activities necessary for an individual to react to a perceived threat. The stress felt by an individual becomes the controlling factor. The ability to control stress and anxiety levels is vital to an evaluation of the situation. In a fire, evaluation is the stage in which the individual decides what initial action to take; in most cases this involves either leaving the building or fighting the fire. Figure 4.1 relates these decision processes. The three processes prior to the evaluation stage normally must be completed within a few seconds due to the nature of fire generation and propagation. The characteristics of the physical environment at the time of evaluation are important in devising escape or defense plans. Other factors that may be important are proximity to exits, smoke propagation, flame spread and the influence of others.

As in the validation phase, the individual is vulnerable to the influence of others. Rather than relying on the their own judgment, people often tend to imitate the responses of other observed individuals. This phenomenon tends to lead to collective or group behaviors that may be destructive to all. Also important in the evaluation stage is the past experiences of an individual. Some level of familiarity with a situation will tend to reduce anxiety and stress and, therefore, enable the individual to respond with more adaptive behavior than those in unfamiliar roles.

Once the defense plans, whether fleeing or fighting, have be evaluated, the next step is to initiate the behavioral actions. This process is known as commitment. The response that has been evaluated will end in either success or failure. If failure occurs, the individual enters the next process of reassessment and then returns to commitment. If success should occur, anxiety and stress levels are, at least for the moment, diminished, depending on the situation into which the action has put the individual.

The process of reassessment is the most stressful for the individual. Reassessment is entered because a previous attempt to cope with the fire has failed. Reaction to the situation tends to become more and intense and, unfortunately, less selective. As successive failures occur, the individual becomes frustrated and levels of anxiety and stress are heightened. Hyperactivity often ensues as the stress level increases with failed attempts; individuals may even appear frantic. Some people reach a point where they give up losing mobility and the ability to communicate. It appears that these people perceive the threat of the fire as above their level to cope. Thus, they totally withdraw from the situation. This might be termed by many as the onset of panic. However, this is not normally the case. Section 4.2 will discuss this subject in more detail.

All the processes above are dynamic processes. The fire characteristics are changing constantly. The appearance of toxic gases and the propagation of flame and smoke influence all processes. Each process is constantly modified according to the threat. The influence of others also has a significant affect. In definition and validation, surrounding people may affect these processes rather obviously. As the discussion of human behaviors is expanded, appropriate references will be made back to these basic decision processes to further define each topic.

4.2 Panic

All too often the word *panic* is used in describing the actions of people in fires. The use of this term has also become quite frustrating to the behavioral researcher. A classic definition of panic is: [15]

> A sudden and excessive feeling of alarm or fear, usually affecting a body of persons, originating in some real or supposed danger, vaguely apprehended, and leading to extravagant and injudicious effort to secure safety.

From simulation experiments, panic has been defined as: [15]

> "A fear-induced flight behavior which is nonrational, nonadaptive and nonsocial, which serves to reduce the escape possibilities of the group as a whole."

The problem is in the application of this term to behaviors that lie outside the definition. The term panic has been used to describe situations where the behavior was rational and adaptive. This contradicts the definition above. The misapplication of panic is usually by outside observers, i.e. the media and public officials. These people have access to hindsight and outside information that the people involved in the fire do not. In many cases, the actions of the person or people involved were adaptive and rational under the circumstances and with the information available. One must return to the decision processes. Increased levels of anxiety and stress that are apparent can be traced back to the decision process of reassessment. As the number of failed escape attempts increases, the stress of the situation mounts and hyperactivity and frustration ensues. This might also serve as a common description of panic by the outside observer. But, note that under the situation these behaviors or actions may be adaptive and rational in the mind of the person in the fire.

As an example, two people jump from a fifth story building to escape fire and receive serious injuries. Prior to jumping, a number of unsuccessful attempts had been to egress that resulted in serious burns. Is this maladaptive behavior? It would most likely be said that these people panicked. But, did they have any other choice? The stress level of this situation is very high, but to the individuals in the fire, the choice to jump may have been the only recourse, given the information that they had. This appears to be adaptive behavior under the situation.

In crowded situations, the actions of a single person may be maladaptive to the group as a whole, but may be adaptive to the individual. For example, a parent moving against an exiting crowd trying to find a lost child. This is adaptive in that person's mind, but is maladaptive to the group as a whole.

The situations panic is most often describes are those in which multiple deaths occur. Often, there is little evidence to pointing to an actual panic. Then, why is panic continually used to describe these occurrences? Keating and Loftus give one possible explanation in a theory of social psychology called attribution theory. It states: [34]

> "...when the failure of others threaten the stability and predictability of our own world, we try to distance those failures from ourselves. Thus we tend to dismiss accidental fire deaths as the victim's fault: they panicked...we want to believe that the dead or injured were victims of their own maladaptive or panic behavior."

Whatever the explanation, it remains that panic is used describe too many behaviors. A panel on panic at an international seminar assessed the usefulness of the term. It was feeling of the panel that the concept was troublesome, but its use was ingrained through its frequent appearance in media accounts.

4.3 Behavioral Tendencies

People involved in fire situations tend to exhibit very similar behaviors. What is it that makes people act in a certain manner? Some researchers have explained what they term social factors. There are a number of common behavioral tendencies that can almost assuredly be observed in people in fire situations. These tendencies are important in that a profound effect can be seen in the egress of occupants. In most instances, the time it takes to evacuate a building is increased, which can lead to the loss of lives. The study and identification of these behaviors will help designers in creating more efficient egress systems.

Most people go to and leave work the same way every day. Not only do they take the same highways and roads, but also the same stairs, doors and corridors. This is one of the strongest patterns identified in the literature regarding behavioral tendencies. People do what is familiar and instinctive, such as use familiar exits. It is likely that people will travel longer distances to use a familiar exit rather than use unfamiliar exits. In fact, Sime have found familiarity to be the primary influence in exit choice. [49] This is a factor that is not taken into consideration by building codes in egress system design. The result is that people may travel longer distances and pass up closer exits. The significance lies in the fact that travel distance is a very important design parameter in egress systems. Another problem lies in the realization that a disproportionate number of people tend to use the same stairwell causing overcrowding and, ultimately, longer egress times. [12]

For example, take a building with a design that causes one stairwell to be used more than the other two or three stairwells. People enter through the "main" stairwell and go to their office the same way everyday. The process of going to work may almost be compared to a habit. In situations of high anxiety, habits are going to dominate decision making. If the occupants are forced to evacuate, habit will take over and a vast majority of the those people will egress the same way they do during normal times when leaving work. In fact, some may not even be aware of alternate ways out of the building. The result is that most of the people try to use the main stairs at the same time causing excessive delays in using this path. Relatively few people will use the other stairs. The problem is that the stairs were designed from a code viewpoint to accommodate a more evenly divided fraction of the occupant load than may actually occur. It can be speculated that occupant familiarity with the entire building layout would lead to decreased evacuation times.

The use of emergency exits relates directly to the issue of familiarity. Many buildings have a main entrance and exit and a number of emergency exits. These exits typically are equipped with panic hardware and alarms, so they are only used in emergencies. Emergency exits are not part of the normal circulation design of a building. This can have a significant effect on its use in an emergency. In fact, exits marked "Emergency Exit" often have the opposite effect of encouraging use during a fire.[49]

Behavior of people in groups seems to differ from that of one or two individuals. People will tend to follow a crowd when evacuating a building. If a group of people run for a particular exit, others are sure to follow. This phenomenon is also prevalent in detecting and reporting fires. A classic study was performed by Latané and Darley. This study shows the influence of social factors. The findings indicated that the presence of others lessened the likelihood of an individual reporting a fire. Subjects of the study were male undergraduate students. When alone, 75 percent of the subjects reported the smoke, with more than three quarters of those reporting the fire within four minutes. [34] However, when placed in a room with nonreacting others, the smoke was reported only 10 percent of time. [34] When three subjects were placed in a room, a single subject reported the smoke only 38 percent of the time. One possible explanation can be found from the decision processes discussed in Section 4.1. The processes involved in this situation are recognition and validation. Recall that these two stages of decision making are influenced by the presence of others. This behavioral experiment may help to explain the passiveness or dismissal of threat cues in situations where others are present. It shows that people behave conservatively in public places, such as restaurants, movie theaters or stores. The tendency toward this type of behavior is well documented in fires in these types of occupancies. Whatever the cause, the consequences of this type of behavior can lead to delays in starting egress.

Another behavior that has been observed is people looking to authority figures for information and direction. People will instinctively rely upon the individuals that they typically look to for directions in the work place. Managers and other authority figures are expected to give information in the early stages of a fire. Any delay or hesitation on their part will inevitably lead to longer egress times and the consequences associated with this.

All the behavioral tendencies described above are detrimental to the egress of occupants. A particular characteristic that can be quite helpful in fire situation is that people often assume familiar roles. A fact that is somewhat related to the paragraph above. Role assumption refers to people performing familiar tasks. This often is case with employees in a restaurant or a store. In studying the Beverly Hills Supper Club fire, Swartz found that people continued to assume their roles during the fire. [56] The staff of the club continued to assist their patrons who assumed a more passive role. It was noted that the staff in most cases tended to assist their particular tables or areas. Swartz implies that the loss of life could have been much greater were it not for the altruistic behavior of the staff. Bryan observed similar behavior in a study of nursing home fires. The study showed that the staff continued to perform their roles of responsibility even at some risk to themselves.

4.4 Observed Behaviors

Human behavior in fire situations is difficult to characterize. There has been much interest with social scientists and fire department personnel in obtaining this information. The primary manner in which this information has been obtained is through research studies in which people involved in fires were interviewed at the fire scene [43]. Interviews usually were conducted by fire department personnel. Wood's study in the early seventies in Great Britain was the first to use this approach.[60] Bryan used the same approach in a study conducted in the Baltimore/Washington D.C. area [10]. The primary objective of Bryan's study was to verify the data from Wood's study that had been collected on people movement through smoke [10]. Another similar study was conducted by Sime. This study was on a smaller scale than the previous two. In fact, Sime only gathered interview data for four buildings [49]. Other analyses were employed in addition to the interviews to reach conclusions.

The way in which a person reacts to fire is dependent on a number of factors. Individual factors include the role assumed, previous experience, education, personality and the perceived threat. The perceived threat is significant in the behaviors of people. People will react differently when they smell smoke as opposed to when they witness black smoke and flames. The way in which people are alerted that a fire is in progress determines to some degree the reaction of the occupants. Half of those involved in Bryan's study were alerted by either smelling smoke or being notified by others [10]. Other means of awareness of the fire include [10]:

- noise
- saw smoke
- saw fire
- heard fire department
- explosion
- felt heat
- electricity went off
- pet

A comparison of the British and U.S. studies show that the means of awareness were consistent between the two. The perceived threat with each of the above signals is quite different. The level of anxiety and stress resulting from each can vary significantly and influence the behavior of the individuals.

The environment also has bearing in the physical characteristics of the building and the available means of egress. In addition to these, the reactions of others in the area also have an influence [15]. The behavior of people closest to the fire will influence those further away. For example, if a person smells smoke and goes to try and find the source, the resulting reaction will be different than if he had chosen to warn others immediately. This will occur because the fire will have grown, perhaps significantly, during the time in between.

The one consistent characteristic of human behavior in fires is that it is generally altruistic and purposeful. [15] Although panic is often used to describe behavior in fires, it seems that this nonadaptive behavior is the exception, rather than the norm.

Bryan, Project People

Bryan's study, *Project People*, was carried out to verify the data from Wood's study. Much of the first part of the study is a statistical analysis of the input parameters. This included analysis of the fire scenarios and the study population. Fire incidents were analyzed according to geographic location, time of year of the fire, weather conditions during the fire and time of day of the fire. [10] Other analyses included fire and smoke characteristics of the fire, area of fire origin, floor level of fire origin, building characteristics (occupancy and height) and fire protection characteristics of the building. [10]

The study population was broken down in similar depth. The study population consisted of 584 people. [10] The first breakdown of the participant population was a demographic analysis. The participants were separated by geographical location, occupation, national origin, gender and age. [10] Further analysis was also done on the building population at the time of the fire, evacuation before or after fire department arrival, occupants not leaving building and occupants rescued.

One of the topics focused on was the significance of familiarity. Specific inquiries were directed at this subject on Bryan's questionnaire. Responses of the population were analyzed according to whether they either lived, worked or were visiting the building. A vast majority of those in this study ($\approx$94 percent) either lived or worked in the building. [10] Bryan also obtained information from the participants regarding the time that they had to gain familiarity with the building. For example, the number of months or years one had lived or worked in the particular building. Additional information was also gathered on the participants feeling of safety in the building. This contributes directly to their frame of mind and anxiety level when they first found out about the fire. Again, most people, approximately 83 percent, felt the building was safe. [10] Bryan also included questions about the belief of safety in particular components of the building.

Also obtained was information on the individual's distance from the fire, since it has been indicated that physical proximity is critical in determining an individual's response. [10] This information applies to the threat perceived by individuals, which would affect the decision process. It seems to be a good assumption that the closer a person is to the fire, the more threatening the fire is to that individual. Since a vast majority of the fires incorporated in the study were residential, most people were in close proximity to the fire. About two-thirds of the people were within 6.1 meters (20 feet) of the fire. [10] Another important fact that Bryan investigated was the incidence of prior fire experience or training. Although the two are not the same, it was assumed that people with such experience would react differently than those who did not. [10] A number of analyses were done on this information including the organization that provided the training, the number of times training was received and the date of the last course. For those with previous experience, frequency and most recent experience were the most pertinent pieces of information.

The next section of the report deals with the actions of the participants. The data was analyzed according to the first, second and third actions of the participants. In the study, a total of twenty four actions were identified and used for the study. A category titled "other" was used to cover actions by only one or two people. The actions identified in the study are: [10]

- Notified others
- Searched for fire
- Called fire department
- Got dressed
- Left building
- Got family
- Fought fire
- Got extinguisher
- Left area
- Woke up
- Nothing
- Had others call fire department
- Got personal property
- Went to fire area
- Removed fuel
- Enter building

- Tried to exit
- Went to fire alarm
- Telephoned other relative
- Tried to extinguish
- Closed door to fire area
- Pulled fire alarm
- Turned off appliances
- Checked on pets

First second and third actions were all analyzed relative to characteristics within the participant group. First action were broken down according to gender distribution, influence of previous training, effect of previous fire experience, belief in safety of building, distance from the fire and pervious alarms in the building. [10] Second and third actions were analyzed according to sexual distribution only and compared to each other and the first actions. [10]

Of particular interest in this thesis is the effect of smoke on the behavior of the participants. Bryan began by looking at the effect of smoke spread on the first actions of the participants. [10] It was decided to separate the severity of smoke spread into two categories; (1) Room and First Floor and (2) 2 to 7 Floors. [10] It should be noted that the extent of smoke spread was recorded by the fire department officer and many cases this may have been worse than the conditions at the time of the participants first actions. [10] In both categories of smoke spread, the most common first response was "notify others." [10] The first six actions in the list above were common to both categories in varying orders with the exception of "got dressed", which was much more prevalent in buildings with smoke spread of two to seven floors. [10] This was perhaps due to the fact that more extensive smoke spread was more likely during nighttime hours. [10]

The effect of smoke spread was evaluated with respect to the distance and time needed for egress. Of primary concern was the movement of people through smoke. Approximately two-thirds of the participants moved through smoke during the fire incident.[10] The mean distance moved through smoke of those who reported a distance was 9.08 meters (29.8 feet).[10] The population was further analyzed according to previous fire experience, previous training and gender. The final breakdown done with the people who moved through smoke was the visibility. First, people were classified according to the distance moved through smoke. The three categories for distance moved were (1) greater than visibility, (2) equal to visibility and (3) less than visibility. [10] More than 80 percent of those who travelled through smoke moved a distance greater than or equal to the visibility. [10] Lastly, specific distances that people moved through smoke were identified. The data showed that nearly 80 percent of the population moved through smoke with a visibility of less than 9.1 meters (30 feet). [10] This section provided useful information for the development of visibility criteria in Chapter 6.

Another portion of the study which was particularly useful was that on "turned back" behavior. Bryan looked at the subpopulation that was forced to turn back due to the effects of smoke, heat or both. Nearly 20 percent of the total population and 30 percent of the people who moved through smoke were involved in this behavior. [10] The visibility distance was the key parameter focused in on the analysis. Of the people that indicated a visibility, the mean distance at which turned back behavior occurred was just under 3.1 meters (10 feet). Of those who turned back, over 75 percent turned back at visibilities of 3.7 meters (12 feet) or less. Only 15 percent turned back in visibilities of 3.7 meters (12 feet) to 9.1 meters (30 feet).[10] This indicates that the majority of people travelled through rather dense smoke. This is to be expected because of the large number of residential occupancies involved in the study. These occupants were more likely to be familiar with the egress routes than people in other occupancies.

The raw data was then analyzed relative to the area of smoke spread in the building with no areas of statistical significance found. This was done while also looking at the reason for turning back. Over 60 percent cited smoke as the reason for turning back. [10] Another 30 percent listed both smoke and heat as the reason. [10] Bryan surmised that the people that turned back due to both were primarily affected by the smoke due to the very low number of people affected by heat only. [10]

The next constraint was the gender of the participant. Bryan found that the incidence of turned back behavior was almost equal among males and females. Turned back behavior relative to previous training was also addressed. The number of people included in this group was so small that Bryan feels that the statistical computations may have been affected. [10] Next, previous fire experience was considered. The number of participants that turned back and had previous fire experience was about 20 percent. [10] The rank of reasons for turning back were the same as for the total population. [10]

Wood, A Survey of Behaviour in Fires

Wood's study performed in 1972 was the model for Bryan's study. A summary of the main findings is included in Canter's book, <u>Fires and Human Behaviour</u>. This study, performed in England, involved 952 fire incidents and over 2000 people. Over 50 percent of the fires occurred in residential buildings. Other statistically significant occupancies included factories (17 percent), multi-occupancy buildings (11 percent), mercantile (7 percent) and institutional (4 percent).

In post fire interviews, the primary focus was in first behaviors of the occupants. Of the first behaviors noted, the four most frequent were:

- Fight the fire
- Contact the fire brigade
- Investigate fire
- Warn others

A number of outside factors were found to effect the first behavior of the occupants. The most frequent first action, fight the fire, was dependent on how serious the occupant thought the fire was. The more serious the fire, the less likely one was to stay and fight the fire. It was also noted that familiarity with the building layout did not play a role in a person's decision to leave immediately. Persons who had previous fire experience were no more likely to call the fire brigade than others. In fact, these people were more likely to fight the fire. Some generalizations are also drawn to gender and age in the first actions of the occupants.

Other behaviors that were analyzed included variables that led to increased evacuation time and factors that led to reentry behavior. The main influences in increased evacuation times were smoke spread and home environment, most likely due to people either fighting the fire or attempting to save personal belongings. Reentry behavior was observed much more in men than women and in the daytime hours versus nighttime.

Movement through smoke is of primary interest in this thesis. This data should not be confused with turned back behavior. Of the incidents in the study where smoke was present, 60 percent of the people attempted to move through smoke. Almost half of those people moved distances in excess of 10 meters. The fact that such a large percentage of people attempted to move through smoke was an unexpected finding.

Comparison of Bryan and Wood

The two studies done by Wood and Bryan are very similar. Wood completed his study in England in 1972. Bryan's study was performed in the United States and completed in 1977. The main goal of the later study by Bryan was to correlate the data that was gathered by Wood. [10] In fact, Wood participated in the design and planning of Project People (primarily on the questionnaire). This section will report some of the results of comparisons that are particularly important to this thesis.

Comparisons between the two studies were based solely on the numbers. No attempt was made to explain the differences the two studies. The first comparison looked at is the occupancies that the fires took place in. The number of fire incidents was much higher in Wood's study; 952 to 335. Both studies had residential as the most common occupancy, with a larger percentage in Project People. The two studies differ in the other main occupancies. Bryan's study had a large percentage of apartment buildings, and 2 percent or less of all other occupancies. [10] Wood's study had a large number of factories and a nearly equal percentage of apartments and shops. [10] The fact that the buildings in Bryan's study were predominately residential could turn out to be significant when comparing results because of the influence of familiarity on behavior.

The other important comparison was that on effects of smoke on the occupants.

The interesting observation is that a large percentage of people moved through smoke in both studies, 60 percent in Wood's study and 62.7 percent in Bryan's study. Of those in both studies that moved through smoke, a large percentage (75 and 80 percent respectively) did so at visibilities of 9.1 meters (30 feet) or less. The primary observation that is of interest in this thesis is turned back behavior. The comparison of the two studies is shows that most occupants turn back at visibilities of 3.7 meters (12 feet) or less. Wood's study showed that more than 91 percent turned back at visibilities of less than 3.7 meters (12 feet). Bryan's study had a lower percentage of around 76, most likely due to the fact that a larger percentage of the occupancies were residential. This data will be particularly useful in characterizing visibility criteria.

Sime, Human Behaviour in Fires, Summary Report

Sime conducted a study in the mid-eighties that took a different approach than Wood and Bryan. This study chose to focus on a series of highly detailed case studies as opposed to a questionnaire applied to a large number of fires. A total of five fires were used along with two monitored evacuations and two video-disc simulations. Sime contends that previous studies had weaknesses, primarily in the insufficient knowledge of the relationship between the people's behavior and the architecture of the building. [49] The objectives of this study were "to determine what factors may deter people who are escaping from a fire from using internal escape routes, and having established the factors, to assess their importance." [49] The factors include, in no particular order: [49]

- Smoke obscuration
- Fire characteristics (heat and smell)
- Familiarity with escape routes
- Characteristics such as age or infirmity
- Advice provided
- Light levels and light sources
- Role in occupancy
- Group dynamics and attachments
- Location and proximity to exit
- Information/communication on fire in progress
- Fire exit signs

The methodology of Sime's study varied in a number of ways. First, only five case studies were conducted on real fire incidents. The case studies involved major fires with extensive smoke spread. The analyses were comprehensive studies of the dynamics of exit choice behavior. Mapping studies were done on these fires based on police witness statements which were linked with Fire Brigade Investigation Reports. [49] Movements of people were traced on architectural plans and travel distance were recorded. Similar to previous studies, statistical analyses were conducted on the actions of the people. In this study, an "action dictionary" of 57 actions was assembled and later narrowed to 23. [49] Analyses of the fire incidents indicated that the floor location of the fire had more bearing that the travel distance. [49]

The portions of Sime's study that set it apart from those of Wood and Bryan are the monitored evacuations and the video-disc simulations. The second phase was the monitored evacuations. These were set in two lecture theaters that were identical except for location of the exits. [49] The goal of these evacuations was to establish the relative effects of architectural (exit position) and social factors on paths of movement. [49] These were particularly useful in that precise measurements could be made of people's movement times. Results showed that there was a general tendency to use the nearby exit. [49] It should be kept in mind that this was an assembly setting as opposed to a more complex architectural design. The important influences in exit choice behavior from this phase of the study were: [49]

- visibility and location of exits
- proximity of exits
- familiarity with escape routes
- instructions from authoritative source

It is interesting to note that on average, two-thirds of the egress time was spent in the time to start egressing, leaving one third for actual travel time. [49] One explanation from interviews is that the people indicated that they thought the alarm signified a drill and not real fire situation. [49] They also said that they still would have considered it as such in an emergency without further information. [49] This is significant in that building codes lend so much importance to travel distance and exit width when it appears that most of the time is spent in deciding to leave. Further findings by Canter and Wood tend to support this conclusion.[12,60] They found that people tend to ignore ambiguous cues and tend to investigate only when the cues persist. [28] Also, in multiple occupancy buildings, the trend was that an audible cue, a falling object or breaking window, alerted the occupant to the fire. [28] This indicates that people ignore initial cues and, thus, increase the time to start egressing. Another study was conducted in a theater after installing a sign ("Fire Exit Only") and restricting opening of the door to the inside only. The results showed a marked decrease in the usage of the fire exit as compared to the original study. [49] This supports the claim that fire exits are less likely to be used due to the restricted use and lack of familiarity. The results of the video-disc simulation were helpful in determining exit choice behavior, however the results were not definitive.

The literature review conducted in this study indicated that there is an assumption of a relationship between a visibility of 10 meters and reluctance to move through smoke. [49] However, the results of the study indicated that visibility had to be reduced to a few meters before movement through smoke was strongly deterred. [49] Sime's study concludes that a strict relationship between visibility and movement is unlikely without taking into account factor such as occupancy, familiarity, building architecture and goal of movement. [49]

4.5 Summary

The previous sections presented much of what is known about the influence of human behavior on people movement in fires. Much of the information was background required for a better understanding. Human behavior is both complex and difficult to predict for individuals. That is clear from the discussion. However, some significant factors that can be used in a building lifesafety analysis are as follows:

1. Familiarity plays a very important role in egress behavior. The more familiar people are with the surroundings, the more likely they are to move through thicker smoke.

2. Using particular routes or paths in a building on a regular basis is habit forming. If these routes are blocked during a fire, people will have a difficult time adjusting and finding other means of escape.

3. The type of occupancy relates directly to the level of familiarity the occupants have with the buildings and egress routes. Occupants of residential type occupancies are much more likely to be familiar with egress routes.

4. In occupancies where people are unfamiliar with the building, the main exit(s) is much more frequently used than side or emergency exits, likely causing congestion and increased egress times.

5. People tend to mimic the actions of others in emergency situations. Therefore, large crowds of people will be "attracted" to main exits.

6. Panic is both misused and overused in describing behavior in fire situations. Therefore, it is unnecessary to attempt to model it in the egress analysis.

7. Building architecture plays a significant role in human behavior. The more complicated, the more likely people are to move slower and feel higher levels of anxiety.

8. People who work in the building, such as waiters and waitresses, are likely to help patrons escape a fire.

These aspects of human behavior can be incorporated into the egress analysis. The computer egress model that was used in the building analysis does not simulate human behavior. Strategies were developed to simulate the behaviors listed above in the egress model. These factors will be discussed further in Chapter 8.

The CIB/W14 workshop building will be used to illustrate how the list above may be incorporated into the lifesafety analysis. The building is a six story structure containing multiple use groups. The total area is approximately 2700 m^2. Occupancies in the building include hotel/apartments, retail stores, offices, restaurants and recreational/assembly areas.

The building's occupants must be considered in how they relate to the factors described above. The occupancies contained in the building are predominantly for entertainment. Therefore, most people will use the building perhaps, as much as, once a week. Such infrequent use of the building by the majority of the people suggests that they are unfamiliar with the egress system. It can be expected that most people will use the main exits and that side and emergency exits will be under-utilized because many occupants do not know where they are located. Crowds of people will be moving to the main exit which will attract more people.

There are a few offices in the building, and it can be assumed that a small number of people are employed in the building. Thus, a small number of people use the building on an every day basis and will be somewhat familiar with the building circulation system. They may be able to assist others who are less familiar with the layout of the building.. However, these people also may be accustomed to using the same path in and out of the building every day.

The building circulation patterns are relatively simple. Large foyers in most areas connect to the means of egress. However, note that the side exits may be difficult to locate in emergencies and, thus, will be used much less than the main stairwell.

These factors will be taken into account in the egress analysis. Further discussion on the egress analysis can be found in Chapter 8.

5.0 Characteristics of People Movement

The building codes allow egress for all the people in a building. However, the provisions in the codes have no real technical basis. Many research projects have focused on identifying the characteristics of people movement. Pauls, Fruin, Togawa, the London Transport Board and others have performed work in this area. [42,43,20,58,35] Topics that have been addressed include occupant speeds in different egress components, flow rates, evacuation times, queuing and crowd movement. People movement is included in the egress analysis in the Engineering Method's lifesafety analysis. Data on occupant speeds and flow rates will be used to calculate inputs to the egress computer model. Research has led to the development of computer models that simulate people movement with some newer models attempting to incorporate human behavior. This section will discuss the important parameters the define people movement.

Typically, one would think that the only way to improve one's chances of escaping a burning building is to move faster. It has been shown that this is not entirely true through the examination of human behavior, which shows that the time to decide to leave has a substantial impact. However, speed is a significant factor in reducing egress times once a person starts to leave a building. Other measures of people movement are flow and density. Flow describes the number of people passing a point in a unit of time. This is normally expressed as pedestrians per foot width of walkway or stairway, per unit time. Density is a measure of the number of people per unit area. Often this is expressed in tenths of people, which is hard to visualize. The reciprocal of density, area per person, is much more useful.

Perhaps the most famous study performed in the area of people movement is that done by the London Transport Board in the late fifties. The committee was set up to study the flow of passengers in subways in order to assist in designing new facilities. Observations were made by counting the number of people passing through selected components in a given time, by measuring the number of people in a given area and measuring their speed. Controlled experiments were also conducted to assist in interpreting the results of the study.

Conclusions from the study were made regarding specific components of the system. Appendix D of the report contains tables listing the width, shape, flow per minute and flow per minute per foot of width for specific components. [35] Stairways are also listed and include an additional column for the number of stairs. One conclusion that the study considered important was the fact that connecting components should be considered as a system in which the maximum possible flow would be determined by the most restrictive element, usually a stairwell. [35] Therefore, it was recommended that stairways be of sufficient width to accommodate the expected traffic. It was also observed that there was an unconscious adjustment of speed with changing concentrations on all types of components.[35] At a certain point a maximum is reached and the flow remains essentially constant from that point on. Thus, no analogy could be drawn to fluid flow. [50] Actually, the argument was that fluid flow is essentially incompressible and the velocity is independent of density. [50] However, the study found that movement was highly dependent on density. [50] This showed that there could be no analogy drawn to fluid or gaseous flow.

Togawa also did a study in the fifties. A good deal of work was done surveying walking on level ground, sloped ground, through doors and on staircases in a variety of occupancies including department stores, apartments, theaters, museums, hotels and commuter train stations. [50] Work was done on the subject of individual walking versus group walking. Togawa's discussion of walking begins with a look at its regulating factors. It is shown that walking, although taken for granted by most, is very complex and is affected by over 20 factors which are classified into four major categories [56]:

- Circumstantial Conditions (weather, surface etc.)
- Physical Conditions of Pedestrians
- Clothes of Pedestrians
- Psychological Conditions of Pedestrians

There is also discussion of "experimental" walking versus natural walking. It was found that there was a marked discrepancy between the two, thus creating some uncertainty in experimental results. [56]

Fruin conducted studies in various building occupancies and characterized normal speeds and other behaviors under different crowd conditions. [20] Topics of specific concern were the measurement of pedestrian density, walking speed, walking flow rate, spacing, conflict and queuing. [50] The area per occupant was represented by the number of square feet per person, which is the reciprocal of the density. In fact, density has been identified as the most significant factor in determining walking speed. [20] In characterizing normal walking speed, Fruin has recognized some key elements that are not present during crowded evacuation scenarios. These include sufficient area for pacing, sensory recognition and reaction to potential obstacles. [20] As the density increases, there is a decrease in the area per person. Consequently, less room is available for variations in individual speeds as there is not an opportunity to pass slower moving people. This sensory recognition refers to the influences of others on the individual. Reactions to others can occur at distances as great as 7.6 meters (25 feet). [20] Fruin indicates that most people are somewhat affected at areas per occupant of less than 3.7 m^2/person (40 ft^2/person), but normal walking speeds may be expected down to about 2.3 m^2/person (25 ft^2/person). [20] Fruin's study contains data that will be used in the computer analysis, including densities (area per occupant) and speeds.

5.1 Parameters Used in the Analysis

The section above provided a brief overview of some of the research in people movement. The data included in the studies is to numerous to discuss in depth. The studies were used primarily to obtain parameters needed for the egress analysis, which will be discussed in Chapter 8. Data on walking speeds and densities was needed to obtain the input to EVACNET+.

Data from the work of Pauls and Fruin was used. Pauls characterized average walking speeds for a number of egress components including stairs and long and short corridors. The data was taken from a personal communication from Pauls. [42] Data on densities was used from Fruin's work. [20] Densities were presented visually which made the data easier to comprehend. Values used in the analysis for both walking speeds and people densities can be found in Appendix B, Tables B-1 through B-4.

6.0 Tenability

The BFSEM can use a number of factors as the basis for tenability criteria of a lifesafety analysis. Visibility, toxicity and heat are the effects of fire that are most often associated with tenability criteria. The process of using each effect in a building analysis is quite similar. The ease of doing a meaningful analysis based on the current state of information can vary. Nevertheless, a building can be evaluated for any of the fire effects if tenability criteria can be set and transport between the fire room and the target space can be predicted.

Toxicity deals with the thermal, narcotic and irritant effects of the products of combustion. Exposure to heat or flame can cause skin burns, damage to the lungs and systematic overheating. The effects of narcotic gases, the most significant of which are carbon monoxide and hydrogen cyanide, are observed from exposure to low oxygen conditions or any gas which affects the body's ability to utilize oxygen.[5] The lungs and eyes are susceptible to the irritant effects of products of combustion.

Narcotic gases are asphyxiants. Narcotic gases from fires act by preventing either the transport of oxygen to the cells or the use of oxygen at the cellular level, particularly the brain. The overall effects of depriving cells of oxygen are depression of the central nervous system causing symptoms similar to intoxication such as lethargy or euphoria and poor physical coordination. In the advanced stages, the affected people lapse into unconsciousness and death if exposure continues. The primary narcotic gases are carbon monoxide and hydrogen cyanide.

Carbon monoxide acts by binding to hemoglobin which is used to transport oxygen to the cells of the body. The combination of CO and hemoglobin produces carboxyhemoglobin, COHb. Hemoglobin is 200 times more likely to join to a carbon monoxide molecule as opposed to oxygen.[5] Nearly 50 percent of the fatalities from fires have been linked to carbon monoxide. [5] Carboxyhemoglobin percentages of 50-70 percent are considered fatal.[5] The actual point at which death occurs is dependent on the individual. People with circulatory problems or who have been exposed to heat stress, can be incapacitated at lower levels of COHb.[5] Also, it has been found that the COHb at incapacitation is dependent on the level of activity of the individual.[5] Therefore, in order to predict the point at which a person will become incapacitated, the carbon monoxide concentration, the activity level, the health and the size of an individual must be known. This is further complicated by the fact that the effects of CO are additive in an individual as opposed to the effects of visibility.

Hydrogen cyanide, HCN, is more toxic than carbon monoxide, but is not produced in all fires. Hydrogen cyanide blocks the body's ability to use oxygen at the cell level. Effects of HCN include hyperventilation, which further induces the individual to accelerate the intake of HCN. However, the effects of hydrogen cyanide are quickly reversible once a normal breathing environment is reached.

The effects of toxic gases are much more difficult to quantify than visibility. Thus, visibility is more easily used for performance objectives. However, the actual conditions in a fire will be a combination of irritant effects (visibility), toxic gases and thermal effects. Thus, the use of visibility is a somewhat simplified approach. Recall, that the BFSEM lifesafety analysis does not attempt to predict death or injury, but just the *onset* of untenable conditions. It is believed that visibility can be used as a good indicator of untenable conditions.

In this thesis, visibility will be used as criteria for the onset of hazardous conditions to illustrate the process of establishing tenability criteria. Visibility can be related to soot yield and, thus, predicted by a computer model. The value of visibility at the onset of hazardous conditions can be correlated best with data on visibilities that cause people to turn back. There is not an abundance of information available on this subject. Most research in this subject area has focused on the visibility of exit signs. Some research has been done in the area of visibility and decisions with regard to entering smoke, turning back, or attempting other movement.

The attenuation of light by an absorbing or scattering media is described by Beer's Law:

$$\frac{I_\lambda(L)}{I_\lambda(0)} = e^{(-k_\lambda L)} \tag{6.1}$$

where:
$I_\lambda(0)$ = initial intensity of the light beam
$I_\lambda(L)$ = intensity of the beam after traveling the path length L
k_λ = spectral extinction coefficient
L = path length

The extinction coefficient, k_λ, describes smoke's ability to absorb or scatter light. It is dependent on the optical properties and concentration of the soot. The extinction coefficient varies with wavelength,

$$k_\lambda \approx \frac{1}{\lambda^n} \quad where \;\; 0.6 < n < 1.4 \tag{6.2}$$

where: λ^n = wavelength

The exponent n changes according to the properties of the soot. However, this correlation for extinction coefficient is rarely used. It is common to use an average value of k_λ in the visible wavelength range.[5] In order to make predictions of the extinction coefficient, it is necessary to know the soot concentration. The extinction coefficient has been found to be directly analogous to the soot yield.

The use of the extinction coefficient has several key assumptions. One assumption is that no soot is lost to the surrounding surfaces. Therefore, the calculations will give conservative results for an actual fire. Also, properties of the soot itself are assumed to be constant. For example smoke aging (agglomeration, condensation and deposition) is unable to be accounted for due to the lack of practical models.[5] In an actual building fire this would be of little concern since this phenomena is associated with smoldering fires, not flaming enclosure fires.

There are several different equations used for predicting smoke obscuration. Beer's law, (Equation 6.1) can be converted from base e to an equivalent expression in base 10, as shown in Equation 6.3 below.

$$\frac{I(L)}{I(0)} = 10^{-DL} \tag{6.3}$$

where: D = optical density.

The optical density can be related to the extinction coefficient through,

$$k = \frac{D}{2.3} \tag{6.4}$$

The computer models used in this thesis track visibility through the optical density. The analysis uses the extinction coefficient. Therefore, the output data from the computer programs must be converted from optical density to extinction coefficient through Equation 6.4.

Visibility is the maximum distance in which a person can recognize an object through smoke. It requires the transmission of light from the object to the observer. The product of the visibility and the extinction coefficient has been shown to be a constant following Equations 6.5 and 6.6: [5]

$$Vk = C_{Vk} \qquad \textit{for } k < 0.25 \tag{6.5}$$

$$C_{Vk} = \frac{Vk}{0.133 - 1.47\ \ln(k)} \qquad \textit{for } 0.25 < k < 1.1 \tag{6.6}$$

The constant, C_{Vk}, varies with the brightness of the object, brightness of the room and the ability of smoke to scatter light. Equation 6.5 and 6.6 show that the product of visibility, V, and extinction coefficient, k, will always be constant falling into the ranges in Table 6.1 depending on the object that is being looked at. [26] Note that this is independent of the distance to the object.

Table 6.1 - C_{Vk} for Selected Objects

C_{Vk}	Object
5-10	Illuminated Sign
2-4	Reflective Sign
≈ 2	Wall, Floors, Doors, etc

Figure 6.1 below shows a graph of visibility versus extinction coefficient for three different values of C_{Vk}.

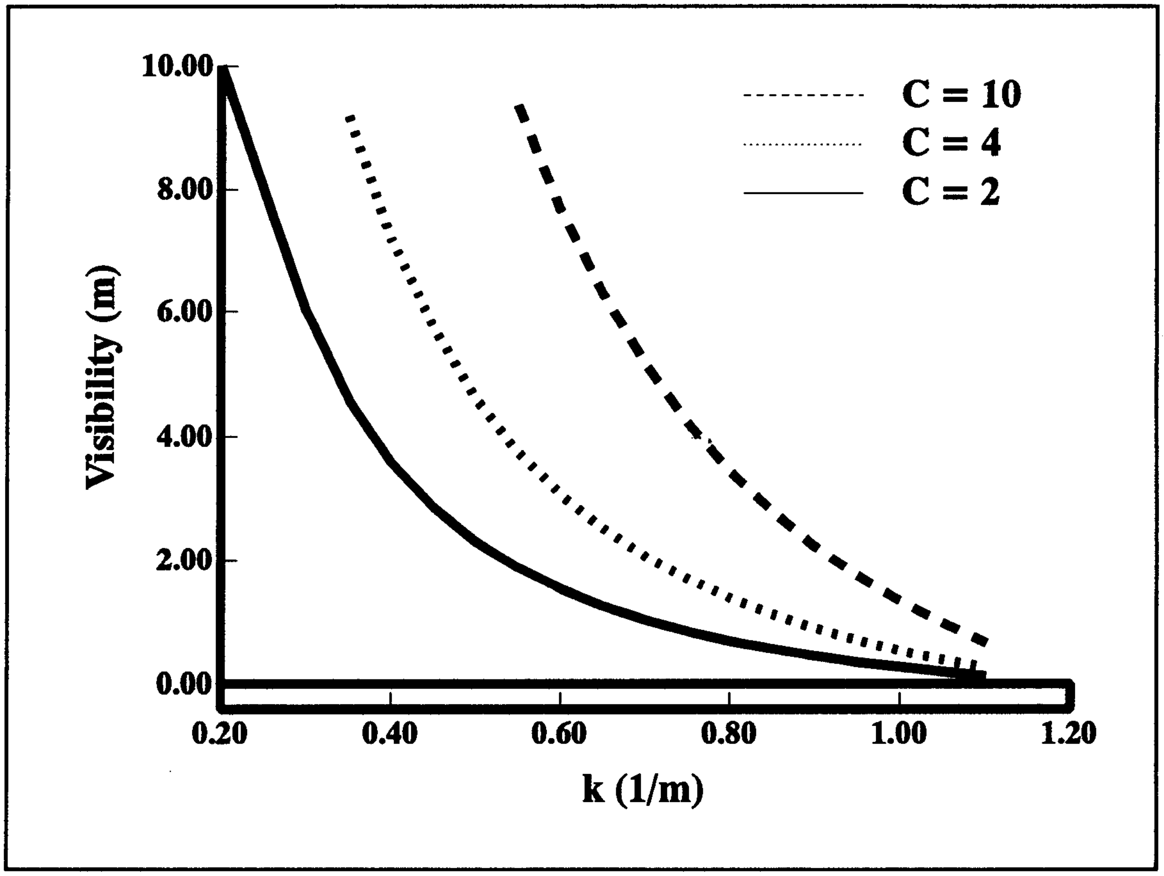
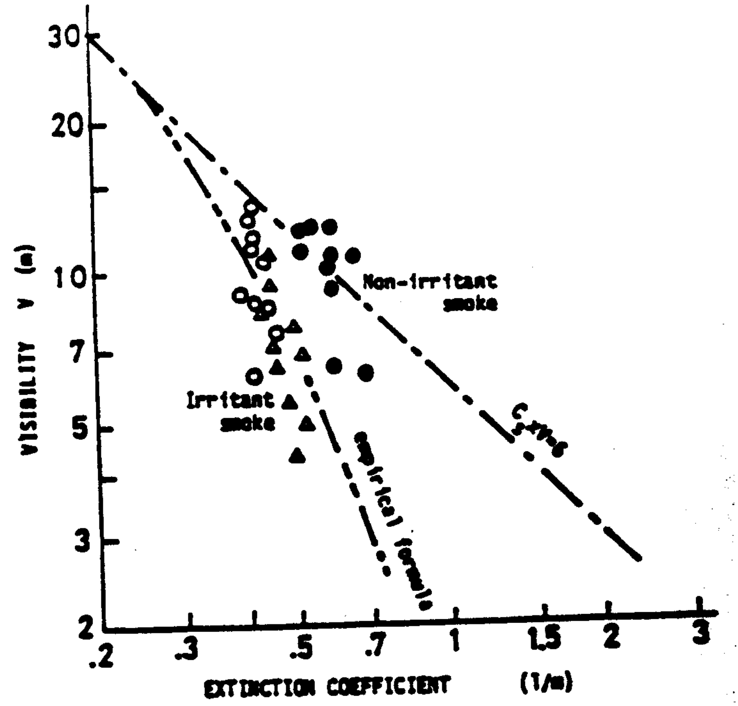
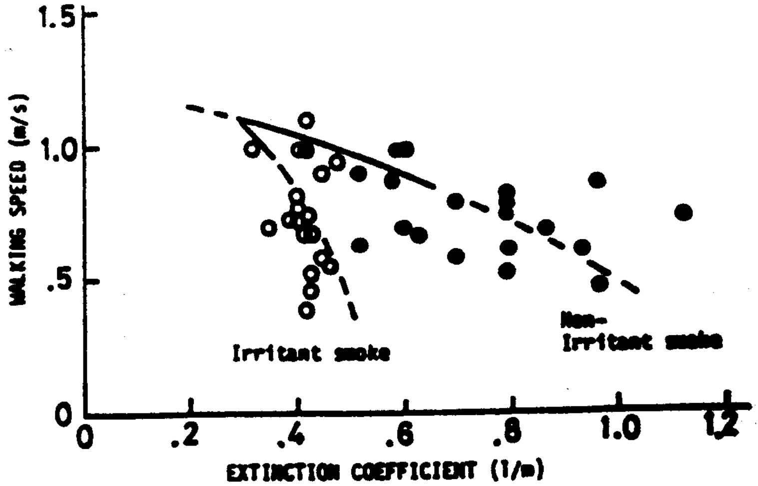


Figure 6.1 - Visibility vs Extinction Coefficient

The physiological effects of smoke, such as burning and watering of the eyes, are accounted for in Equations 6.5 and 6.6. The equations are based on experiments run in irritant smoke from smoldering wood chips.[26] Thus, the irritant effects of smoke are accounted for in Figure 6.1. However, there is no quantitative measure of the irritation from smoke available at this time to draw some comparison between different fuels.

As the visibility decreases, the ability and willingness of occupants to travel through smoke is diminished. Figure 6.2 shows a graph of walking speed versus the extinction coefficient. [26] The graph shows that walking speeds drop off gradually in


30
20
10
7
5
3
2
VISIBILITY V (m)
.2
.3
.5
.7
1
1.5
2
3
EXTINCTION COEFFICIENT (1/m)
Non-irritant smoke
Irritant smoke
empirical formula
C_s·V=8


1.5
1.0
.5
0
WALKING SPEED (m/s)
0
.2
.4
.6
.8
1.0
1.2
EXTINCTION COEFFICIENT (1/m)
Irritant smoke
Non-Irritant smoke

nonirritant smoke as compared to the sharp drop at approximately k = 0.5 1/m in irritating smoke. However, these results were obtained from controlled experiments, which at least minimize, if not eliminate, the psychological effects of an actual fire situation.

There are other factors that affect visibility. Smoke aging (agglomeration, condensation, deposition) should be considered because these phenomena yield larger particle sizes which in turn scatter more light, thus creating lower visibilities. The mode of burning is also important due to the fact that smoldering fires give off more dense smoke than flaming fires. The color of the smoke affects visibility. Visibility in white smoke is somewhat better than in black smoke of the same density. [26]. Building features are another important concern. Ventilation, both mechanical and natural, ceiling heights, automatic door closers and other features govern the spread of smoke and, thus, will affect visibility.

Bryan and Wood obtained data on turned back behavior from questionnaire surveys. In the Project People study, Bryan observed that 63 percent of the people needed to move through smoke to escape the fire. [10] Of those that moved through smoke, over 46 percent traveled distances farther than the visibility. [10] Residential occupancies made up nearly 85 percent of the buildings, and familiarity with egress routes undoubtedly played a role in an occupant's willingness to move through smoke when the exit was not visible. [10] Nearly 25 percent of the people who moved through smoke were forced to turn back due to the effects of smoke, heat or both. [10] Almost all individuals involved in turned back behavior (95 percent) did so at visibilities of 9.1

meters (30 feet) or less. [10] The mean visibility for those individuals who turned back was calculated to be around 3.1 meters (10 feet). [10] Interestingly, this visibility corresponds roughly to a walking speed of zero on Figure 6.3. [26]

Wood had a more diverse group of occupancies.[60] Only 57 percent of the buildings were residential. [10] Thus, more occupancies in this study involved buildings where the occupants were not as intimately familiar with the surroundings. Sixty percent of the population was involved in movement through smoke in this study. [10] Of the people that moved through smoke, almost 44 percent were forced to turn back. [10] A significant portion (91 percent) of the people turned back at visibilities of 3.7 meters (12 feet) or less. [10] Table 6.2 is a summary of the findings from the two studies.

Table 6.2 - Summary of People Movement Through Smoke

Study	Residential Occupancies	Moved Through Smoke	Turned Back	Visibility Turned Back		
				0-12 ft.	12-30 ft.	>30 ft.
Bryan	85%	63%	25%	47.6%	31.7%	20.7%
Wood	57%	60%	43%	64%	11%	25%

In Table 6.2, Bryan's study involved a much larger percentage of residential buildings as compared to Wood's study. Even though a comparable ratio of people in the two studies moved through smoke, there is a large difference in the fraction of people that turned back. Only 25 percent of those who moved through smoke turned back in Bryan's study compared to 43 percent. This data supports the finding that familiarity plays a significant role in egress behavior.

There are other factors that were not considered in the data above. Sime conducted a study which performed a more thorough analysis on only five case studies. None of the buildings incorporated into that study were residential. [49] It was noted in Chapter 4 that a visibility of 10 meters is the point at which people are inclined not to attempt egress.[49] However, it is generally thought that smoke is not a strong deterrent until the visibility is reduced to a minimum of a few meters, as was the case in the previous studies. [49]

Unfortunately, it is not appropriate to have a single value of visibility for the onset of hazardous conditions. This value should be dependent on the individual building and its occupants. Below is a list of factors that should be considered when choosing a value for the onset of hazardous conditions.

- Floor on which a person is located
- Occupancy
- Familiarity with egress routes
- Building circulation patterns
- Occupant physical and mental condition

The location of a person within a building will influence the conditions in which that person is most likely not to proceed through smoke. For example, an individual on the second floor of building will be more likely to move though dense smoke than an individual on the tenth floor of the same building. The person on the second floor may be willing to move through smoke with a visibility of 3.1 meters (10 feet) or less, whereas the person on the tenth floor may turn back when the visibility is 9.1 meters (30 feet) or more. In other words, the closer a person is to the exit or perceived safety, the more likely he is to try and reach that goal rather than to stop and await rescue. Therefore, the higher the floor that a target space is located on, the higher (more restrictive) the visibility criteria should be.

The occupancy of a building is important regarding the occupant's relative familiarity with the escape routes. In large office buildings, retail stores, hotels and multi-occupancy buildings, many occupants will, in most cases, be unfamiliar with the possible escape routes. Often, people are familiar with the exit path that they use when they leave the building. However, if that route becomes blocked, occupants will be forced to use another with which they may be unfamiliar. A smaller amount of smoke will cause to turn back. In residential type occupancies, such as apartment buildings, the residents should be more familiar with the building architecture and the various means of egress. Even if a small number of people are unfamiliar with the building, consider that people mimic the behavior of others and are likely to follow others to safety. With this in mind, people in these occupancies are more likely to travel through denser smoke to reach exits.

Building circulation patterns are another consideration in choosing the visibility criteria. It is obvious that buildings with complicated circulation patterns will be more difficult to escape from in a fire. Large open areas, winding passageways and dead end corridors will greatly affect people's ability to egress from a building. In cases where the building circulation is complicated, the visibility criteria will be more restrictive.

Table 6.3 shows a suggested tenability criteria for a building. The values are suggested visibility distances that may be used as tenability criteria for a building analysis.

Table 6.3 - Tenability Criteria: Visibility (ft.)

	Lower Floor	High Floor	Low Floor	High Floor	
Familiar	15	25	10	20	**Non-residential**
Familiar	10	15	10	15	**Residential**
Unfamiliar	20	30	20	25-30	**Non-residential**
Unfamiliar	20	30	15	25	**Residential**
	Complicated	**Complicated**	**Uncomplicated**	**Uncomplicated**	

This table was developed through subjective judgment involving general situations. It should be considered as an illustration of the nature and magnitude of the establishment of tenability criteria. In the absence of consensus performance criteria, the engineer must use his own subjective judgment in developing appropriate criteria for each individual case.

6.1 Example Case

The building used in the CIB/W14 workshop will be serve as an example case. The building is a six story, multi-use facility with a total floor area of 2700 m^2. Floor drawings can be found in Appendix A, Figures A-1 through A-5. Occupancies contained within the building include retail stores, restaurants/bars, recreational, offices and hotel. It is believed that the area around the main stairwell on the third floor is of particular concern. A large number of people will egress through this section of the building. Movie theaters on the third floor and the recreational areas on the floors above will likely have the majority of their occupants egress through this section of the building. The stairwell and the adjacent foyer will be the target areas. The target area is shown below in Figure 6.4. The entire floor layout can be found in Appendix A, Figure A-3. The room of origin is a third floor office connected to a foyer, which connects to the main stairwell. Both the foyer and the stairwell are considered target spaces. The stairwell serves the recreational areas on the floors above and the large occupant load from the movie theaters on the third floor.

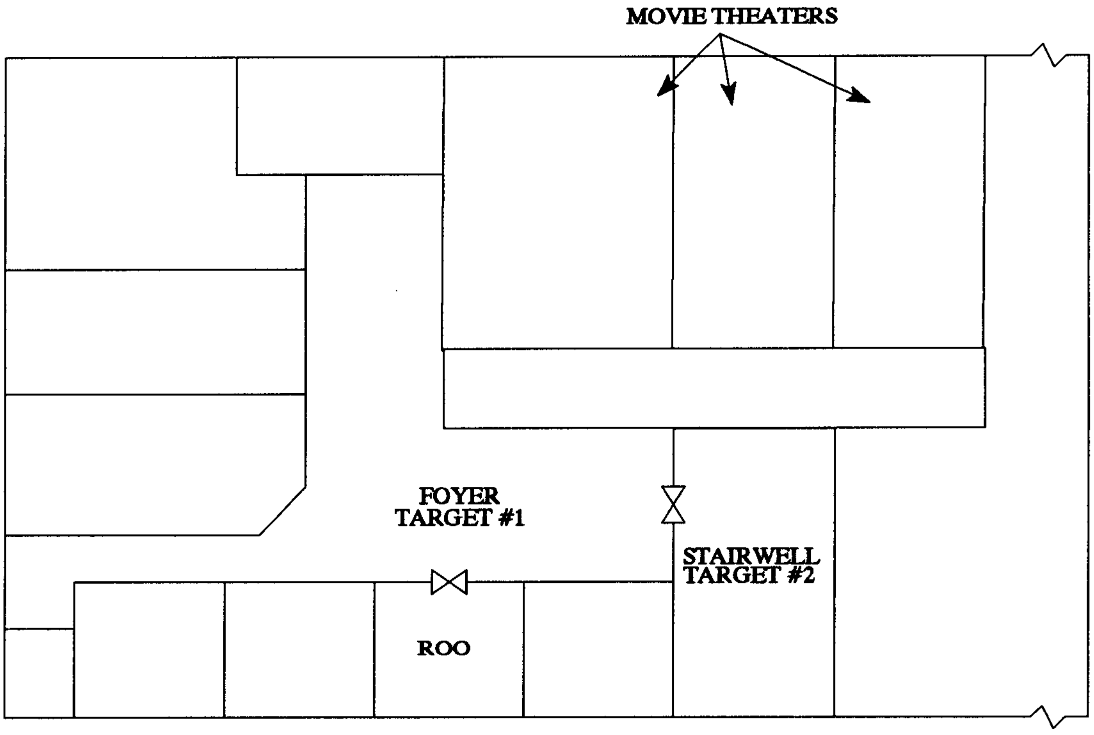


Figure 6.3 - Layout: Second Floor Ulster Building

The appropriate value for the visibility can be found by analyzing the considerations presented in the previous section:

- Floor on which a person is located
- Familiarity
- Occupancy
- Building circulation patterns

Both target spaces are located on the third floor. The third floor will be considered an upper floor for this analysis. Most facilities in the building are the types that people would use perhaps once or twice a week. There are some offices, but these contribute a very small portion of the total occupant load. Therefore, people using the building would generally be unfamiliar with all egress routes. The building is a multi-use facility containing no residential occupancies. The building circulation from the third floor up is somewhat complicated. All surrounding rooms connect to large foyers. Should these foyers become filled with smoke, an occupant may have difficulty locating the exits. Using these criteria,

- Located on an upper floor
- Unfamiliar with egress routes
- Non-residential occupancies
- Complicated building circulation patterns

a approximate visibility criteria can be determined from Table 6.2. From Table 6.2, the tenability limit is selected as a visibility of 6.1 meters (20 feet) or less. The foyer and stairwell have different characteristics which must be considered in choosing a final tenability criteria for each space. The foyer is a large open space. After the visibility drops below 6.1 meters (20 feet), people may encounter difficulty in locating the exits. Therefore, the tenability limit should remain at 6.1 meters (20 feet). In the stairwell, it is believed the tenability limit can be dropped to 3.7 meters (12 feet) because the occupants are "guided" down by the close proximity of walls and handrails.

These criteria will be used in the smoke movement analysis. Visibilities will be converted to extinction coefficient using Figure 6.1. The corresponding extinction coefficients for 6.1 meters (20 feet) and 3.7 meters (12 feet) are 0.29 1/m and 0.36 1/m respectively. These two values will be the tenability criteria for the foyer and stairwell.

7.0 Smoke Movement Modeling

The objective of the smoke movement analysis in the BFSEM is to determine the length of time that a target space is tenable. In this thesis, visibility is selected for the determination of tenability. Computer models will be used to predict the visibility over time of the target space. Two computer models were selected; FAST and CFAST. Originally FAST was chosen as the computer model to predict smoke movement in the building. Later it was determined that the mechanics in CFAST were better suited for the smoke analysis. Both models will be discussed in this section.

CFAST will be used to develop to deterministic smoke curves. Using these curves as a basis, the probablistic smoke curves will then be generated. The probablistic curves will convey the degree of belief that one has in the deterministic curves.

7.1 HAZARDI

The HAZARDI software is a collection of data, procedures and computer programs that are used to simulate the important phenomena occurring in fires. HAZARDI is based on a zone fire model, FAST, that allows simulation of up to 6 rooms with user defined connections and room size. The user is also able to define surface materials. The software allows the user to track smoke layer depth, temperature of both upper and lower layers, species concentrations, optical density and other phenomena. For this thesis, the primary concern is the optical density. For a given fire scenario, FAST can track the phenomena at a user specified interval. From FAST, the visibility may be tracked in a target space, and the time at which untenable conditions occur may be estimated. The procedure for developing smoke curves for the target space will be discussed later in this section. First, a brief overview of FAST will be presented, including some the assumptions and limitations inherent in the model.

The major functions of FAST include [46]:

- the production of energy, smoke and gases by one or more burning objects in a room
- the buoyancy driven transport of energy and mass through series of user-specified rooms and connections
- the resulting temperatures, species concentrations and smoke optical densities after accounting for heat transfer to surfaces and dilution and mixing with air

A number of calculational techniques from many disciplines have been incorporated into FAST. In some cases, fundamental laws such as conservation of mass, momentum and energy have been used. In others, complicated phenomena are predicted using empirical correlations. Within the correlations are assumptions that lead to uncertainties in the results. The inherent assumptions and limitations should be understood.

The transport of energy and mass between compartments is done in the model FAST.[46] FAST is a zone or control volume model. The primary assumption in FAST and other zone models is that a room may be divided into two or more zones. Each of these zones is assumed to be uniform in temperature and composition. All rooms in the model have two zones, with the exception of the room of origin which has an additional zone for the fire plume. The uniformity of the layers is an approximation of the two zones which are commonly observed in fires. Temperature and composition variations do occur within layers. However, these variations generally are small compared to the differences between layers. Beyond the zone model assumption, FAST is a mixture of established theory (conservation equations), correlations (entrainment coefficients) and approximations (post-flashover combustion chemistry), for conditions where there is no theory or data.[46]

The definition of the fire scenario within FAST requires detailed specifications. Many conditions associated with the fuel and the surrounding air must be identified and entered into the program. Inputs to FAST include:

- Heat release rate
- Heat of combustion
- Mass loss rate of the fuel
- The position of the fire
- Limiting oxygen index
- Ratios for estimating species concentrations including H/C, C/CO_2, CO/CO_2
- Type of fire (constrained or unconstrained)

The fire heat release rate is user specified. The heat of combustion must also be supplied, and from these two inputs the pyrolysis rate of the fuel is calculated. This data and information for some common fuels is included in the database in HAZARDI called FIREDATA. Data is only presented for a small set of products. The data for fuels is obtained from cone and furniture calorimeter tests on individual samples. These are not necessarily representative of behavior in similar items. In fact, some variation could be expected from identical items in successive tests. Consequently, the calculated results for any of these conditions will produce some uncertainty.

There are many uncertainties involved with small and large scale testing. In large scale testing, such as the furniture calorimeter, a number of sources for uncertainty exist including measurement error and the degree to which free-burning conditions are not achieved due to radiation from gases under the hood or lack of air entrainment [46]

Also, factors such as the fuel position within the room have not been investigated [46] In the case where small scale calorimeter data is used, it is often extrapolated to predict the behavior of the full scale item. Lastly, little data is available on smoldering combustion, high external heat flux conditions or low oxygen conditions.[46]

FAST requires that the user specify the type of fire that is being modeled. The two choices are unconstrained and constrained fires. For an unconstrained fire, all burning takes place inside the plume. For the constrained fire, burning will take place where there is sufficient oxygen. Constrained fires (type 2) are the only type to employ oxygen combustion chemistry. [46] In this type of fire, the model can track species such as soot, hydrogen, carbon dioxide, oxygen and carbon monoxide. However, this requires user-supplied ratios for which limited data is available.

Another possible source of error is contained in the entrainment coefficients, which are empirically derived values. [46] In a compartment model small errors in these coefficients are multiplicative as the flow continues away from the source. [46] Therefore, this could result in large errors in compartments farthest from the source. Data has shown that there is good agreement with three room fires, but more validation needs to be done for larger amount of rooms. [46]

In actual fires, the lower layer accumulates smoke and gases from mixing with the upper layer at doors and along walls. Doorway mixing has been included in the form of a mixing coefficient. However, mixing along the walls is not accounted for because of the lack of associated theory. Therefore, the lower layer concentrations may be underestimated. Lower layer temperatures may also be underestimated due to the fact that convection from the floor and lower walls is the only means of heat transfer. Radiation from the upper layer is not implemented.

Lastly, FAST contains a library of material that may be used for the ceiling, the floor and the walls. The data for these materials was taken directly from manufacturer's sources.[46] No attempt has been made to verify the data or to determine if the values are representative.[46] This, obviously, could lead to errors when calculating heat transfer to the surroundings.

7.2 CFAST

CFAST is the upgrade of FAST. It is the result of a merger between its predecessor, FAST, and CCFM.VENTS. The basic program works almost identically to FAST. The upgrade is in the mechanics the model employs.

The most important advance in CFAST over FAST is in the treatment of the conservation equations. Originally, pressure was assumed to be steady state and the equations were simplified. In CFAST, the equations are solved in their original differential form. This allows easier inclusion of various predicted quantities as they can simply be introduced in the source terms of the differential equation. [4872] The use of the differential equation also provides a model that works over a larger range of initial conditions. [4872]

The major functions of CFAST include [45]:

- the production of enthalpy, smoke and gases by one or more burning objects in a room
- the buoyancy driven, as well as forced, transport of energy and mass through series of user- specified rooms and connections

- the resulting temperatures, smoke optical densities and gas concentrations after accounting for heat transfer to surfaces and dilution and mixing with air

A number of calculational techniques from many disciplines have been incorporated into CFAST. In some cases, fundamental laws such as conservation of mass, momentum and energy have been used. In others, complicated phenomena are predicted using empirical correlations or even educated guesses. Within the correlations are assumptions that lead to uncertainties in the results. The inherent assumptions and limitations should be understood.

CFAST is a zone model. The primary assumption in CFAST and other zone models is that a room may be divided into two or more zones. Each of these zones is assumed to be uniform in temperature and composition. All rooms in the model have two zones, with the exception of the room of origin which has an additional zone for the fire plume. The uniformity of the layers is an approximation of the two zones which are commonly observed in fires. Temperature and composition variations do occur within layers. However, these variations generally are small compared to the differences between layers. Beyond the zone assumptions, the model is a mixture of established theory, empirical correlations and approximations for phenomena for which there is no theory. One approximation that greatly influences results is that of post-flashover combustion chemistry. [45]

An important limitation of CFAST is the absence of a fire growth model. [45] The program utilizes a user-defined fire. Many conditions associated with the fuel and the surrounding atmosphere must be identified and entered into the program. Inputs to CFAST include:

- Heat release rate
- Heat of combustion
- Mass loss rate of the fuel
- The position of the fire
- Limiting oxygen index
- Ratios for estimating species concentrations including H/C, C/CO_2, CO/CO_2
- Type of fire (constrained or unconstrained)

The fire heat release rate is user specified. Thus either small or large scale test results must be used as the heat release rate. Both have limitations associated with them. Small scale calorimeter test results may be extrapolated to full scale behavior through empirical correlations. [45] The use of a correlation limits the accuracy of the data. In the case of large scale calorimeter tests, an item is ignited under a hood and proceeds to burn under assumed open burning conditions. [45] The degree to which open burning conditions have been achieved is unknown due to radiation from gases under the hood or lack of air entrainment. [45] In both kinds of testing, measurement errors are a concern. Data is present for a small set of products. The data for fuels is obtained from cone and furniture calorimeter tests on individual samples. These are not necessarily representative of behavior in similar items. In fact, some variation could be expected from identical items in successive tests. Consequently, the calculated results for any of these conditions will produce some uncertainty. The heat of combustion must also be supplied, and from these two inputs the pyrolysis rate of the fuel is calculated.

CFAST requires that the user specify the type of fire that is being modeled. The two choices are unconstrained and constrained fires. For an unconstrained fire, all burning takes place inside the plume. For the constrained fire, burning will take place where there is sufficient oxygen. Constrained fires (type 2) are the only type to employ oxygen combustion chemistry. [46] In this type of fire, the model can track species such as soot, hydrogen, carbon dioxide, oxygen and carbon monoxide. However, this requires user-supplied ratios, for which limited data is available.

Another possible source of error is contained in the entrainment coefficients, which are empirically derived values. [45] In a compartment model small errors in these coefficients are multiplicative as the flow continues away from the source. [45] Therefore, this could result in large errors in compartments farthest from the source. Data has shown that there is good agreement with three room fires, but more validation needs to be done for larger amount of rooms. [45]

In actual fires, the lower layer accumulates smoke and gases from mixing with the upper layer at doors and along walls. Doorway mixing has been included in the form of a mixing coefficient. [45] However, mixing along the walls is not accounted for because of the lack of associated theory and, therefore, the lower layer concentrations may be underestimated. Lower layer temperatures may also be underestimated due to the fact that convection from the floor and lower walls is the only means of heat transfer.[45] Radiation from the upper layer is not implemented.

The mechanisms available to move enthalpy and mass are the plume created by the fire source and the jet formed by hot upper layer gases flowing through openings. [45] When the upper layer drops to very low level and the gases flow through low openings, such as closed doors, the gases are accumulated in the next room's lower layer for a time.[45] Thus, the lower layer of the room to which the gases are flowing may have a higher temperature than the upper layer for a short time. However, no hazard will exist during this time because the temperatures are so low. [45]

7.3 Analysis Technique

The two models discussed above, FAST and CFAST, have essentially the same inputs. The information required for analysis is room dimensions, connection dimensions, wall/floor/ceiling material, fire heat release rate and the ratio of C/CO_2 in the fuel. From this information, the optical density can be tracked in target spaces throughout the simulation.

Identification of the heat release rate is based upon the occupancy type of the room of origin. Note that t^2 and steady state fires are not used because these do not most closely represent the fire.

The most difficult aspect of the smoke modeling is the estimation of C/CO_2 ratios for common fuels. Data on this ratio is available for a limited number of fuels. Data was found in the SFPE Handbook for some homogenous materials including gases, liquids, solids and solid foams. [15] Yield information for specimens under well ventilated flaming fires and nonflaming fires is presented for a number of materials. The yield (ψ) is the grams of a substance (CO, CO_2, O_2, soot, etc.) produced per gram of fuel burned. Instead of attempting to characterize the ratio for the conglomeration of fuels in the room, it was decided to take an upper and lower range of the C/CO_2 ratio from the data on homogenous materials under the flaming and nonflaming conditions. To obtain the upper and lower limits of the ratio to be used, a C/CO_2 ratio was calculated for all the materials tested. This was done by dividing the soot yield (ψ_{soot}) by the CO_2 yield (ψ_{CO2}). After calculating this ratio for the over 50 materials listed, the limits were found to be:

- Upper bound (nonflaming) = 5.75
- Lower bound (flaming) = 0.08

Those yields are typical for smoldering fires and for the early stages of an enclosure fire. Thus, the ratios that would be present in an actual enclosure fire would likely be somewhere between 0.08 and 5.75. It is shown that the production of unburned fuel increases exponentially as the oxygen level drops.[15] Thus, as the oxygen level drops, the production of unburned fuel will rise faster. The typical enclosure fire will tend to remain in the flaming combustion region and the actual ratio will tend to remain significantly lower than the ratio for nonflaming fires. The upper and lower bounds of the C/CO_2 ratio are estimated to be:

- Estimated upper bound = 0.8
- Estimated lower bound = 0.2

The ratios are assumed constant through the simulation. Thus, in order to obtain an envelope, one simulation should be done using each of the estimated ratios. Note that the upper bound of the ratio is conservative.

There is a wide range of nomenclature in smoke obscuration literature. There are also three widely used systems of measurement. The extinction coefficient, optical density and obscura are the same quantity measured in different systems. Recall from Chapter 6, that these quantities describe smoke's ability to absorb or scatter light. The visibility data obtained from the simulation is the optical density, OD, at each time step.

Optical density is the smoke obscuration in the base-10 measurement system. This must be converted into extinction coefficient. The extinction coefficient, k, is the identical quantity in terms of the natural logarithm. This can be found from the optical density using the following correlation:

$$k = \frac{OD}{2.3} \qquad (7.1)$$

CFAST and HAZARDI have plotting programs that enable the user to obtain the raw data without manually taking it from the model output. These programs allow phenomena to be isolated and written to ASCII files, which are easily imported into spreadsheet programs where calculations may be performed and the data can be graphed. These are known as the deterministic smoke curves. This process may be accomplished in a short period of time. The extinction coefficient for both the upper and lower bounds are then plotted to give a bandwidth of extinction coefficients in the target space.

The final step is constructing the probablistic smoke curves. These curves indicate the confidence that one has in the deterministic curves. Below is a list of the general steps in constructing smoke curves. This is taken from the BFSEM chapter on constructing smoke curves.

1. Identify the room of origin.

2. Select the target room.

3. Select the computer program that will be used to model smoke movement and the level of visibility.

4. Do enough computer runs to get a sense of smoke behavior for the building and to construct an envelope describing the upper and lower bounds of expected smoke tenability for the target space.

5. Define the level of tenability acceptable in the target space.

6. Determine from the smoke tenability envelope of number 4 and the tenability criteria of number 5, the upper and lower bounds of time at which the target space will be tenable.

7. Identify the major building features and computer use variables that would influence the credibility of the computer results in their simulation of the tenability conditions in the target space.

8. Score the features and variables of number 7 with regard the influence on the time at which the target space becomes untenable.

9. Construct the smoke curve, as illustrated in Figure 6.1. The curve expresses the degree of belief, as a probablistic measure, that the target space will remain tenable for the time duration noted on the abscissa.

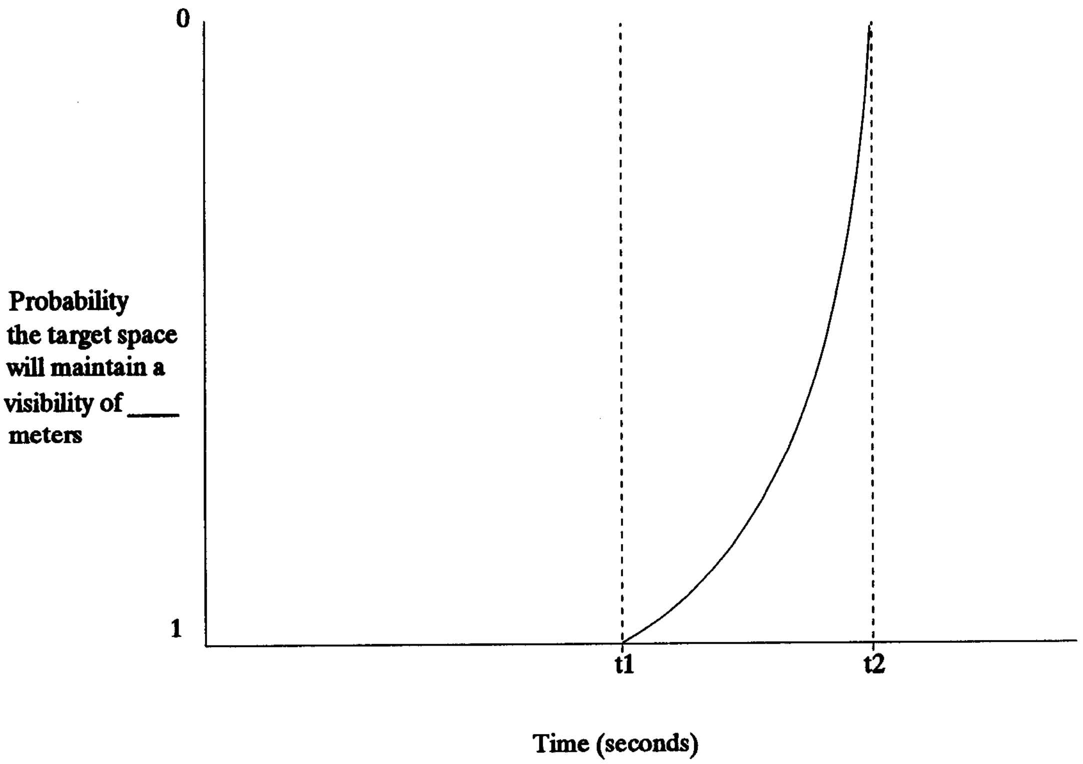


Figure 7.1 - Probablistic Smoke Curve

The shorter time, t_1, represents the time before which the target space is certain to remain tenable. The time, t_2, represents the time beyond which the target space is certain to be untenable. These times, in Figure 7.1, are adapted from the deterministic smoke curves obtained by computer modeling. The probability of maintaining tenability in the target space is along the y-axis, going from 1 (certain tenability) to 0 (certain untenability).

The tenability criteria, as calculated by the extinction coefficient, selected in Step 5, is used as a basis to identify the times, t_1 and t_2, as well as the envelope of reasonable tenability expectation. Selecting tenability criteria is discussed in Chapter 5. The process for obtaining the times, Step 6, is best explained in an example. Suppose four cases were examined for an area. The tenability criteria is set at an extinction coefficient of 0.3 1/m. The time on each of the four graphs that corresponds to an extinction coefficient of 0.3 1/m is found. These cases appear to bracket the reasonable performance conditions. The lowest time becomes the point t_1 on the probablistic curve. The highest time becomes t_2.

The most difficult part of creating the probablistic curve is Steps 7 and 8, because one must take the limitations and uncertainties of the computer analysis into account. Uncertainties and recognized limitations may shift the curve to the right or the left or they could flatten out the curve giving a larger range of times. The process of accounting for the uncertainties is accomplished by listing them and determining if they make the time to untenability longer or shorter. A weighting system, similar to movie ratings, is used to differentiate between the uncertainties. For example, if uncertainty A makes the results much less conservative, one might give it four stars. Likewise, if uncertainty B makes the results slightly less conservative, one might assign its importance as one star. The list of uncertainties, along with subjective judgment, will then be used as the basis to construct the curve in Step 9. An example will be discussed in depth in the following section.

7.4 Example Case

The building from the CIB/W14 workshop will be used to illustrate the process. The building is a six story, multi-use facility with a total floor area of 2700 m^2. The area that was selected for analysis is the area main stairwell and surrounding areas on the third floor. This area is expected to become particularly congested. This area serves the movie theaters and the recreational facilities on the floor above. The layout of the area is shown below in Figure 7.2. The area can be seen in relation to the rest of the building on the Second Floor drawing, Figure A-3, in Appendix A.

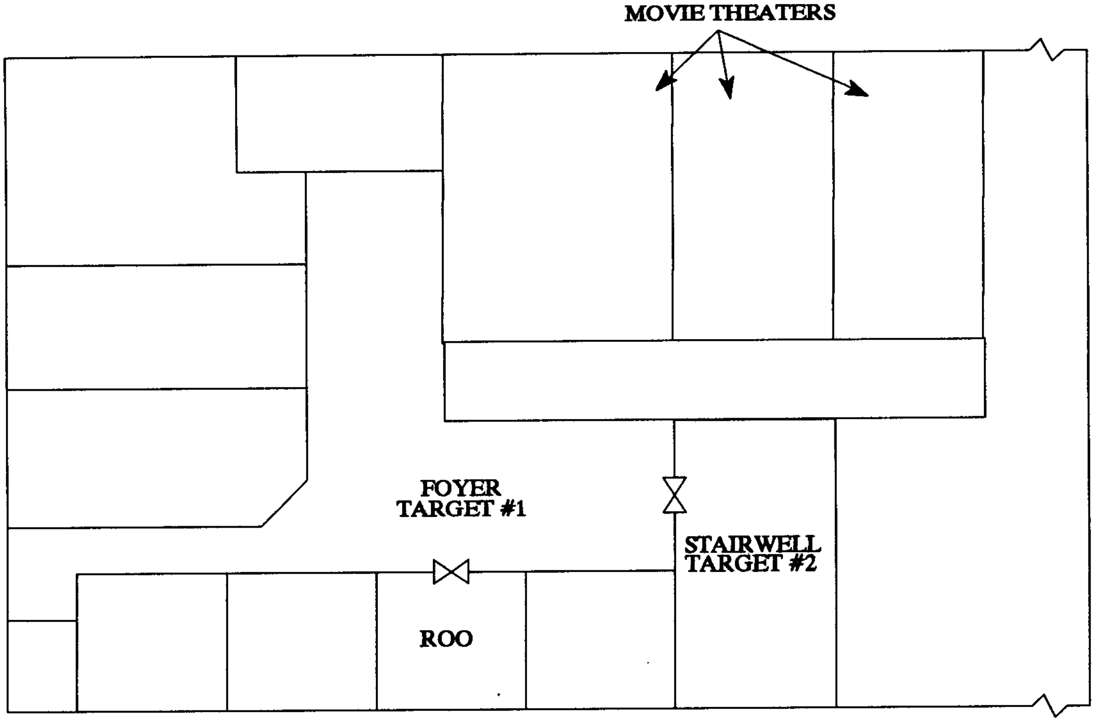


Figure 7.2 - Layout: Second Floor Ulster Building

From Steps 1 and 2, the room of origin and the target space(s) must be selected. The room of origin is assumed to be the office noted. Smoke is assumed to spread out into the foyer and the main stairwell. The foyer and stairwell both will be selected as target spaces. There are two doors; one between the Room of Origin and the foyer and another between the foyer and the stairwell. The dimensions of the rooms are shown below. Note that the computer requires the dimensions of the foyer to be an equivalent rectangular space.

	Length	Width	Height
• ROO	9.1 meters	7.6 meters	3.1 meters
• Foyer	12.2 meters	25.9 meters	3.1 meters
• Stairwell	18.3 meters	9.1 meters	9.1 meters

The room and connection dimensions were all entered into the computer model. A typical heat release rate from an office fire was used. The heat release rate of the design fire is shown in Figure 7.3a. The actual fire was not as severe due to limited oxygen supply in the room. The actual heat release rate is shown in Figure 7.3b.

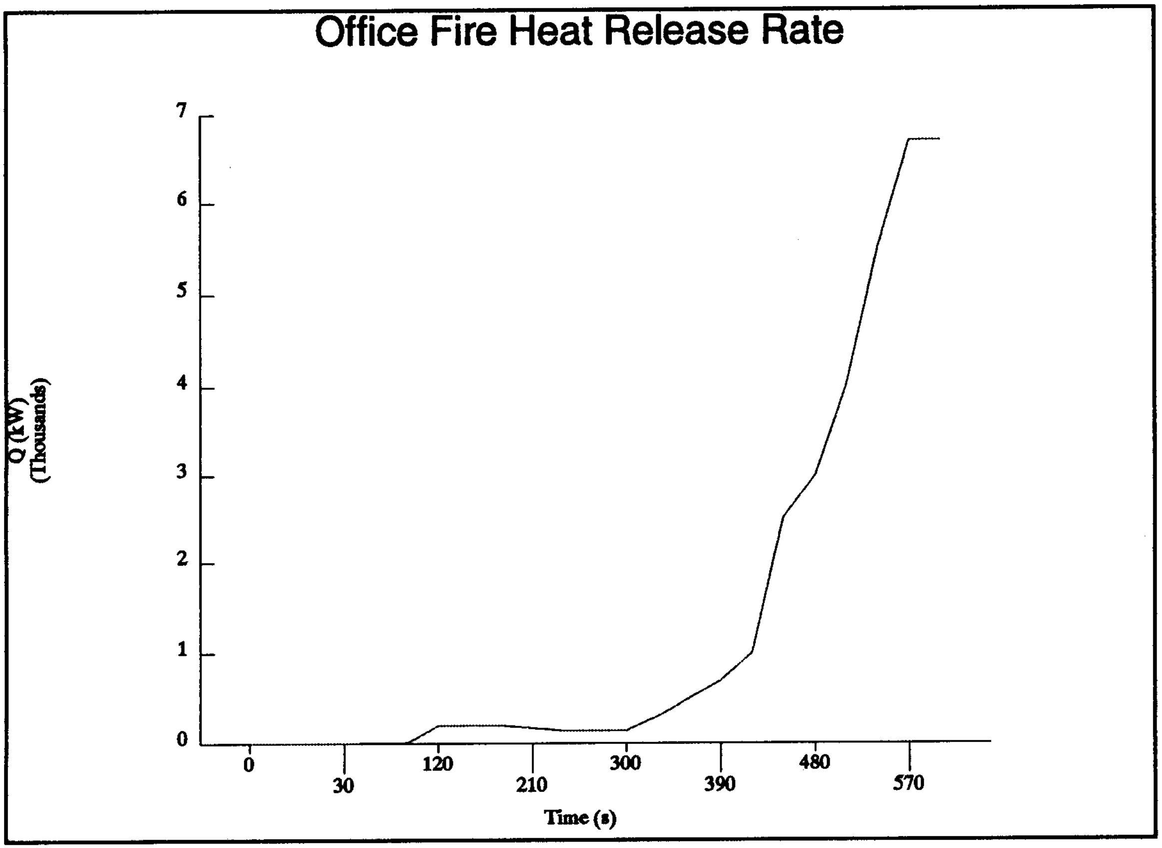


Figure 7.3a - Design Fire

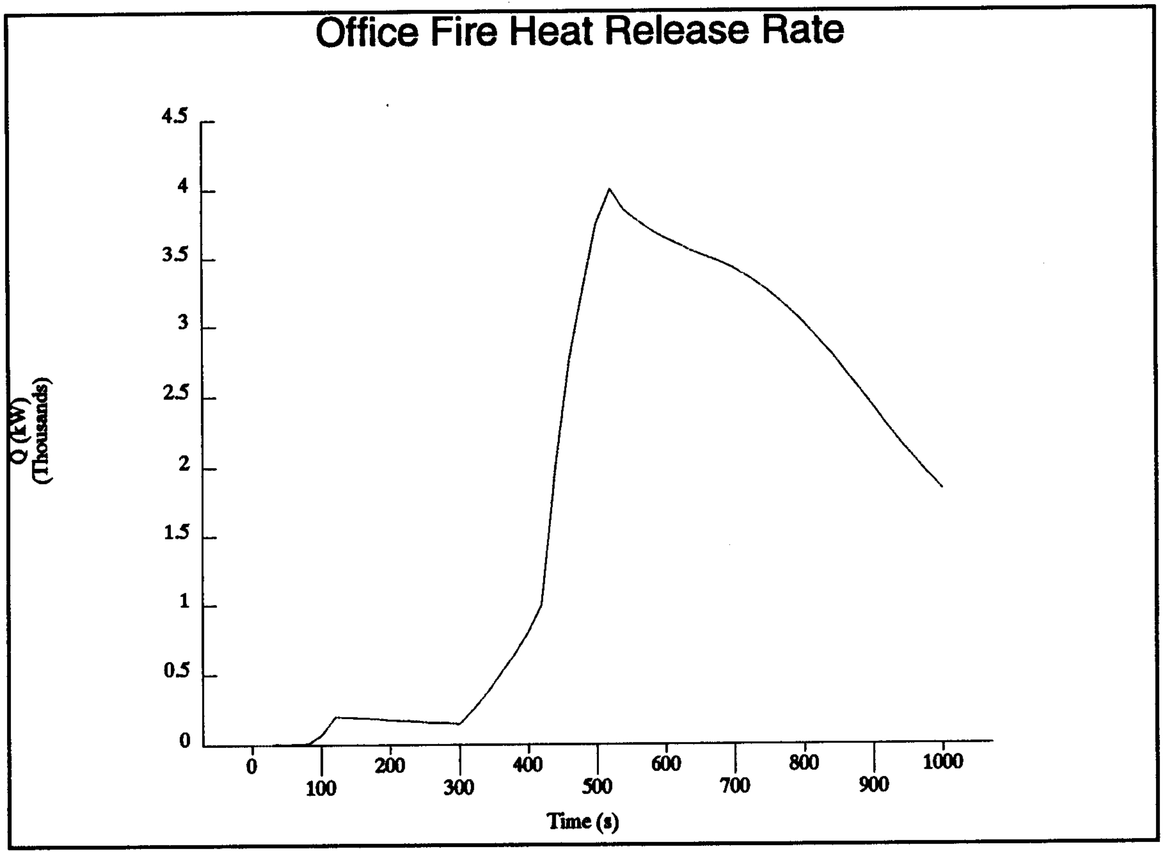


Figure 7.3b - Actual Heat Release Rate

Note that the actual fire reaches its peak of 4+MW around 500 seconds, while the design fire continues to increase to about 7 MW. The reason the fire diminishes is the lack of oxygen due to the size of the room and the expectation that the fire is ventilation controlled. The simulation indicates that flashover also occurs about 500 seconds. Note that the post flashover fire behavior is an approximation in FAST and CFAST due to the lack of theory.

The input data required to track the optical density is the soot to carbon dioxide ratio (C/CO_2). This ratio is the kilograms of soot produced for each kilogram of carbon dioxide produced. The method by which this data was attained was discussed in Section 7.3. An upper and lower bound for this ratio was used, which will produce an envelope of possible values for the extinction coefficient.

Four different scenarios were looked at to get a sense of smoke behavior in the spaces, as in Step 4:

- ROO door open/Stairwell door open
- ROO door closed/Stairwell door open
- ROO door closed/Stairwell door closed
- ROO door open/Stairwell door closed

Two runs were made for each configuration using each value of the C/CO_2 ratio, giving a total of 8 runs per computer model. The upper bound of the C/CO_2 ratio was 0.80 and the lower bound was 0.2. These are higher than those calculated from Beyler's text because Beyler's values were for flaming combustion at 20.9% oxygen. [5] In an actual enclosure fire, the ratio will be higher as the oxygen level drops, leading to more products of incomplete production.

The optical density from the model was converted to extinction coefficient from Equation 6.4. Graphs of the results of the upper and lower bounds of C/CO_2 for each room of origin were then constructed in a spreadsheet program. The resulting graph gives a range of extinction coefficients for the duration of the simulation. The graphs for the foyer and stairwell are shown below in Figures 7.4 through 7.11. These graphs are known as the computer generated deterministic curves. Note that the scale is different for each drawing. Input files for the computer runs are located in Appendix C.

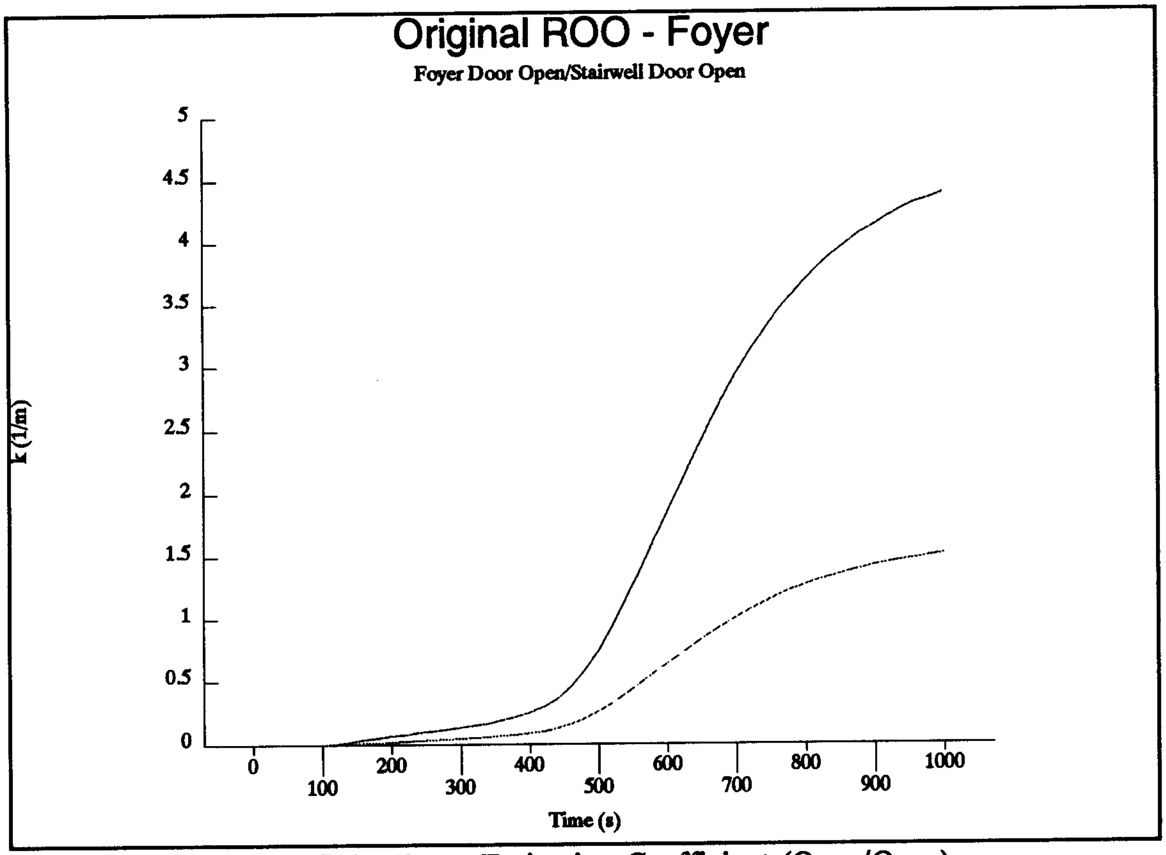


Figure 7.4 - Foyer Extinction Coefficient (Open/Open)

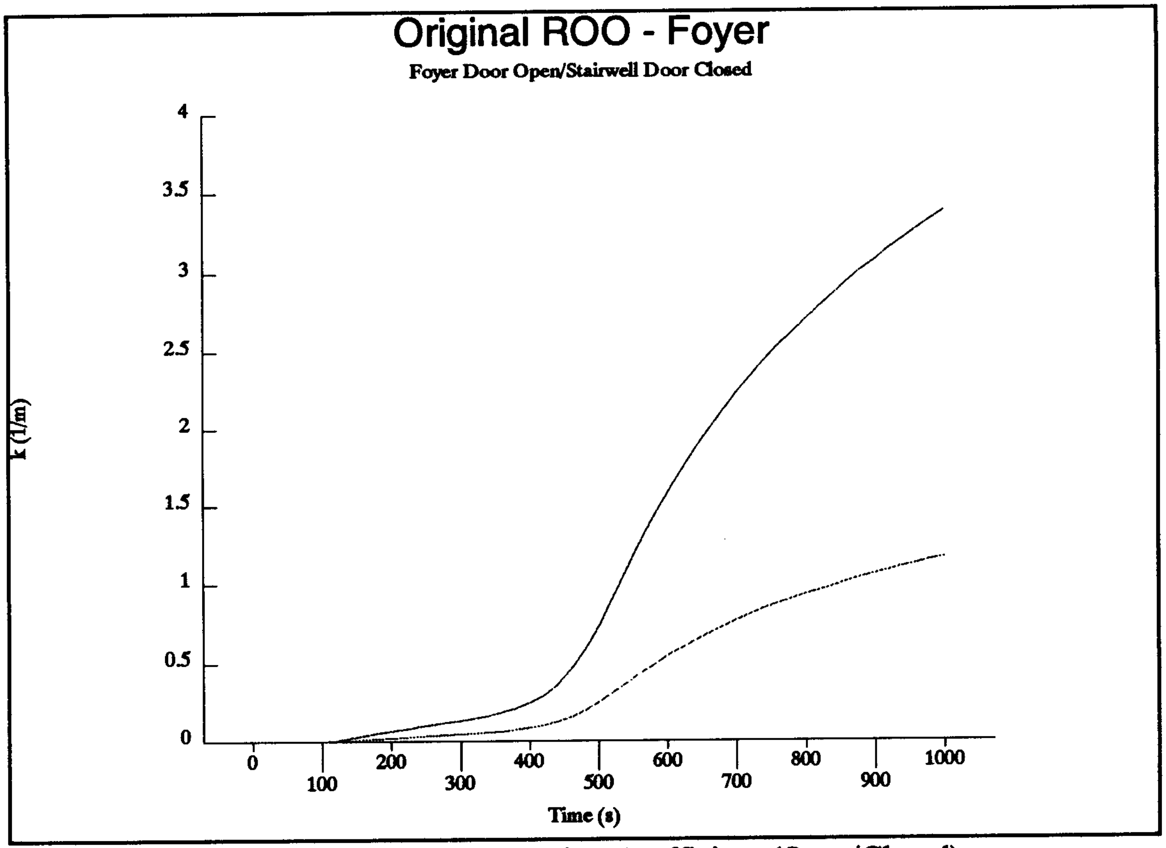


Figure 7.5 - Foyer Extinction Coefficient (Open/Closed)

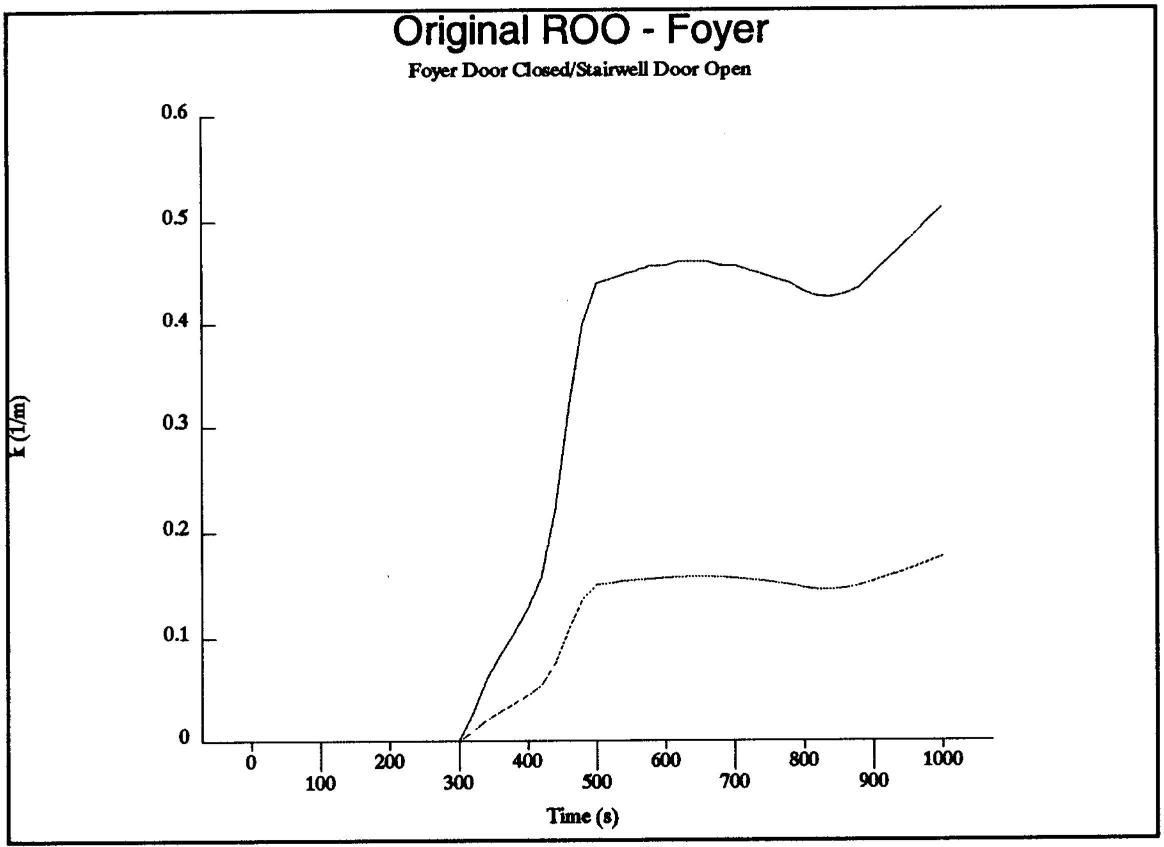


Figure 7.6 - Foyer Extinction Coefficient (Closed/Open)

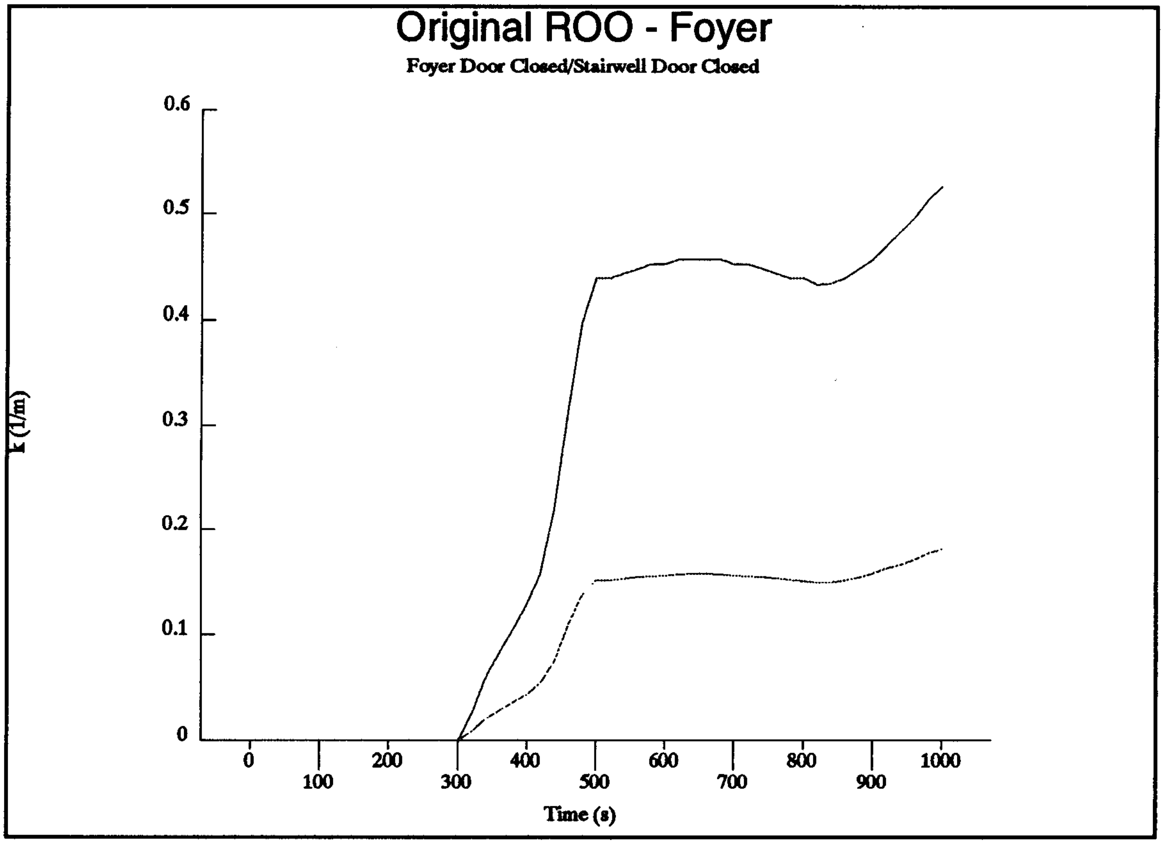


Figure 7.7 - Foyer Extinction Coefficient (Closed/Closed)

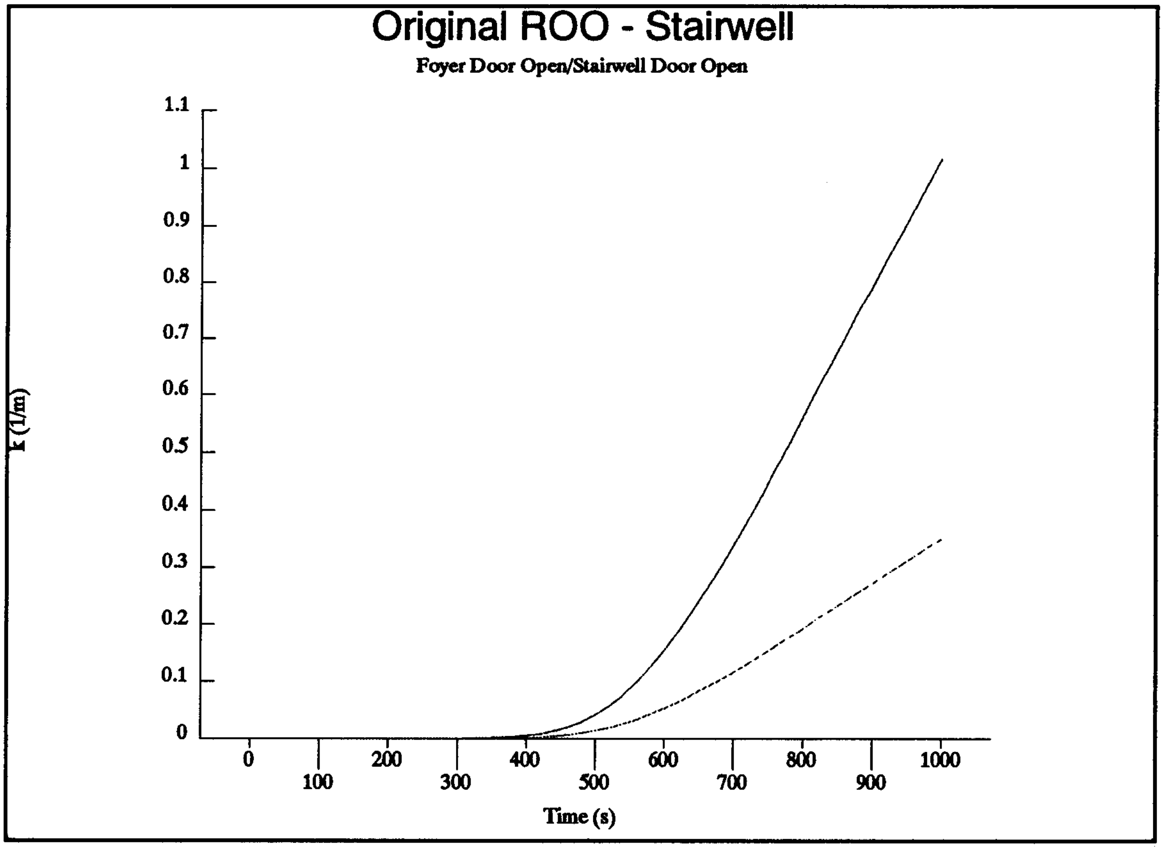


Figure 7.8 - Stairwell Extinction Coefficient (Open/Open)

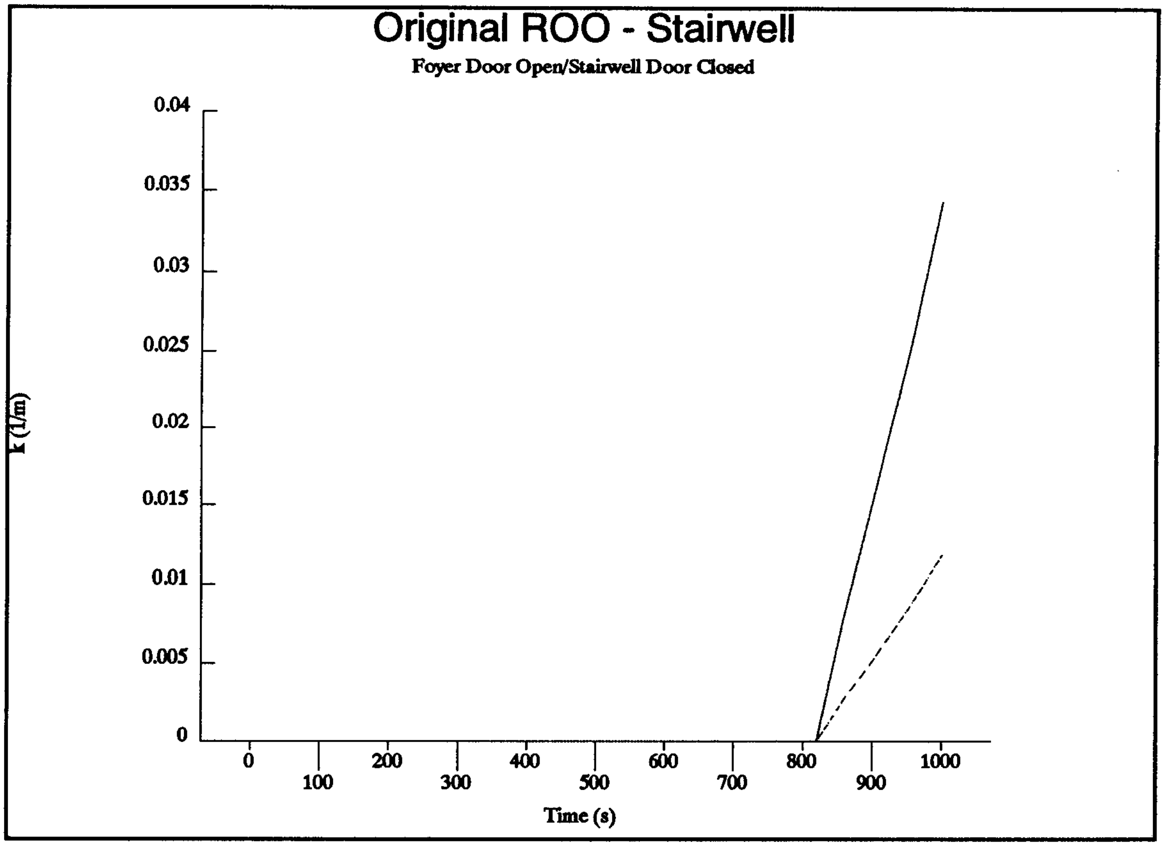


Figure 7.9 - Stairwell Extinction Coefficient (Open/Closed)

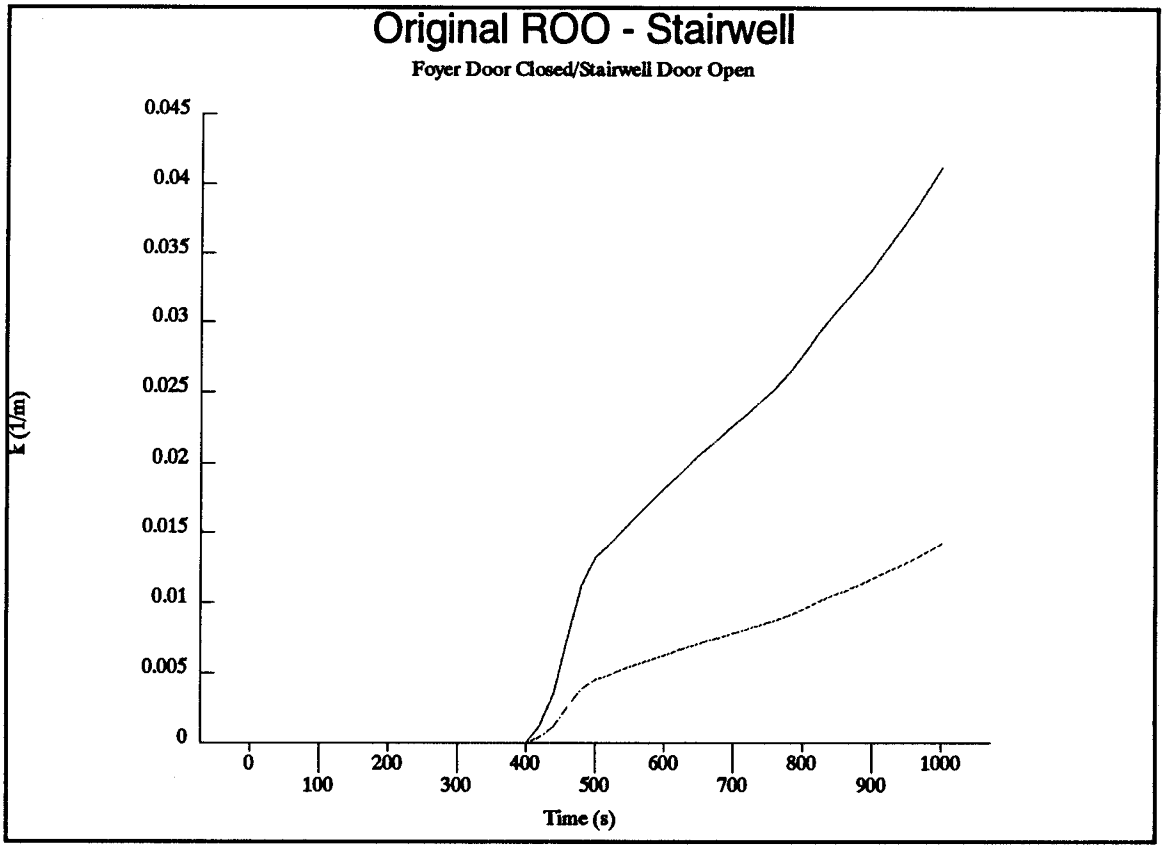


Figure 7.10 - Stairwell Extinction Coefficient (Closed/Open)

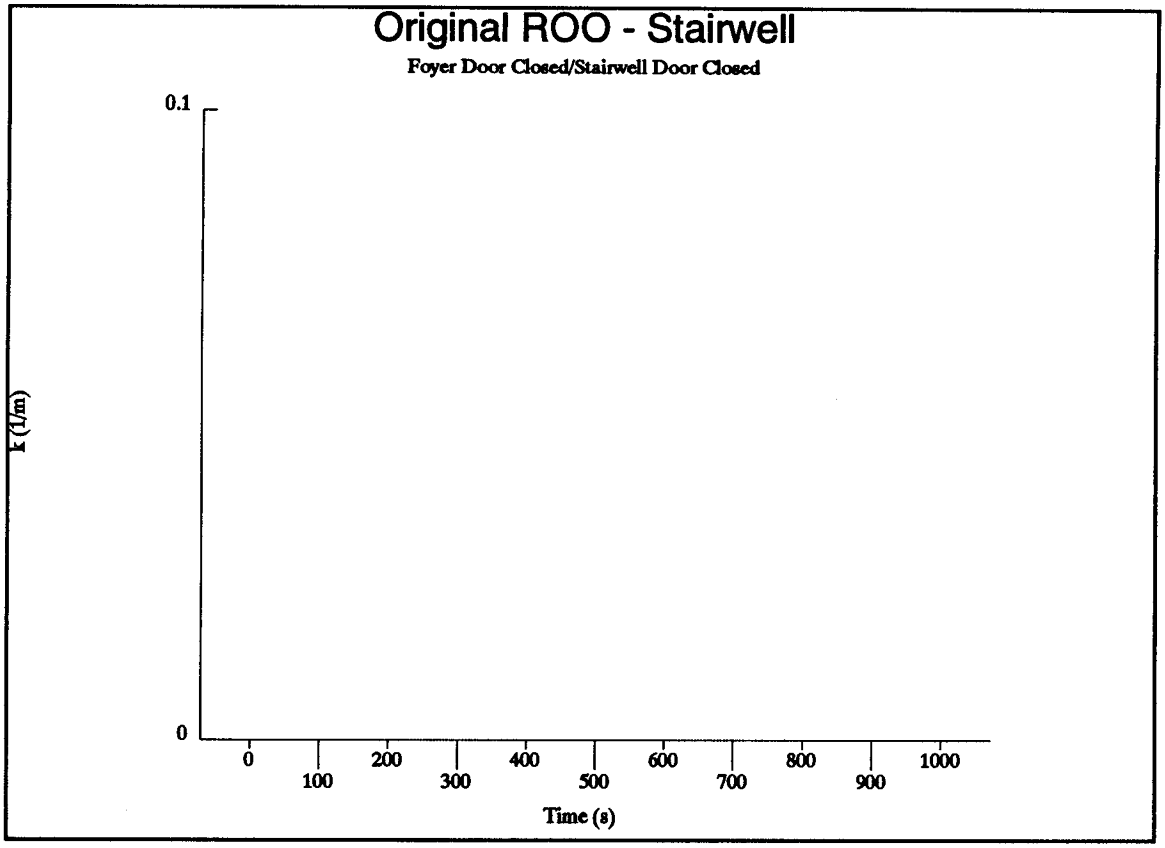


Figure 7.11 - Stairwell Extinction Coefficient (Closed/Closed)

The next step, number 5, is to determine the tenability criteria. This is discussed in detail in Section 6.1. For this building, a visibility of 6.1 meters (20 feet) has been chosen as the tenability criteria for the foyer, and 3.7 meters (12 feet) for the stairwell. This visibility must be represented in terms of an extinction coefficient. From Section 6.1, the corresponding extinction coefficient has been determined to be approximately 0.29 1/m for 6.1 meters (20 feet) and 0.36 1/m for 3.7 meters (12 feet).

In Step 6, find the times on each of the graphs that corresponds to an extinction coefficient of 0.29 1/m in the foyer and 0.36 1/m in the stairwell. From the graphs, these times for the foyer are:

- Figure 7.4 - 350 seconds
- Figure 7.5 - 400 seconds
- Figure 7.6 - 400 seconds
- Figure 7.7 - 350 seconds

Therefore t_1 = 350 seconds and t_2 = 400 seconds. Next, the uncertainties in the analysis must be taken into account to draw the probablistic smoke curve. Table 7.1 below is a table of uncertainties that will be incorporated into drawing the curve, weightings and the direction, if any, the results should be shifted. The weightings are based on a scale of four stars, four stars having the most impact and one star the least. This table is a combination of Step 7 and 8.

Table 7.1 - Uncertainties in Deterministic Analysis

UNCERTAINTY	Weighting	Change in Time
Estimation of C/CO_2 ratio	**	Shorter
Zone model approximation	*	
Post-flashover combustion chemistry	***	
Little information on low O_2 conditions	**	
Smoke loss to other rooms and the outside is unaccounted for	*	Longer
All openings that could contribute oxygen to the fire not accounted for	*	Longer
Heat release rate of the fire	***	Shorter

The two factors that seem to impact the curve the most are the C/CO_2 ratio and the post-flashover combustion chemistry. The C/CO_2 ratio is the lone input that controls smoke production. The information that is available for the smoke production ratio is for open burning conditions only. Therefore, the data is only valid for the early moments of an enclosure fire. In an actual enclosure fire, the ratio would vary with the amount of oxygen. Tewarson noted that the CO/CO_2 ratio increased exponentially as the oxygen level dropped. It is assumed that the same effect would be observed in the C/CO_2 ratio. It is not known what would be the best approximation of the ratio. But, it is possible to infer that more smoke will be produced earlier in the fire, thus, the time to untenable conditions will be shorter than the computer analysis indicates. This does also introduce a good deal of uncertainty into the analysis, hence, the curve would tend to flatten out.

The heat release rate of the fire is controlled in the program. Although the initial HRR is entered into the program, it is adjusted according to the conditions of the surrounding atmosphere. This is particularly apparent in the case where the door to the room of origin is closed. As the oxygen supply is used up, the HRR decreases greatly, never reaching 4 MW. However, not accounting for all openings could significantly influence the HRR. Other openings could provide the means for additional oxygen to reach the fire and thus, the HRR would be higher. The addition of oxygen to the fire would lead to more efficient combustion and the production of less soot and other by-products. This consideration would lengthen the computer results.

The approximation of post-flashover combustion chemistry is another significant source of uncertainty. Since little is known about this phenomena and no guidance is provided in the documentation, this consideration introduces more uncertainty into the analysis and flattens the curve out more.

After taking all the uncertainties into account and weighting their importance, the curve can be drawn. Because of the difference between the computer analysis and the actual conditions, as well as the uncertainties, the probablistic smoke curve is more appropriately represented as a band or envelope. However, because the lifesafety analysis uses a specific curve, the most reasonable curve, shown in Figure 12, is selected.

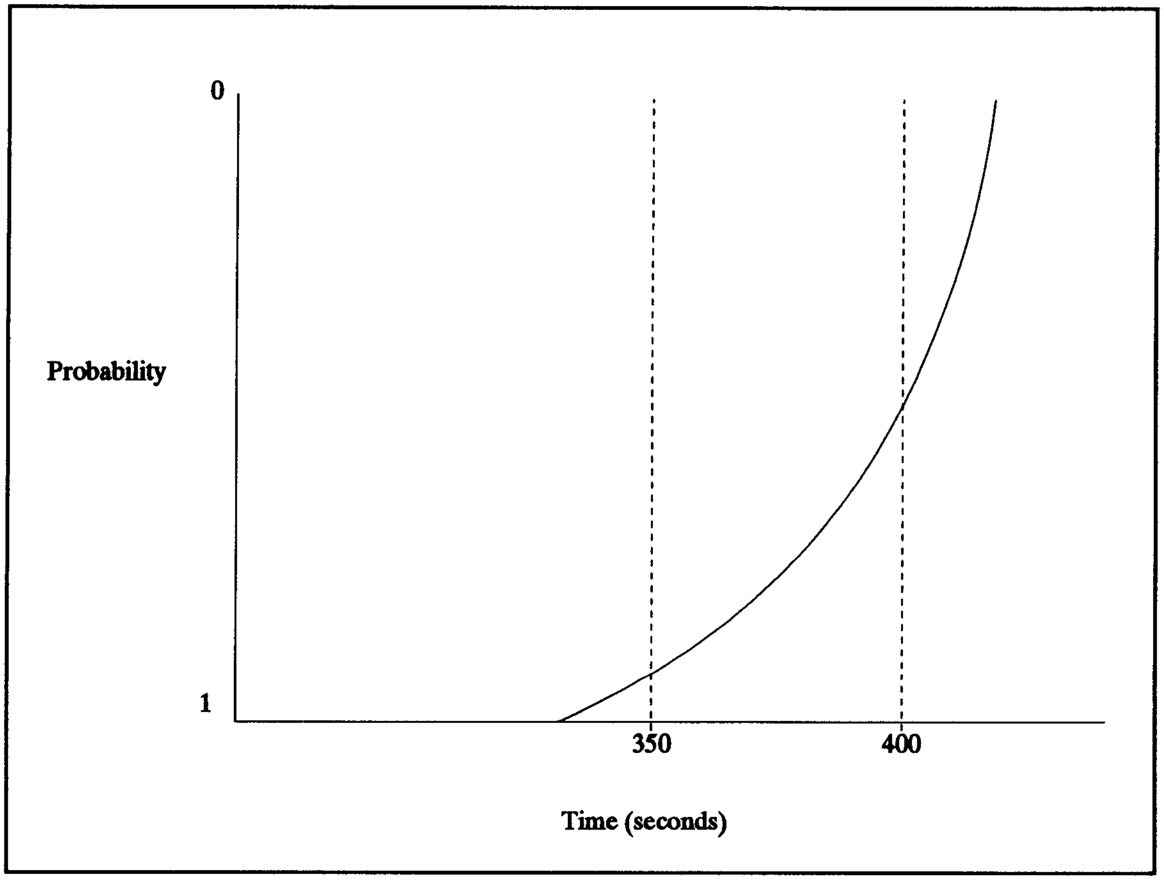


Figure 7.12 - Probablistic Smoke Curve: Foyer

The probablistic smoke curve for the stairwell can be found using the same process. The times to reach untenable conditions, k of 0.36 1/m, on the four graphs are:

- Figure 7.8 - 700 seconds
- Figure 7.9 - > 1000 seconds
- Figure 7.10 - > 1000 seconds
- Figure 7.11 - > 1000 seconds

The logic behind any shifting or alteration in the curve follows a logic similar to that of the foyer smoke curve discussed above. Note that only one simulation produced untenable conditions in the stairwell. After taking into account the uncertainties from Table 7.1, the curve is flattened and shifted to the left. The probablistic smoke curve for the stairwell is shown below in Figure 7.13.

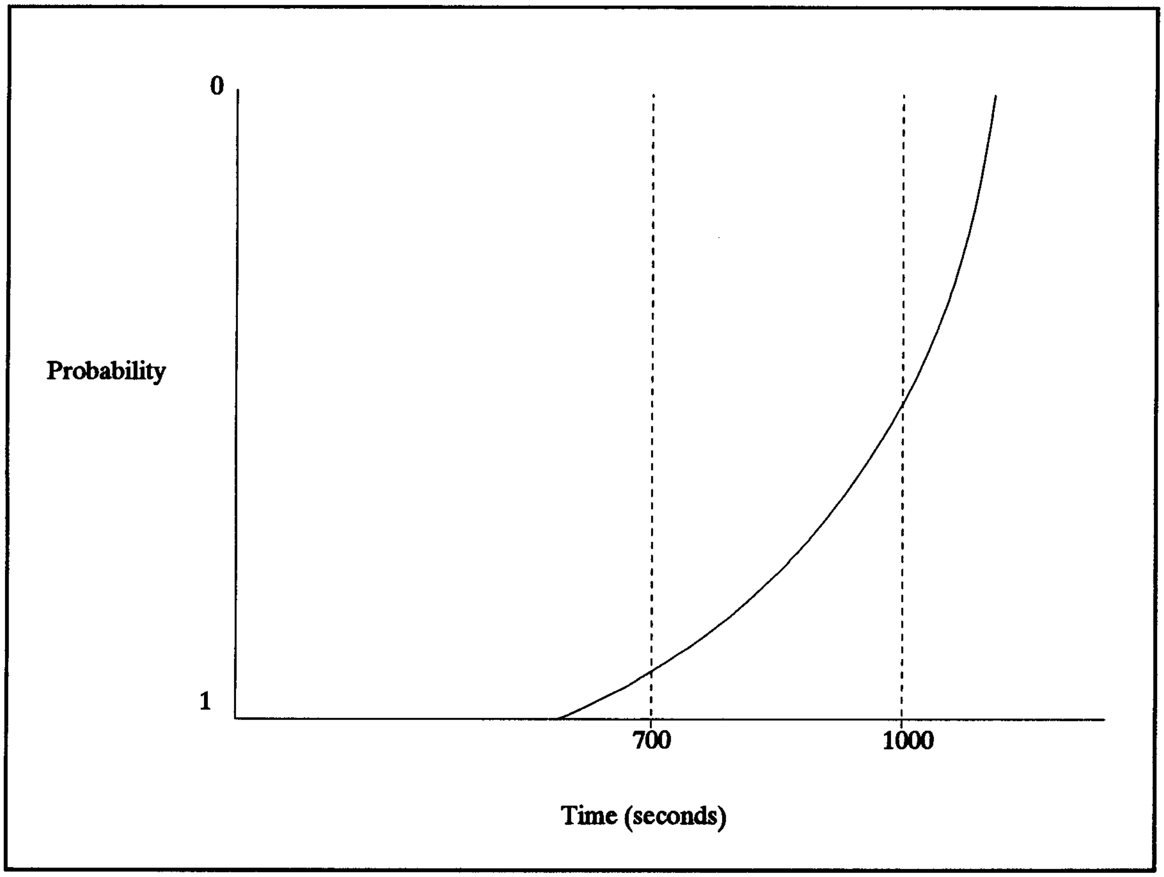


Figure 7.13 - Probablistic Smoke Curve: Stairwell

Figures 7.12 and 7.13 represent the probablistic smoke curves for the foyer and the stairwell respectively. The process of constructing these curves from the deterministic curves has been illustrated. The most involved portion of the smoke movement analysis is constructing the probablistic curves. Note that CFAST was used to model smoke movement, but it is possible to use other computer models to obtain the deterministic curve. .

The probablistic curves will be utilized in the final analysis discussed in Chapter 9. The curves, in conjunction with the egress analysis will be used to determine if people and untenable conditions occupy the same space at the same time. The egress analysis will be discussed in Chapter 8.

8.0 Egress Analysis

Lifesafety analysis in the Engineering Method attempts to determine the likelihood that people and untenable conditions will occupy the same space at the same time. The first portion of the lifesafety analysis of the BFSEM is constructing the smoke curves for target spaces that are critical to the egress of the occupants. Until a simplified automated procedure for constructing smoke curves is developed, the engineer must rely upon the art of selecting target spaces in the building that are the most critical to the evacuation of the occupants. This procedure for constructing smoke curves for target spaces was discussed in Chapter 7.

The second component is the egress analysis which is the determination of the time at which occupants are likely to move into the target space. If the target space becomes untenable before the occupants leave the target space, building performance is defined as unsatisfactory. Conversely, if the target space remains tenable until the occupants have passed through the target space, building performance is defined as satisfactory. This chapter describes the process by which the time it takes the occupants to enter into the target space and, eventually, evacuate the building after they have decided to leave the room from which they originated. Chapter 9 will describe the lifesafety analysis for the target spaces and the process for the entire building.

A time line for people movement must be constructed. The time line starts at established burning and continues through the occupants passing through the target spaces along the route to, eventually, the exit discharge. The Engineering Method evaluates the likelihood that people and untenable conditions will occupy the same space at the same time. Therefore, an intermediate analysis is made for each target space.

The time line for people reaching a target space evaluates the time from the start of the fire until the occupants leave the target space. This depends on the time duration from:

1. Established burning (EB) to detection
2. Detection to alerting the occupants
3. Occupant alerted to occupant decides to leave
4. Occupant leaves to the occupant passes through the exit discharge

Figure 8.1 shows a diagram of the events in the evacuation process. The three events designated b, c, and d, make up the part of the time line which the occupants decide to start egress. The events designated e through i describe the time line to egress the building along the defined path. Figure 8.2 shows an example of an egress time line.

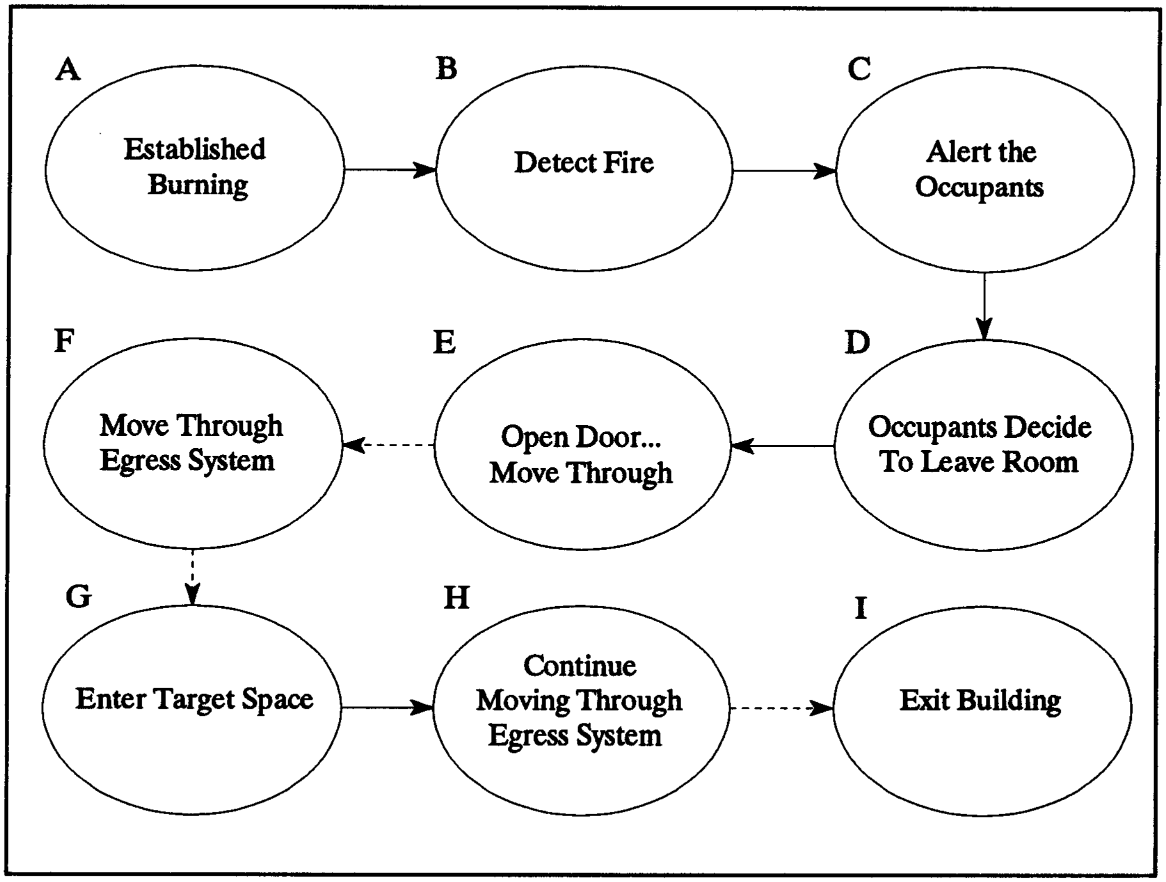
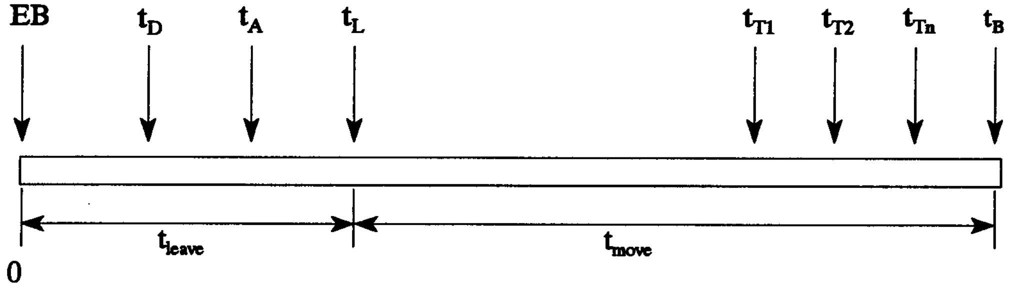


Figure 8.1 - Sequential Events for Egress



Where: EB = Established burning

t_D = Detect the fire

t_A = Alert the occupants

t_L = Leave the room

t_{leave} = Time duration from EB to leaving the room of occupant origin

t_{move} = Time duration from leaving the room to arriving at the target space

t_{T1}, t_{T2}, t_{Tn} = Time to enter target spaces 1, 2, ... , n

t_B = Time to leave building

Figure 8.2 - Egress Time Line: General

The determination of the first part of the time line, the time from the start of the fire to the time the people decide to leave the room, will not be discussed in the analysis. However, this delay is an important part of the analysis because it influences the time to reach the target space(s). The second half of the time line will be simulated using a computer program. This is the focus of the egress analysis. The first part, describing the delay in starting, will be lumped in with the times from the computer simulation. For illustrative purposes, these will be 0, 2, 5 and 10 minutes. This is done because this time is very difficult to characterize. It is dependent on a number of factors:

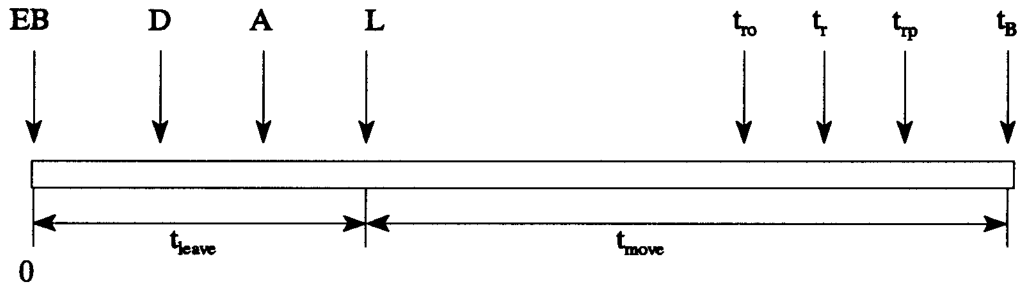
- The location of the fire in respect the occupants
- Any detection systems present, effectiveness and their proximity to the fire
- The growth rate of the fire. Note how the design fire in Figure 7.3a starts out very slow and then grows very quickly. Detection of this kind of fire may take long time as compared to a rapidly developing fire.
- The presence of other people. Section 4.4 discussed how people are less likely to respond to fire cues when in the presence of others than when alone.
- The awareness of the occupants. People are less responsive to fire cues when drowsy or sleeping
- The level of activity in the area. Noisy environments may prevent people from hearing sounds associated with fire such as fire alarms, breaking glass or other falling objects.
- Gender of the occupant. Bryan showed that men are more likely to take some action to find or fight the fire while women are more likely to warn others and leave the area.
- Previous fire experience. People who have been involved in a fire a more likely to notice and act upon any sign of fire.

Most of the factors listed above are dynamic, always changing. Balancing all those factors would be very difficult, even if they were static. Therefore, instead of creating some hypothetical time line, this part of the time line was simply estimated as four possible times and added to the results from the computer simulations..

The egress analysis described here will determine the time from leaving a room to reaching the target space. The primary information that this portion of the analysis will provide is the time to egress and the time to clear the target space. Therefore, the model that is used must be capable of giving "snapshots" of target areas during the simulation. Some aspects of human behavior, discussed in Chapter 4, will also be incorporated into the model. This will lead to the development of the three times needed in the analysis:

- Most optimistic reasonable time
- Most reasonable time
- Most pessimistic reasonable time

Although a single time may be more desirable, it is recognized that uncertainties in the analysis and in human capabilities and decisions will result in a distribution of people and times entering the target space. Nevertheless, these times are sufficient to provide an understanding of the performance of the building and its occupants. The revised time line, with the range of these three times, is shown in Figure 8.3.



Where:
EB = Established burning
D = Detection
A = Alert the occupants
L = Leave the room
t_{ro} = Most optimistic reasonable time
t_r = Most reasonable time
t_{rp} = Most pessimistic reasonable time
t_B = Time to leave the building
t_{leave} = Time duration from established burning to leaving the room
t_{move} = Time duration from leaving the room to exiting the building

Figure 8.3 - Egress Time Line Showing the Three Times

The three times can be considered in relation to some typical aspects of human behavior. The engineer must have a feel for the types of occupants in the building.

Subjective judgment is used to provide the logic and rationale for relating the computer simulations to the actual building. The most optimistic time is the fastest the engineer feels that the people can egress through the target area. Under these conditions, the occupants may be motivated to move as fast as they can. A number of characterizations are possible. Perhaps the fire cues, such as smoke and heat, were taken seriously and people perceived a real threat. The fire may have been detected and confirmed very quickly. The building may be equipped with an intercom system to give the occupants instructions. Recall from Chapter 4 that employees are apt to assist others less familiar with the building. Other actions also are possible.

The most reasonable time is the time that the engineer feels is most likely in a fire emergency. The most optimistic and most pessimistic times allow the engineer to bracket the most likely time to give a sense of the expected variation. Again, some knowledge of typical occupants and subjective judgment are needed. The building architecture should be taken into account. For example, there may be many connections, open doors, vertical openings or HVAC to allow for the spread of smoke. Or perhaps, smoke does not spread quickly and the people do not move as fast as they might otherwise move because they do not perceive a serious threat. Typical physical and mental condition of the occupants must be considered.

The most pessimistic reasonable time is the longest that the engineer feels it will take the occupants to clear the target space. The rationale behind the choice of time similar to the development of the other two times. Below is a list of factors that should be considered in all cases:

- Occupants typical physical and mental condition
- Preparedness of employees
- Building architecture
- Extent of smoke spread
- Intercom systems
- Typical aspects of human behavior

The remainder of this chapter will provide a brief description of the computer model chosen for the analysis, EVACNET+. The attributes and procedures for this model will be discussed in depth. The process of performing the egress analysis will be discussed thoroughly. Finally, an analysis of two target spaces in the CIB/W14 workshop building will be given to demonstrate the application.

8.1 EVACNET+

EVACNET+ is a program developed originally for air traffic control that was adapted to modeling building evacuations. The program is developed as a network of nodes and arcs to represent the building circulation system.

Nodes represent rooms (WP), corridors (HA), stairways (SW), landings (LA) and exit discharges (DS). The data required for nodes is its capacity and the initial capacity at the start of evacuation (time = 0). Nodes are defined by a two letter abbreviation describing the area (shown above in parentheses), the number of the room, the number of the floor, the capacity and the initial capacity. For example, WP1.1,12,10 would represent work place (room) 1 on the first floor with a total capacity of 12 people and an initial capacity of 10 people.

Arcs represent the connections between nodes. Input data for each arc includes the dynamic capacity and traversal time. An arc is defined by the originating node, the destination node, the dynamic capacity and the traversal time. For example, WP1.1-HA1.1,4,1 would represent the arc from work place 1 on the first floor to corridor 1 on the first floor with a dynamic capacity of 4 and a traversal time of 1 time step. The length of the time step is defined in the program and may be varied. A maximum of 60 time steps are allowed by the program, so the length of the time step is will depend on the simulation. Due to the form of the governing equations, a higher degree of accuracy can be achieved by using smaller time steps.

The results from EVACNET+ represent the optimum evacuation time for a given scenario. The model does not represent human behavior or other conditions, such as fire. Human decision making may simulated by slowing occupant speed or by changing the flow volume. Deleting certain arcs or nodes to "cut off" escape routes is an effective way of simulating a fire. It should be noted that the results are not the absolute time for a given scenario. The time from the program the fastest time the building can be evacuated given the speed of the occupants and the capacity of egress components. Nevertheless, results can be extremely useful in ascertaining an entire system's effectiveness by comparing scenarios and determining effectiveness relative to one another.

8.1.1 Assumptions and Limitations of EVACNET+

As with any computer model, there are several assumptions and limitations that must be understood in order to evaluate the results. For EVACNET+, these include:

- Delays in human behavior are not considered.
- The effects of fire and smoke are not modeled.
- The model is linear; travel times and arc capacities do not change with time.
- Individual movement is not traced; people in particular spaces are counted at the end of each time step.
- All doorways are considered open; time to open doors is not considered.
- Obstacles in paths are not considered; these must be modeled as a width restriction.
- User must obtain building dimensions and make judgments on concentrations of people to obtain input data.
- Input data is accepted in integer form only

In using the results, some engineering judgment must be used to compensate for deficiencies in the program, particularly involving human behavior.

The fact that inputs to the program must be entered as integers can be significant. Inputs are calculated in a spreadsheet. The results of the calculations must be rounded off before they are input into the program because only integers are accepted. Therefore, fairly large changes in any input parameter, especially average speed (AS), may not change the input data. As an example, consider a corridor on the second floor of the Ulster building with a width of 3.5 feet and a length of 50 feet. There is no difference in the input data when changing the average speed of the occupants from 180 ft/sec. to 150 ft/sec.

Given:
WR = 3.5 feet
Distance = 50 feet
SPTP = 10 seconds
AS = 180 ft/sec.
AFV = 10 PFM

Results: DC = 5.83 ≈ 6
TT = 1.67 ≈ 2

Given: WR = 3.5 feet
Distance = 50 feet
SPTP = 10 seconds
AS = 150 ft/sec.
AFV = 10 PFM

Results: DC = 5.83 ≈ 6
TT = 2

Notice that a decrease in the average speed of 30 ft/sec. does have a large enough effect to change the traversal time (TT).

It should be noted that the results produced by the computer simulation are the optimum for any given scenario. The user must realize that actual evacuation times may be, in some cases, substantially larger than the optimum time. As with other computer models, the results can not be accepted blindly; some degree of engineering judgment is required to evaluate the results.

8.1.2 Application of EVACNET+

As was noted in Section 8.1.1, some calculations are required to obtain the input values to the model. For nodes, the capacity and initial occupancy are required. The capacity is found by dividing the useable area (UA) by the area per occupant (APAD):

$$Capacity = \frac{UA}{APAD} \tag{8.1}$$

In the analysis, the area per occupant was based on the work of Fruin or the BOCA Code requirements for the areas found in Table 806.1.2 of the code. Using a number of people in excess of the normal occupant load yields a better understanding of where egress problems may occur and the adequacy of the egress system for the building. In the case of the CIB/W14 building, the capacity calculated in Equation 8.1 was used as the initial capacity in many areas. It is unlikely that these areas will be filled to capacity very frequently. It is even less likely that most areas of the building would be filled to capacity at the same time.

Input data for arcs is somewhat more difficult to obtain. The input data for arcs includes:

- dynamic capacity (DC)
- traversal time (TT)

These are based on the average flow volume (AFV), the average speed (AS), the width restriction (WR) and the seconds per time period (SPTP). Dynamic capacity and traversal time are calculated by the following two equations:

$$DC = \frac{(WR)(AFV)(SPTP)}{60} \tag{8.2}$$

$$TT = \frac{(Distance)(60)}{(AS)(SPTP)} \tag{8.3}$$

where:
DC = dynamic capacity
WR = width restriction
AFV = average flow volume
SPTP = seconds per time period
TT = traversal time
AS = average speed

The "60" in each equation is a conversion factor from seconds to minutes. Due the number of variables involved, the calculations are most easily carried out in a spreadsheet program to allow variables to be changed.

The values for average flow volume and average speed were selected from work done by J.L. Pauls.[42] Pauls has done a considerable amount of work in the area of people movement. In a personal communication, Dr. Pauls noted some typical flow volumes and speeds for different egress components. The table below shows the average flow volumes and average speeds for selected components. Values of average speed and average flow volume for unique occupancies and configurations must be estimated using subjective judgment.

Table 8.1 - AFV and AS for Selected Components

Facility	AS (ft/min)	AFV (PFM)
Stairs	100	7
Long Passageway	200-250	10-20
Short Passageway	120-200	5-10

PFM - People per foot of egress width per minute

A building to be analyzed must be divided up into nodes. Nodes consist of rooms, hallways, lobbies, landings and stairs. The program only has the ability to handle up to 100 nodes. In the event a building has more than 100 nodes, there are strategies that can be applied to decrease the number of nodes without greatly affecting performance. One can delete rooms with low capacities and move the occupants into the corridor directly outside the room. These are normally small rooms with very few occupants and the time to travel from the room to the corridor outside the room will be very small. For example, rooms in the CIB/W14 building with a capacity of less than 10 people were deleted and the occupants moved into the corridor directly outside these rooms. The result is a decrease in the number of nodes without a significant increase in egress time.

8.2 Egress Analysis Technique

Earlier in this chapter the two components of the egress time line were discussed. The first component is the time from established burning to the occupant leaving the room. The second is the time from when the occupant leaves the room to the occupant passing through the exit discharge. This section will describe the process by which the time line, shown in Figure 8.2, is constructed. As noted earlier, the first part of the time line, the time to start egressing, is difficult to determine because of the large number of factors involved including human behavior, location of the fire, detection, number of people in the area, number of false alarms experienced and others. Therefore, the factors will be lumped and the delay time will be defined for the occupancy. To illustrate the importance of this time interval to the building performance evaluation, four different times will be used to represent this time period; 0, 2, 5 and 10 minutes. EVACNET+ will be used to estimate the second part of the time line, the time to egress. These times will be added to the times obtained from the computer model. The total times will be used in the lifesafety analysis.

This section identifies the process by which the time durations from the occupant leaving the room to the occupant entering the target space are determined. The time durations are the most optimistic reasonable time, the most reasonable time and the most pessimistic reasonable time. These were discussed earlier in this chapter. Here, the speed of movement is established. The route, distances and obstacles to the target space are also identified. An appropriate computer model is selected to provide a basis for evaluating the time duration to the target space.

The steps in the egress analysis are as follows:

1. Identify the target space(s) to be evaluated
2. Identify the room(s) from which the occupants originate
3. Establish a time duration from established burning to the occupants leaving the room (t_{leave})
4. Determine the time from leaving the room to entering the target space (t_{move}).
    a. Select the computer program for analysis
    b. Do enough computer runs to get a sense of people movement and the related times.
    c. Identify the assumptions in the program and the building features that would influence the credibility of the computer results
    d. Score the factors from (c) with regard to their influence in changing the time to enter the target space.
    e. Select the most optimistic reasonable time, the most reasonable time and the most pessimistic reasonable time.

The results from (4e) become the values of t_{ro}, t_r and t_{rp} to be used in the time line in Figure 8.3.

Section 8.1 discusses in depth the use of EVACNET+. However, recall that EVACNET+ does not take human behavior into account. To obtain more meaningful results from the computer model (Step 4b above), it is important to incorporate the knowledge that has been learned in the research on human behavior. Recall from Chapter 4 the important considerations.

- familiarity has a strong influence on exit choice
- main exits will be used far more than secondary exits; as a result main exit will serve many more people than other exits
- exits that are used for emergencies only will be used very little because they are not in the normal circulation path
- people tend to mimic the behavior or actions of others (i.e. people will follow crowds rather than acting individually).

These aspects may be simulated in EVACNET+ through manipulation of the input data. Recognize that the methods are only approximations of the effects of human behavior and must be taken into account when analyzing the output data.

The effects of human behavior were simulated by adjusting average speed (AS), average flow volume (AFV) and the width restriction (WR). Recall that EVACNET+ simulates the optimum evacuation time for a given scenario. By adjusting these parameters, one can change the optimum flow pattern. Below is a summary of each technique and its effect on the simulation.

1. *Decrease the width restriction (WR) on side stairs and less frequently traveled paths.*

- This will result in less people egressing along these paths and stairs and redirect more people to the main exit(s). A longer evacuation time will also be a result of this change. This is commonly what happens in emergencies.

2. *Decrease the average flow volume (AFV) on side stairs and less frequently traveled paths.*

- This will generally have the same effect as number 1. Very slight changes in the AFV will lower the dynamic capacity of the egress component and cause queuing, diversion to other exits and, in the end, increased egress times.

3. *Decrease the average speed (AS) on side stairs and less frequently traveled paths.*

- Again, less people will use side stairs and emergency exits, which is precisely what happens in actual fires. This is the least effective technique of the three.

The extent to which any of the input data should be manipulated is unique to each building. Several runs may be needed to settle on the appropriate techniques and values. This is rather easy to do, but it should be noted that the subjective judgment of the engineer become important to results, although it may be obvious to the casual observer. EVACNET+ allows the user to check node capacities at any time interval and the destination allocation, the number of people using each exit. Checking destination allocation is particularly useful because it is easy to see if a technique has been successful in diverting people to the main exit.

After completing the computer simulations, the engineer must identify the assumptions in the computer model, as well as, any building features and any other factors that may influence the credibility of the results. This corresponds to Step 4c. Once the list is compiled, the factors must be scored with regard to their influence in changing the arrival time of the occupants at the target space. The scoring is done in the same manner as the scoring of the factors that influence smoke movement discussed in Chapter 7. Each factor is weighted according to how much it affects the results with respect to the other listed factors.

The final step is to select the three times, Step 4e. The next section will provide and in depth discussion of the process through an example case.

8.3 Example Case

The building used in the CIB/W14 workshop will be serve as an example case. The building is a six story, multi-use facility with a total floor area of 2700 m^2. Floor by floor drawings can be found in Appendix A, Figures A-1 through A-5. Occupancies contained within the building include retail stores, restaurants/bars, recreational, offices and hotel. Steps 1 and 2 require the user to choose a target area and room of fire origin. The layout of the target area is shown in Figure 8.3 below. The stairwell and the foyer were selected to be target spaces. These areas can be seen in relation to the building on the Second Floor drawing, Figure A-3, in Appendix A. The room of fire origin is a second floor office connected to the foyer, which, in turn, connects to the main stairwell. The area of occupant origin for the foyer will be the offices surrounding the foyer and the west movie theater. For the stairwell, the area of occupant origin will be the second, third and fourth floors of the building. The stairwell serves the recreational areas on the floors above and the large occupant load from the movie theaters on the third floor. The determination of the first part of the egress curve (Step 3) has been discussed at length in Section 8.0.

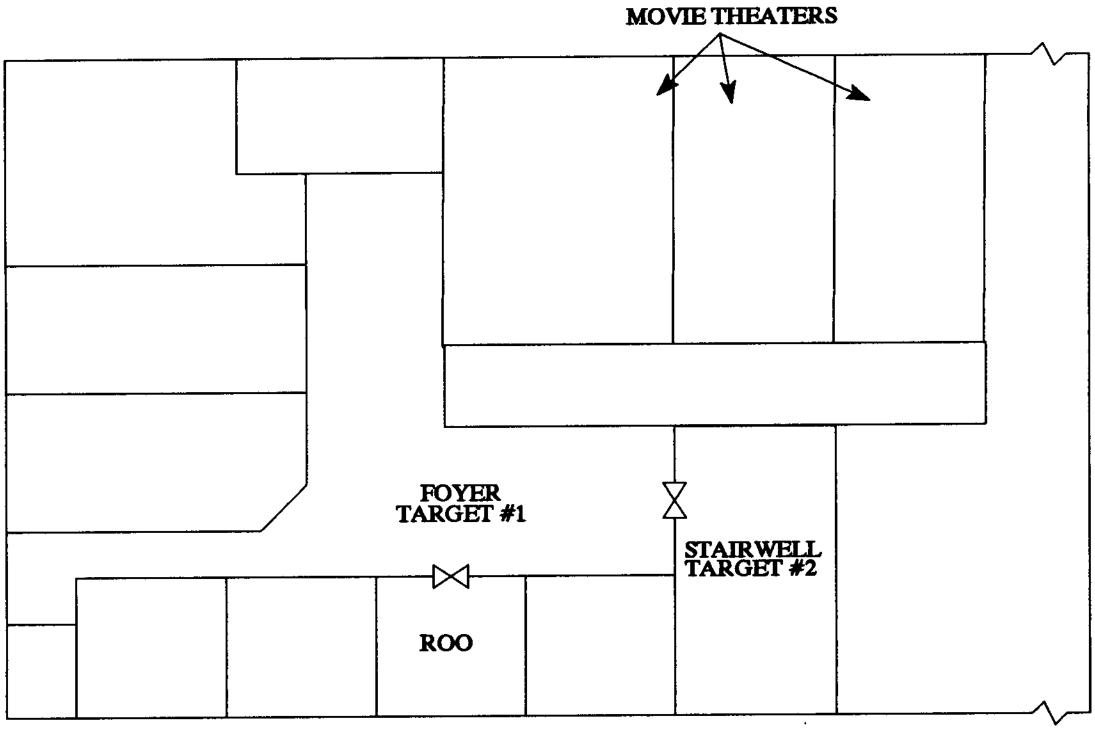


Figure 8.4 - Layout: Second Floor Ulster Building

Step 4b involved running EVACNET+ for enough situations to get an understanding of the egress patterns and times. The building layout with the defined nodes can be found in Appendix B, Figures B-1 through B-5. The total number of nodes exceeds the 100 allowed by the program. Therefore, many nodes, with initial capacities of 10 occupants or less, were removed and each one's initial capacity moved into the component nearest to it. The nodes removed were not critical to egress. Node capacities were found using Equation 8.1. The area per occupant (APAD) for each occupancy was taken from Table 806.2 in the 1990 BOCA Code. Table B-1 lists the nodes used and the floor area, APAD, capacity and initial capacity for each. The total number of occupants for the simulations was conservatively high at 1964 because most areas were assumed to have the maximum loading because of the use and design of the building.

The arcs for EVACNET+ were defined next. Arc definition is the controlling factor in the evacuation time. Therefore, manipulation of the arc input data will produce the three times required in the framework; the most optimistic reasonable time, the most reasonable time and the most pessimistic reasonable time. Note that these are not total evacuation times. The time to start egressing, which will be a fixed number, must also be added. Input data for arcs was obtained using a spreadsheet program which allowed easy manipulation of the data. Average speed data was acquired from a personal communication from Pauls. [42] Values for average flow volume were obtained from either Pauls or Fruin. [42,40] Tables B-2, B-3 and B-4 in Appendix B show the arc data.

In order to simulate some of the common human behaviors, the input data was adjusted between each run. This was accomplished with a combination of the strategies presented in Section 8.3. The only other distinction made between the runs was the average speed. In each component of the egress system, the average speed was lowered 20 feet per minute between each run. This value was selected as a reasonable approximation of the decrease in speed between the three simulations. There were many other simulations run. The three simulations that were chosen to characterize the most reasonable optimistic, most reasonable and most reasonable pessimistic times can be found in Appendix B.

EVACNET+ has a function that allows the user to look at individual nodes at any time period in the simulation. This is known as a *node contents profile*. This is shown for the target spaces in each simulation printout. The printouts can be found in Appendix B. The primary time of interest is the last time in which there are any occupants in the target space. Other important information shown in the printout includes the total evacuation time and the destination allocation. Table 8.2 below summarizes the results of the computer simulations.

Table 8.2 - Time to Clear Target Spaces

Model ID	Time to Clear Foyer	Time to Clear Stairwell
Optimistic	300 sec	370 sec
Reasonable	350 sec	400 sec
Pessimistic	400 sec	430 sec

Before the four values for time to decide to leave, 0, 2, 5 and 10 minutes, are incorporated, Steps 4c and 4d must be completed. These steps involve identification of the assumptions and limitations of the computer model, as well as the important features of the building architecture, and determining their influence on the computer results. The list will then be separated into factors that change the results of the computer analysis and factors that add uncertainty to the results. The target space for the in depth example below is the stairwell. Table 8.3 lists the factors that change the computer results and the weighting for each. Table 8.4 lists the same factors and approximates an equivalent amount of time, in seconds, for each of the simulations. Table 8.5 lists the other factors, which add uncertainty to the computer results, and the corresponding weighting. Weightings are based on a four star scale, four stars for the most influential and one for the least.

Table 8.3 - Factors Changing the Computer Results

Factors Changing the Time to Egress	**Weighting**
Results are optimum time for all simulations	***
Delays due to human behavior not accounted for	**
Obstacles such as fallen people or other objects are not accounted for	*
Doors are assumed open; time to open doors not accounted for	*

Table 8.4 - Approximate Equivalent Times

Factors Changing the Time to Egress	t_{ro}	t_r	t_{rp}
Results are optimum time for all simulations	+30	+45	+75
Delays due to human behavior not accounted for	+15	+30	+50
Obstacles such as fallen people or other objects are not accounted for	+5	+15	+30
Doors are assumed open; time to open doors not accounted for	+5	+10	+20

Table 8.5 - Factors that Cause Uncertainty in the Computer Results

Factors that Cause Uncertainty in Time to Egress	Weighting
Human behavior is simulated in the program using the strategies from Section 8.3	**
Effects of smoke and fire are not accounted for; may cause occupants to slow down or speed up depending on density	***
Occupant speeds are approximated	*
Flow rates are approximated	*
The computer model is linear. Speeds and flow rates can not change with time which they actually do	**
Computer program accepts integer input only. Calculated parameters must be rounded off	**

The factors above must be considered in arriving at the final approximation of the three times to egress. The time added on to the most optimistic reasonable time was 55 seconds. Most the time is added because the computer program simulates the optimum time to egress. Some time is added on to compensate for human behavior. Minimal time is added to account for obstacles and opening door. This produces the most optimistic time. Therefore, the effects of these factors should be minimal. Smoke spread will be light to moderate to achieve egress in this time. The appearance of smoke will heighten the perceived threat to the individual, which in turn may cause the person to move faster, assuming that visibility is still fairly high.

An additional 100 seconds was added onto the most reasonable time. Again, a good portion of the time is added to compensate for the fact that the program results are the optimum time. The situation that best characterizes this situation is one in which there is little evidence of a fire, such as when the door is closed to the room of fire origin. In this case, the individual is slow to react to cues and will move slower because the perceived threat is low. Door and obstacles will not be significant problems in this situation.

A significant amount of time, 175 seconds, is added on to the most pessimistic reasonable time. As in the first two cases, time must be added on because the result is the optimum time. The time added is larger than the first two because it is likely that there may significant delays caused by smoke and heat. The environmental conditions in this scenario are assumed to be questionable. Therefore, the times added for human behavior, obstacles and door opening must be increased from the most reasonable scenario.

Table 8.5 lists the factors that bring a degree of uncertainty into the computer results. The most significant source of uncertainty is not knowing the effects of smoke. Smoke could have an effect on the time to egress in either direction. The most obvious effect of smoke is that visibilities could be reduced forcing the occupants to slow down. Conversely, a small amount of smoke will alert the occupants to the fire, enhance the perceived threat and make the people move faster.

The strategies developed in Section 8.3 to simulate human behavior are only approximations. The strategies were used to simulate the effects of familiarity and other social factors on egress. Subjective judgment was used to evaluate to what extent the strategies should be utilized. It is unknown if the strategies made the results higher or lower than an actual situation. These approximations could cause significant errors in the results as indicated by the weighting in Table 8.5.

Occupant speeds and flow rates were taken from work done by Pauls and Fruin. [42,20] The data from these sources was obtained by simulations and observation of normal everyday pedestrian traffic patterns. In applying the data to a fire situation, there is an inherent amount of uncertainty. Actual speeds and flows rates could be either higher or lower. Another factor that adds uncertainty is the fact that the model is linear. The model is a static model in that input values remain constant throughout the simulation. The net effect on the results could be significant.

Recall from Section 8.1.1 that the inputs to the model must be in integer form. Input data is calculated in a spreadsheet program, but then must be rounded off for input into the program. Any fraction greater than or equal to 0.5 was rounded up to the next whole number. Conversely, fractions less than 0.5 were rounded down. The instances of rounding up or down is not known, but can be assumed to fairly equal. Thus, this uncertainty may nearly cancel itself out. However, there is still some uncertainty, because the effect could be more critical in egress components that are essential to timely egress. It is believed that this factor adds a moderate amount of uncertainty to the analysis. This contributes to the band of pessimistic to optimistic time intervals.

The final step is to combine the times from the computer simulation with the time to start egressing. Recall that this will be represented as four fixed times: 0, 2, 5 and 10 minutes. In adding these times, there must be some adjustment in computer results for the longer times to start egress. The long delay will allow for the development of smoke and other products of combustion that will slow the occupants. The determination of how much time to add is subjectively determined based on conditions that can be clearly described. In this way, the values can be discussed in a rational manner by all interested parties.

The analysis of the times for the foyer is identical to the stairwell. Results of the foyer analysis are presented in Table 8.6 below along with the stairwell results. The times listed are the time from established burning to the occupants reaching the target space. Figure 8.5 shows the four egress time lines for the stairwell and Figure 8.6 shows the egress time lines for the foyer.

Table 8.6 - Total Time to Egress

Time to Start Egress	Stairwell			Foyer		
	t_{ro}	t_r	t_{rp}	t_{ro}	t_r	t_{rp}
0 minutes	425	500	605	355	450	575
2 minutes	545	620	725	475	570	695
5 minutes	750	900	1000	720	820	950
10 minutes	1100	1275	1400	1050	1225	1400

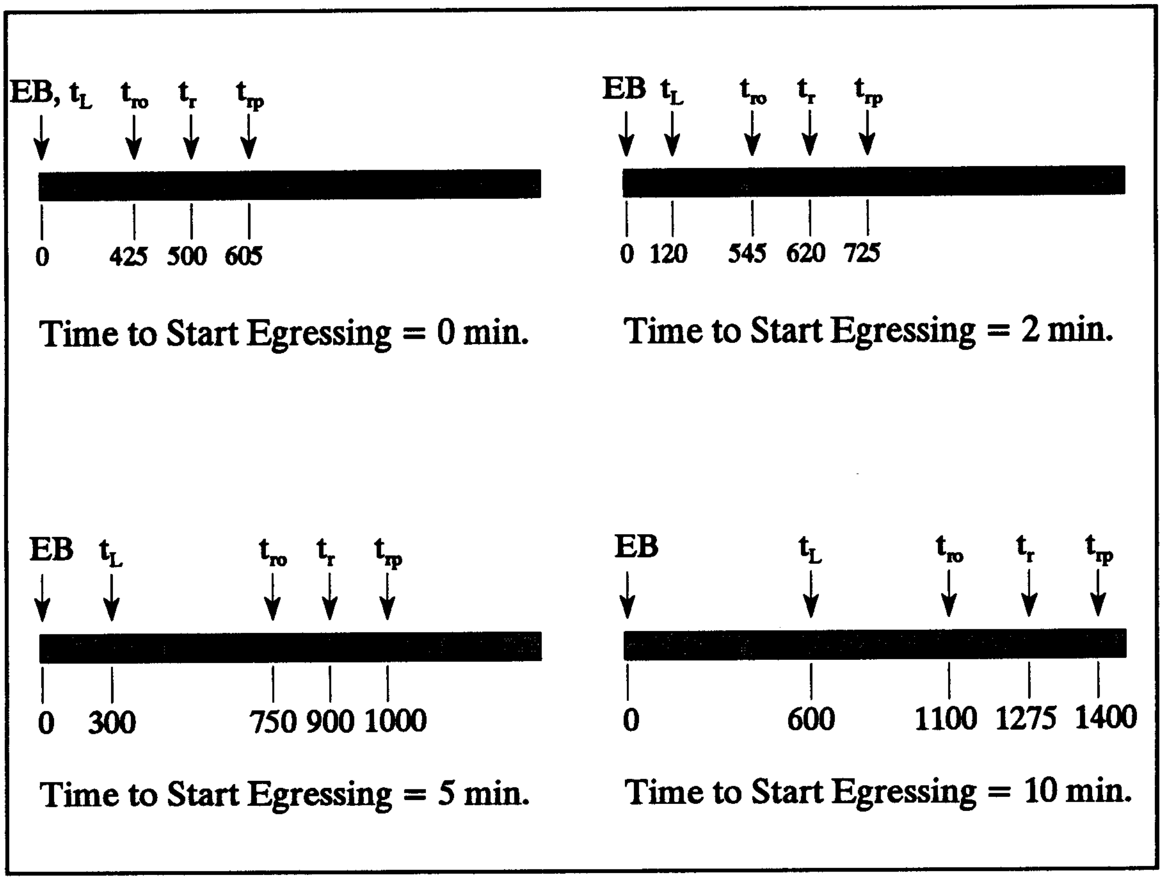


Figure 8.5 - Stairwell Egress Time Lines

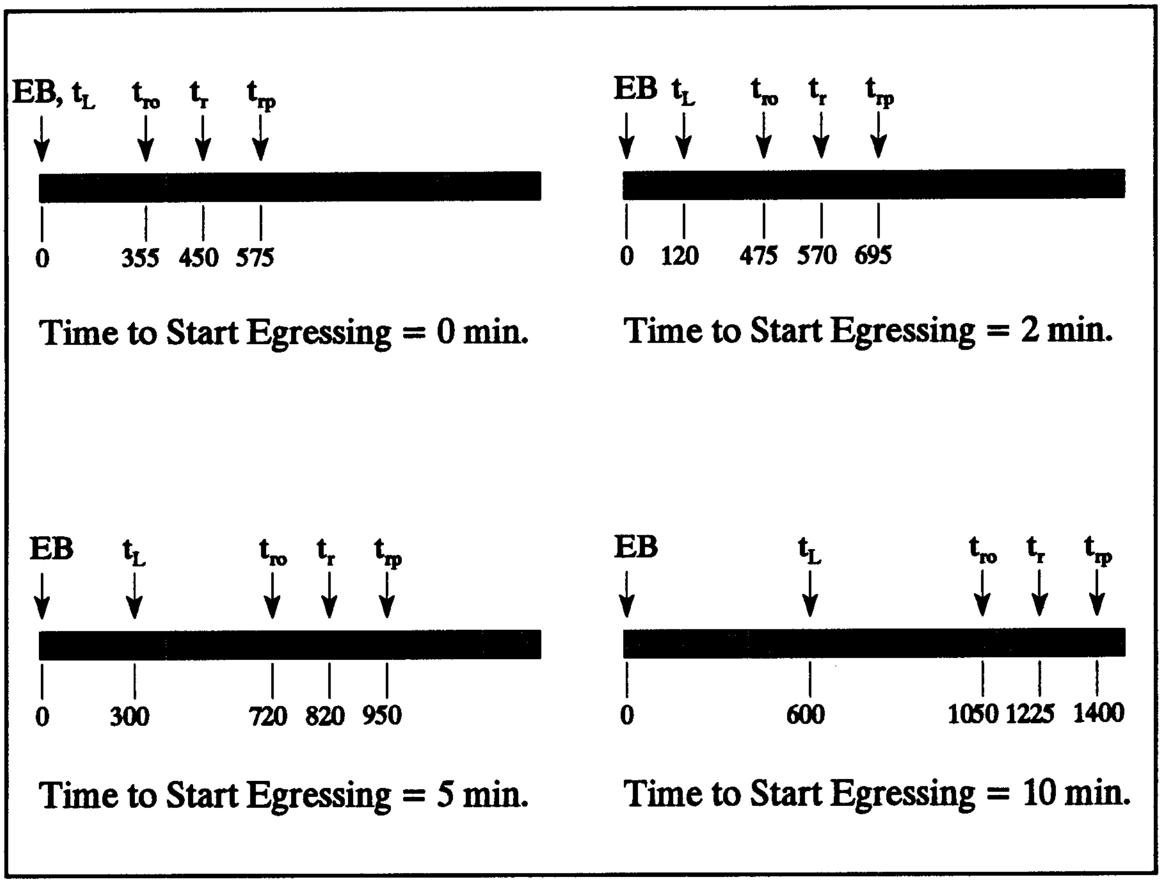


Figure 8.6 - Foyer Egress Time Lines

The egress time lines above will be combined with the smoke movement analysis to complete the lifesafety analysis. This is discussed in Chapter 9.

9.0 General Discussion

The lifesafety analysis in the BFSEM attempts to identify whether people and untenable conditions occupy the same space at the same time. The theory behind the analysis is described in Chapter 3. The lifesafety analysis for a building is based on two analyses. One involves a smoke movement analysis, resulting in smoke curves for the target spaces, and the second is an egress analysis, resulting in time lines for occupant movement to the target spaces. The previous two chapters have shown the processes for the smoke curves and the time lines for people movement. The goal of this chapter is to take the results from Chapters 7 and 8 to demonstrate a lifesafety analysis for a specific building. The assumptions and weaknesses in the analysis that must be taken into account also will be discussed in this chapter.

9.1 Building Overview

The building used in the example is the design building for the CIB/W14 workshop. The building is a six-story structure containing multiple use groups with an approximate floor area of 2700 m^2. Many different occupancies are housed with the building including hotel/apartments, retail stores, offices, restaurants and assembly/recreational areas. The floor plan of the building shows only five stories. The mezzanine level above the first floor is also considered to be a floor. The plans showing the layout of the building are located in Appendix A, Figures A-1 through A-5.

The ground floor of the building, shown in Figure A-1, is an area similar to a mini-mall. There are six stores and one restaurant on the floor. Note the dashed lines on the drawing indicating the mezzanine level. This is considered another level. There is an opening in the ceiling, shown in Figure A-2, connecting the ground floor to the first floor. There are four exits from the ground floor, one on each side. There is also one stairwell from the ground floor to the first floor.

The first floor is shown in Figure A-2. The interior of the floor is open to the ground floor. There is a dining room and a public bar in this area. Note that the interior is open to the stairwell serving the upper floors. Smoke produced by a fire on the ground or first floor will be able to travel up the stairwell due to the stack effect. The remainder of the first floor is separated from the interior. This area is either a hotel or apartments having a total of 20 rooms. There are two main exits on the east side and the south side. There is also an emergency exit located in the southwest corner. Both the east stairwell and the emergency exit are separated from the rest of the floor.

The second floor contains a number of offices and a conference hall. The main feature of this floor is the three movie theaters which have a maximum occupancy of around 300 people. This floor should be noted for its potentially high occupant load. Note the two main stairwells in the east and south and the emergency exit in the southwest. All three exits are separated from the other spaces on the floor.

A plan for the third floor is shown in Figure A-4. This floor is comprised primarily of offices. The large area in the north is the pool plant. This area potentially houses machinery and dangerous chemicals. The occupant load is very low for this area, and for the floor as a whole. The exits are identical to those on the second floor.

The fourth and top floor of the building can be seen in Figure A-5. This floor contains a health club with a workout area, pool and dressing rooms. This area also has a potential for a high occupant load with the large spectator section around the pool. There is also the possibility that this area may be used as a rehabilitation area which may be occupied by handicapped people.

Since the building involves the rehabilitation of an existing building, its construction is a combination of wood joist and concrete. The interior core of the building, indicated on Figures A-2 through A-5 by the dotted line, is comprised of concrete floor slab with reinforced concrete columns. The rest of the building is constructed of wood timber joists and floors with plaster and lath ceiling assemblies.

There are two designs for the building. The original design is shown in Appendix A, Figures A-1 through A-5, followed by a revised design, Figures A-6 through A-10, that meets the minimum requirements of the 1990 Building Officials and Code Administrators (BOCA) building code. The revised design required additional egress paths. This requirement was met with the addition of a stairwell in the northwest corner of the building. The original design was used for the example of egress analysis with the BFSEM.

The area selected for the base analysis is on the second floor. The first target space is the main stairwell serving movie theaters on the second floor and other recreational facilities on the floors above. The foyer, shown below, was selected as a second target space. A number of offices and other occupancies that contribute a small fraction of the occupant load are also located on these floors. The room of fire origin is the office labeled "office 6" on Figure A-3. The layout is shown below in Figure

9.1.

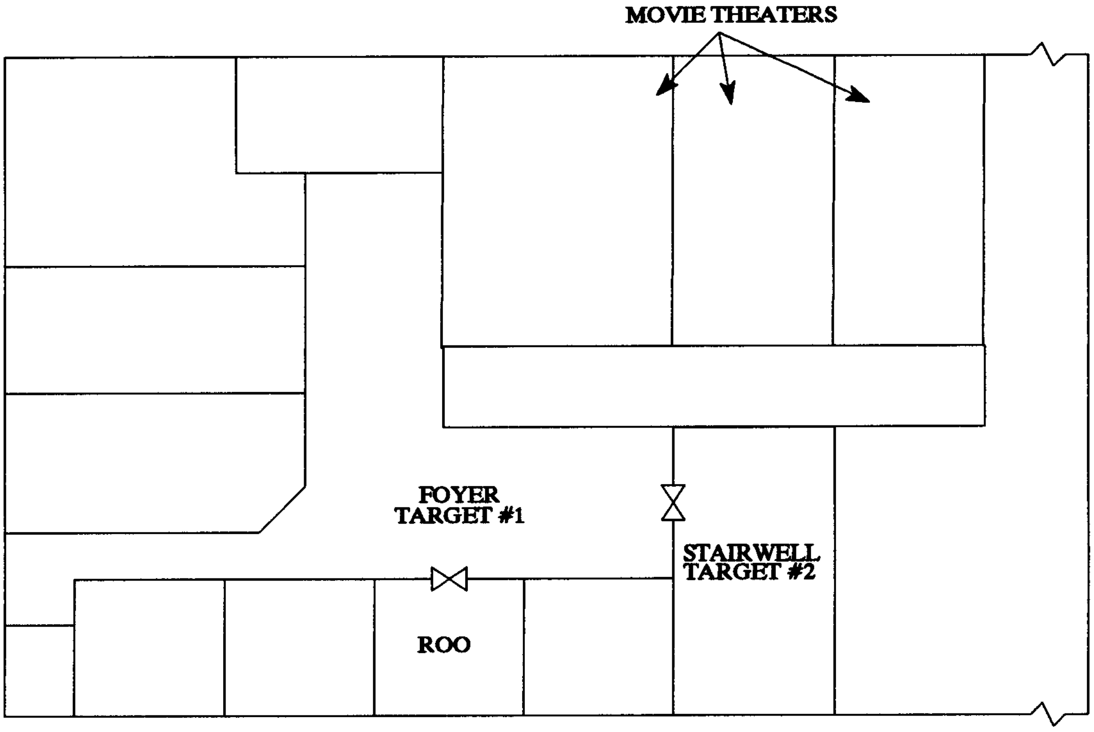


Figure 9.1 - Layout: Second Floor Ulster Building

The lifesafety analysis involves a combination of the activities described in Chapters 7 and 8. The goal of an egress analysis is to determine whether the occupants and untenable conditions occupy the target spaces at the same time. The smoke movement and egress analyses are done in the same time frame and, therefore, can be directly compared. The tools needed for the analysis are presented below in Figures 9.2 through 9.5.

9.2 Lifesafety Analysis

The initial step in the BFSEM lifesafety analysis is to identify the critical target spaces in the building. The base analysis areas on the second floor that have been chosen are shown in Figure 9.1. If the BFSEM lifesafety process were automated for rapid analysis, smoke curves could be generated for each potential target space. Since it is not yet automated, smoke curves are constructed for the more critical target spaces and the other target spaces are evaluated by comparison. A similar process is used for the egress analysis. Time lines are constructed for occupant movement to each target space. Since automation has not yet been achieved, time lines are constructed for the critical spaces. The additional occupant origination areas are evaluated by comparison. The probablistic smoke curves and the egress time lines for both target spaces were described in Chapters 7 and 8, and are shown below in Figures 9.2 to 9.5.

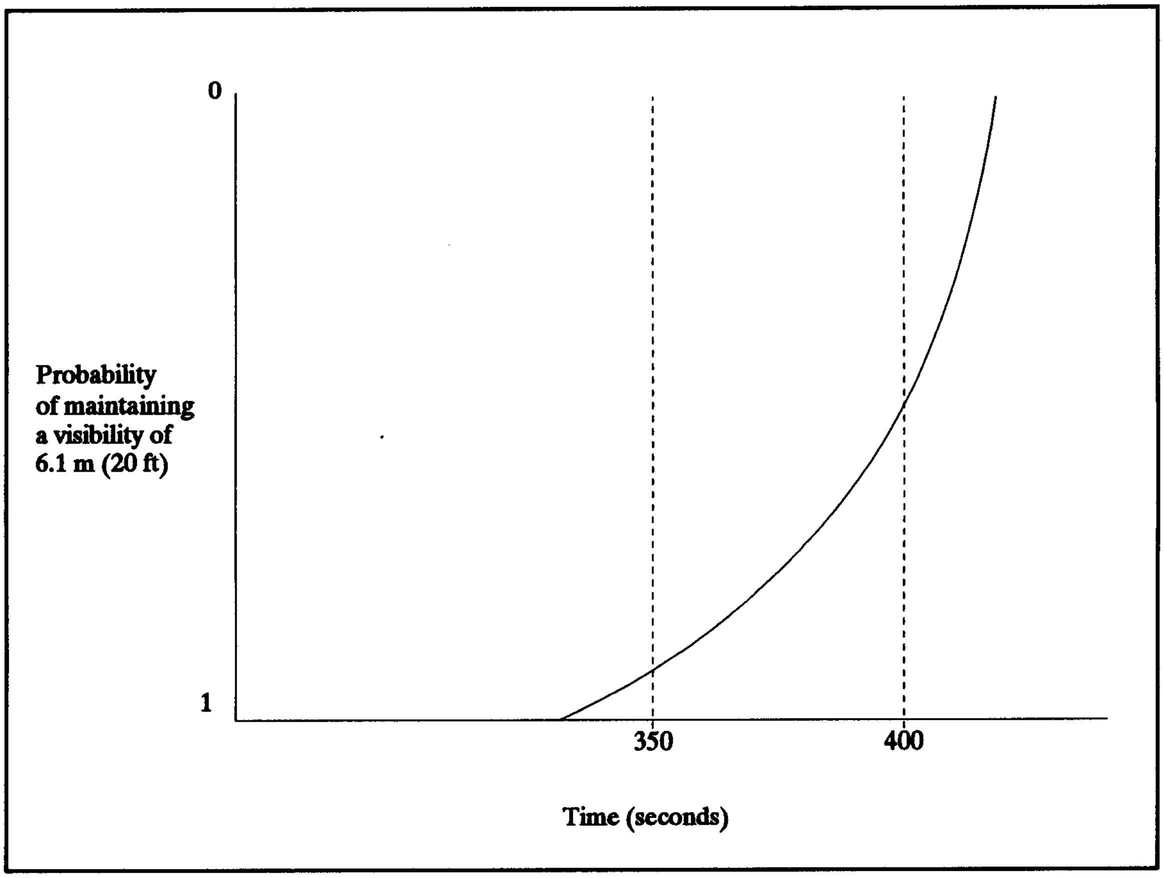


Figure 9.2 - Smoke Curve: Foyer

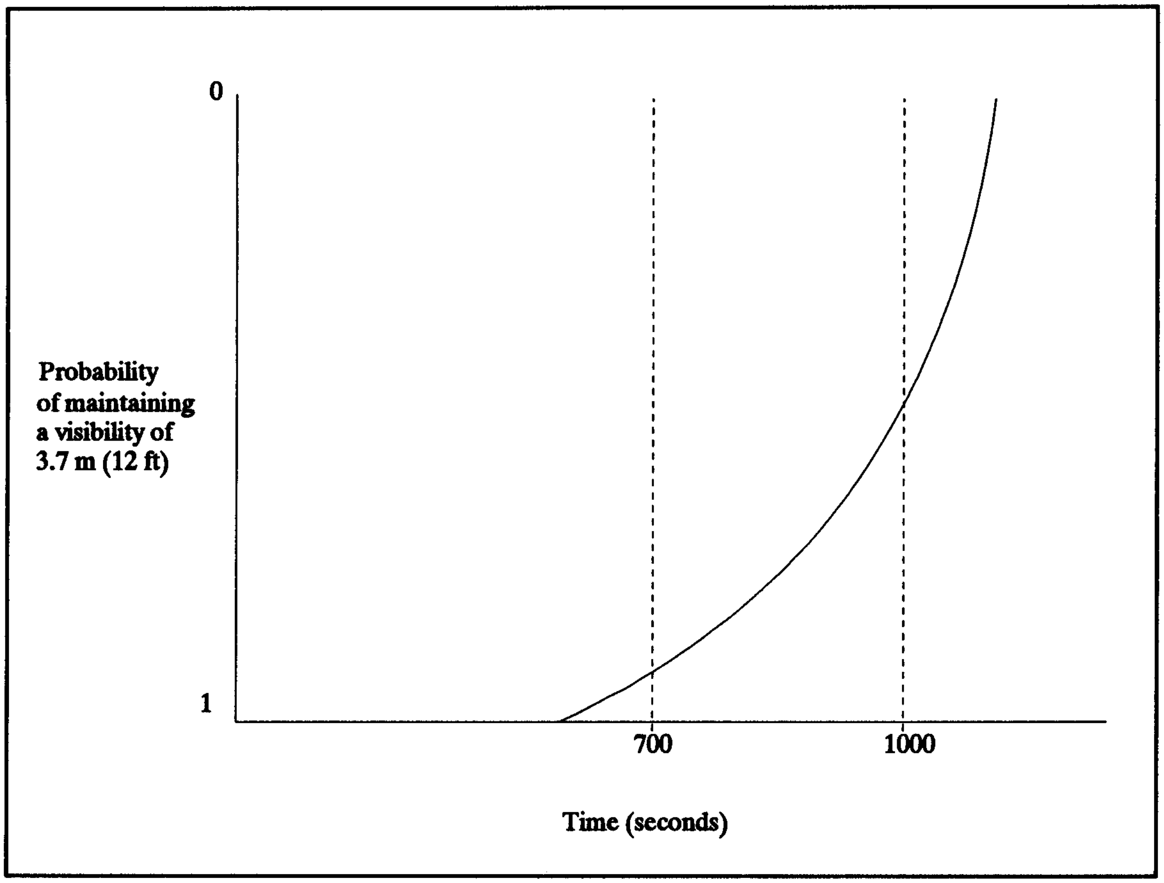


Figure 9.3 - Smoke Curve: Stairwell

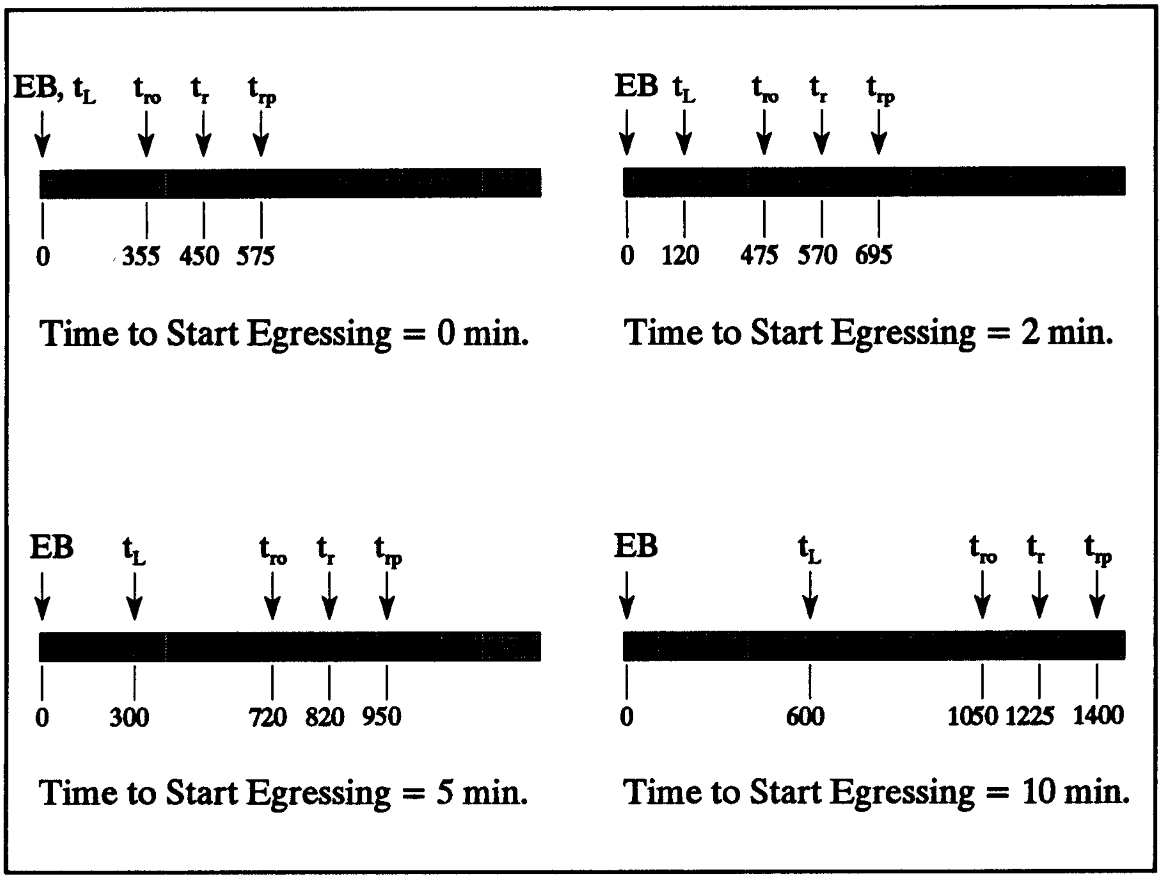


Figure 9.4 - Foyer Egress Time Lines

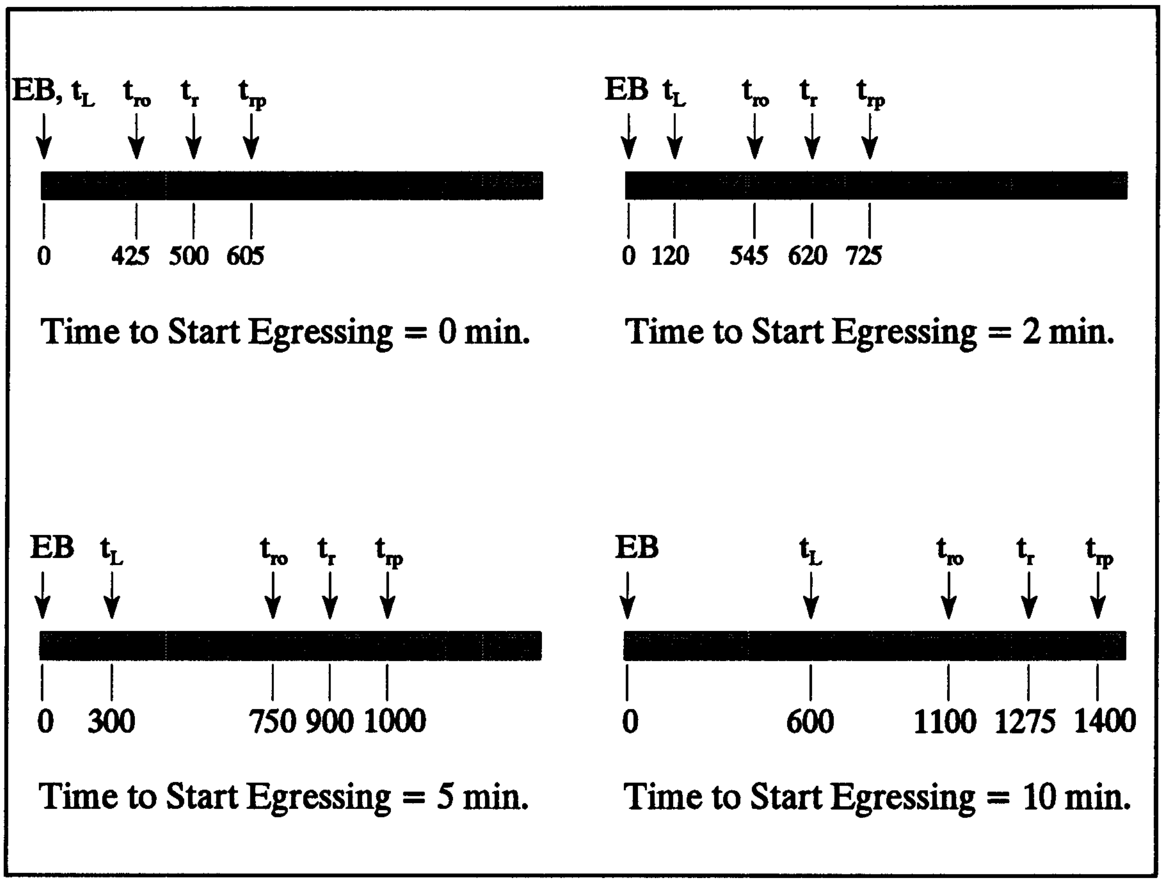


Figure 9.5 - Stairwell Egress Time Lines

In the description of the egress analysis, Chapter 8, the time to start egress was defined as the time from established burning to the occupants deciding to leave the room of occupant origin. For illustrative purposes, four time durations to start egress movement were used; 0, 2, 5 and 10 minutes.

Using the information above, the likelihood that people and untenable conditions will occupy the same space at the same time will be determined. This is done by comparing the time lines with the smoke curves. The time in which the egress time line intersects the smoke curve gives the probability that an occupant and untenable conditions will occupy the same space at the same time. This procedure is illustrated for a hypothetical situation in Figure 9.6. This becomes a measure of the building's performance. Table 9.1 shows the results of the comparison the two analyses for the target space described in Chapters 7 and 8. All data is obtained from Figures 9.2 through 9.5.

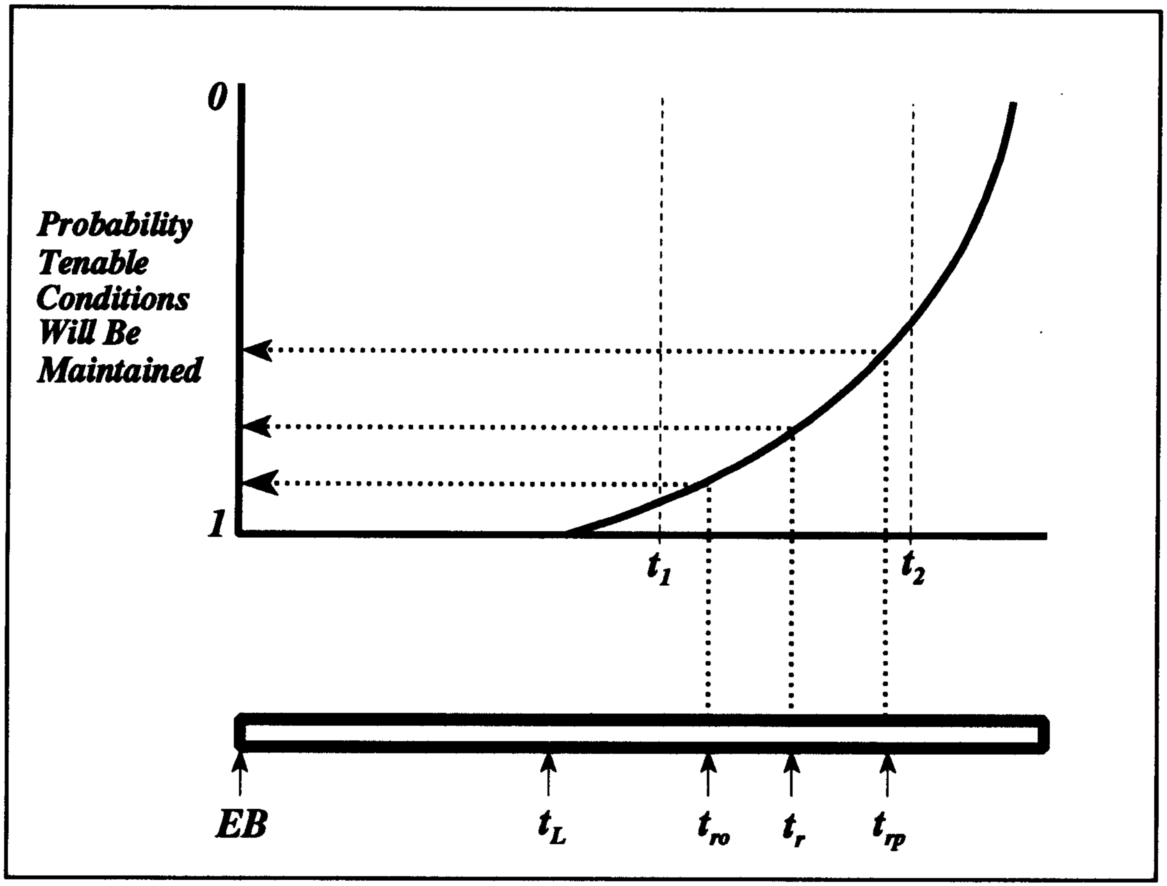


Figure 9.6 - Illustration of Determination of Probabilities

Table 9.1 - Comparison of Smoke and Egress Analyses

Target Space	Time to Start Egress	Egress Times			Probability of Success in Leaving Target Space		
		Opt.	Likely	Pess.	Opt.	Likely	Pess.
Foyer	0 minutes	355 sec	450 sec	575 sec	0.95	0.15	0
Foyer	2 minutes	475 sec	570 sec	695 sec	0.10	0	0
Foyer	5 minutes	720 sec	820 sec	950 sec	0	0	0
Foyer	10 minutes	1050 sec	1225 sec	1400 sec	0	0	0
Stairwell	0 minutes	425 sec	500 sec	605 sec	1	1	1
Stairwell	2 minutes	545 sec	620 sec	725 sec	1	1	0.85
Stairwell	5 minutes	750 sec	900 sec	1000 sec	0.75	0.60	0.50
Stairwell	10 minutes	1100 sec	1275 sec	1400 sec	0.20	0	0

From Table 9.1, it can be seen that there will be a problem with the foyer for all conditions of egress. The stairwell also could be a problem area, especially as the time to start egress increases and the likelihood that the stairwell door will be open for occupant egress. From the analysis above, the building performance for the second floor is clearly unsatisfactory.

The next phase of the analysis is to inspect other target spaces and rooms of origin in the building. This may be done by comparison of conditions to the more carefully studied spaces or by constructing additional smoke curves and egress time lines. This analysis will look at every floor of the building and determine if any other spaces are also potentially hazardous when considered as a place of fire or occupant origin. Each floor, beginning with the ground floor, will be analyzed as to the likelihood that people and untenable conditions will occupant the same space at the same time. If necessary, additional detailed analyses may be needed for other building areas.

On the ground floor, all areas present a nearly equal likelihood of causing untenable conditions for stairwell target spaces. A fire in any room on the ground floor will spread smoke up to the first floor through the opening in the ceiling. Recall that the first floor is open to the south stairwell. Smoke on the first floor will spread up the south stairwell due to the stack effect. Untenable conditions will occur in the south stairwell at a shorter time period than the second floor base case. Occupants on the third and fourth floors will likely be forced to seek alternate escape routes regardless of the time to start egress. Second floor occupants will have difficulty egressing. If the time to start egress is less than approximately five minutes, most occupants of the second floor should be able to egress safely. Occupants on the ground and first floors should be able to egress safely due to early detection and time to start egressing and also, due to much of the smoke, at least initially, spreading into the stairwell.

Rooms of fire origin in the section of the first floor open to the ground floor will perform much the same as areas of the ground floor. Smoke from these fires will spread up the south stairwell. Even less time will be available for people on the upper floors to safely egress down the south stairwell because the fire will be closer and, consequently, the stairwell will become smoke logged earlier. Occupants from the second, third and fourth floors are likely to encounter untenable conditions and will be forced to seek alternate routes of escape. In order for occupants to be able to safely egress down the south stairwell, time to start egress would have to be within three to five minutes. One of the hotel rooms, along the south and west walls, as a room of fire origin could present some difficulty to occupants egressing down the emergency exit.

However, a fire in one of these rooms would likely be rather small and the door to the emergency exit should remain closed after the small number of occupants exit from the hotel area. Therefore, there should be little danger to the occupants egressing in the emergency exit from the floors above. Other rooms of fire origin in the southeast corner will inhibit occupants egressing down the east stairwell. However, if the door to the stairwell remains closed for the majority of the time allowing safe egress for the occupants from the floors above, the fire in theses rooms should not pose a significant threat as in the other locations.

The second floor was the area of the detailed target space analysis. Offices to the west of the south stairwell, as rooms of fire origin, will have similar affects on the south stairwell and the foyer as the original room of fire origin. People from the movie theaters and floors above will likely encounter untenable conditions in the foyer and may encounter untenable conditions in the stairwell depending on the time to start egress. A room of fire origin to the east of the south stairwell would present a greater problem than the original room of origin. The foyer outside these rooms is smaller and will fill with smoke faster. Both main stairwells are located off this foyer and will begin to fill with smoke faster than the room of fire origin originally studied. The foyer definitely will be a problem for egressing occupants on the second, third and fourth floors. However, occupants on the ground and first floors should have little difficulty evacuating.

The layout of the third floor is similar to the second floor, except for the pool plant located above the movie theaters. The occupant load of this floor is significantly lower than the second floor. Offices are the only occupancy to contribute to the occupant load. A fire on this floor would behave similar to the one considered on the second floor. However, the occupants should be able to clear any target space on this floor before untenable conditions develop because the travel distance is shorter and there are very few other people to slow travel speeds. Occupants on the fourth floor should be able to clear the third floor stairwell before the onset of untenable conditions because the distance to the target space is shorter and they will not encounter a large occupant load that could slow travel speed until they reach the second floor. The major concern is that time to start egressing may be extended. This will certainly cause problems.

The fourth floor contains the fitness center and pool. A fire in any area of this floor should not prevent occupants from exiting safely. A fire on this floor will be detected relatively early by occupants and should allow enough time to get off the floor before untenable conditions develop. Travel distance to target spaces is much shorter than any of the previous scenarios for people on the fourth floor. Once people get to the stairwell and start downward, they should not encounter hazardous conditions because the smoke should not travel down the stairwell until the occupants have cleared the building. Likewise, people on the floors below should not encounter untenable conditions. Handicapped occupants will encounter the same difficulty as in any building because of delays in starting and longer periods of time needed to move to the spaces.

9.3 Building Alternatives

The initial smoke curves are based on the condition that the fire continues to burn without suppression. This provides an understanding of the basic building behavior for this condition. In this case, the example building would pose substantial problems for occupants attempting to leave the building. When this is recognized, the BFSEM suggests that alternatives be selected that change the smoke generation or the smoke movement. Either the fire and smoke generation or the building may be changed to alter the smoke movement to the target spaces. Some illustrative potential changes that may be considered are as follows:

- Installation of sprinklers for early extinguishment of the fire to reduce smoke production
- Pressurization of the stairwells to inhibit the spread of smoke into that space
- Earlier notification of the occupants and an intercom system to give instructions to expedite egress times
- Installation of automatic door closers to inhibit smoke movement from to target spaces
- Separate and enclose the south stairwell from the mall area to prevent smoke from moving into the stairwell

Of the list above, the two modifications that will have the greatest effect are the installation of sprinklers and separation of the south stairwell. Sprinklers will greatly reduce the smoke spread from most any fire by either suppressing or controlling the fire. Figure 9.7 illustrates a smoke curve with fire suppression at an early stage. The dotted line in Figure 9.7 represents the portion of a smoke curve where fire suppression is achieved. With smoke spread reduced, occupants from all floors can egress more safely.

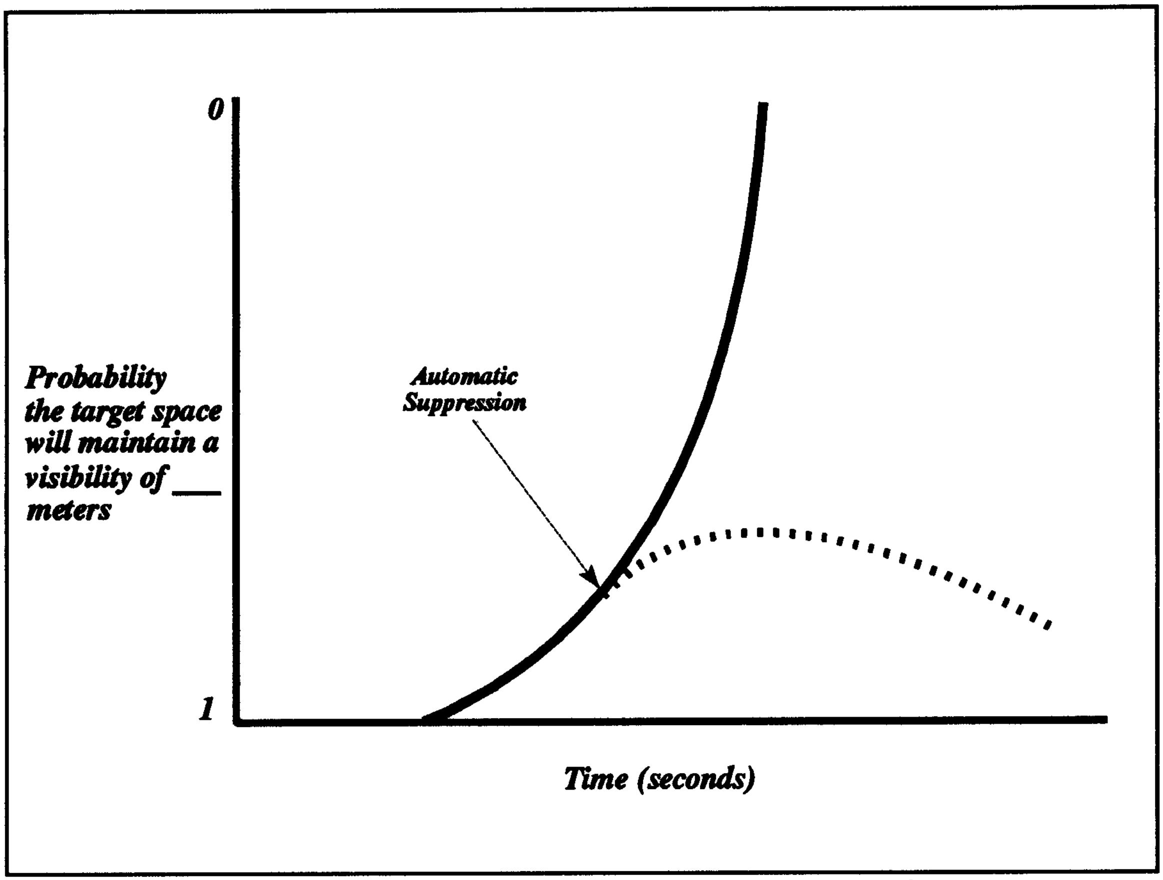


Figure 9.7 - Smoke Curve with Automatic Suppression

Another means of improving lifesafety in the building is to pressurize the stairwells. Pressurization would prevent smoke from moving into the stairwells, which are the most crucial portion of the egress system. If the stairwell were to remain relatively smoke free, occupants will be able to egress from the building more safely.

The installation of better detection systems and an intercom system to give instructions to the occupants addressed the first part of the time line, the time to start egressing. The intercom system and better detection will decrease the time between established burning and the occupants deciding to leave the room of occupant origin. This type of notification will encourage occupants to start egressing earlier and identify the seriousness of an actual fire as opposed to a fire drill.

The installation of automatic door closers is another option to improve lifesafety in the building. Door closers will inhibit the movement of smoke to target areas. Thus, tenable conditions will be maintained in target areas longer allowing the occupants extra time to egress safely.

The BFSEM lifesafety analysis has identified in the building. Through comparison to the target spaces in the base case analysis, other areas of the building that could be problem areas have been identified. Lastly, recommendations have been discussed to achieve satisfactory building performance.

9.4 Use of the Computer Programs

There are a number of considerations that must be kept in mind when using the computer programs. A primary recognition is that a number of assumptions and substantial subjective judgment must be used to fill gaps in the computer analysis. Many other factors are inherent in the computer programs and have been discussed earlier. Users must be careful to not blindly accept the output from the computer programs as reality.

1. Smoke movement computer models are only simulations of real fires.

2. Heat release rates are only approximations of *typical* fires in a given occupancy.

3. C/CO_2 ratios are approximated. Actual ratios are dependent on the available oxygen and may be much higher than predicted.

4. Visibility criteria was developed from tests in nonirritating smoke. No substantial difference is observed until approximately 6.1 meters (20 feet). A lower extinction coefficient corresponds to 3.1 meters (10 feet) in the case of irritating smoke as opposed to nonirritating smoke. The difference is rather small. As a result, visibility actually decreases faster than the nonirritating data indicates. The final consequence is the analysis is less conservative than an actual fire in the respect that the time to any given visibility between 3.1 meters (10 feet) and 6.1 meters (20 feet) occurs faster than the computer program indicates.

5. Egress models are simulations of evacuation.

6. Human behavior is not accounted for in EVACNET+

7. Times from EVACNET+ are the *most optimistic* for a given scenario and may be higher than the model indicates

8. The strategies presented for imitating human behavior are only simulations of assumed behavior.

9. Time to start egress is difficult to characterize. Assigning a value to this time is the most practical approach to the problem at this time.

9.5 Uncertainties in Performing a Lifesafety Analysis

The lifesafety analysis procedure presented in this thesis was an initial attempt at testing the feasibility of computer program use with the BFSEM. Although much has been accomplished in defining the method, a number of weaknesses have been recognized.

In the smoke modeling portion, the prime weakness is in the treatment of the soot to carbon dioxide ratio needed to predict the optical density. Most areas will be conglomerations of fuels. Data has been gathered for a number of homogenous materials.[15] Ratios for both well-ventilated fires and nonflaming fires are presented.

The values used to represent these two conditions are averages of the materials listed for each type of fire. However, neither of these conditions are appropriate for most enclosure fires. Well-ventilated conditions are present in the earliest stages of the fire. Nonflaming or smoldering combustion are the conditions under which the most smoke would be produced. Therefore, it is assumed that the actual value is somewhere in between the two values. It was also found that unburned fuel and carbon monoxide rise exponentially as the oxygen level drops.[15] This information was used as the basis for estimating the upper and lower bounds of C/CO_2 ratio used in the smoke movement analysis. The upper and lower bounds form an envelope in which is it is believed the actual value in an office fire would fall. However, there is little information to guide the engineer in choosing upper and lower bounds. Thus, it is possible that the values used in the smoke movement analysis are lower than an actual fire. Therefore, the values used are conservative.

Egress models, as has been stated, provide optimum times. Psychological research has not identified human behavior in fires adequately. This behavior is not included in the computer model. The simulation of common aspects of human behavior are only approximations. EVACNET+ also has some weaknesses in the application of the model. The fact that the input to the model must be in integer form has been discussed in Chapter 8. Another weakness, primarily in its use with the BFSEM Lifesafety Analysis, is that an entire line of input data must be reentered into the program even though only one parameter has changed. This adds a significant amount of time to the overall analysis. It is believed that this could be overcome with slight modifications to the model. All input to the program should be in an editable file so that slight changes can be made more easily, thus speeding up the egress analysis. The egress analysis is the most time consuming portion of the lifesafety analysis. Changes should be made in EVACNET+ to expedite the egress analysis, which would make the lifesafety analysis a more feasible method in terms of time and money spent.

The lifesafety analysis itself is only as good as the people who apply it. The computer models, especially the smoke movement models, require substantial background to use. Perhaps the most significant weakness is the time it takes to apply the method. A large amount of time is spent primarily in the egress modeling. It may, however, just be the program that was chosen for this thesis. Others may be much more user friendly and easier to use. Once the engineer becomes familiar with the programs and the BFSEM, the analysis can be completed within a week, perhaps as short as two days with smaller buildings. Hopefully, if further research is done in this area and some improvements are made to the programs, this method will become a cost-effective means of evaluating lifesafety.

Future work on the BFSEM Lifesafety Analysis should focus on a number of areas. Enhancement of EVACNET+ or use of faster, more user-friendly egress computer model would make the lifesafety analysis more feasible by cutting analysis time and cost. Better characterization of the time to start egress, perhaps on an occupancy basis, will give one more confidence in the results of the egress analysis by using one or two times to start egress as opposed to four. Lastly, the lifesafety analysis should incorporate handicapped persons into the analysis. These improvements will increase the feasibility of the lifesafety analysis by cutting cost and the time involved with the process, as well as, expanding the focus to include handicapped persons.

10.0 Conclusions

A method for the analysis of lifesafety in the BFSEM has been tested for its feasibility for general use. The procedure for analyzing the output data from the computer models also is presented. The BFSEM has been designed to be compatible with almost any computer model. An example is also included as a demonstration of the method.

Building codes and standards, such as BOCA and NFPA 101, have been the primary means of evaluating lifesafety in a building. These sources looked primarily at egress. Lifesafety problems may exist in buildings where all the provisions in the codes and standards are met. The BFSEM lifesafety analysis predicts the performance of the building with regard to the egress of the occupants. In addition to egress, this involves looking at smoke movement and aspects of human behavior. The comparison of the egress and smoke movement analyses predicts the likelihood of people and hazardous conditions occupying the same space at the same time.

It has been shown that computer models can be used as a basis for performing the smoke movement and egress analyses. This thesis has shown how results from computer models can be applied to the individual analyses. Although subjective judgment is relied upon, the final results of the analyses give a good sense of the smoke movement and people movement in the building.

The strengths and weaknesses of the BFSEM lifesafety analysis have been documented in Chapter 9. The long range goal is to automate the process of generating smoke curves and egress timelines for all the spaces in a building. This would greatly simplify the analysis. In the present state of the BFSEM lifesafety analysis, a concern in the application is the time required to compete the analysis. It is believed that the analysis can be applied to a building in approximately three days. This is assuming that the user is familiar with the application of the analysis and the computer programs being used. There are a number of suggestions for further work discussed in Chapter 9. If these were to be implemented, the analysis time would decrease. Thus, with further refinement, the BFSEM lifesafety analysis can be a cost-effective means of evaluating lifesafety in buildings.

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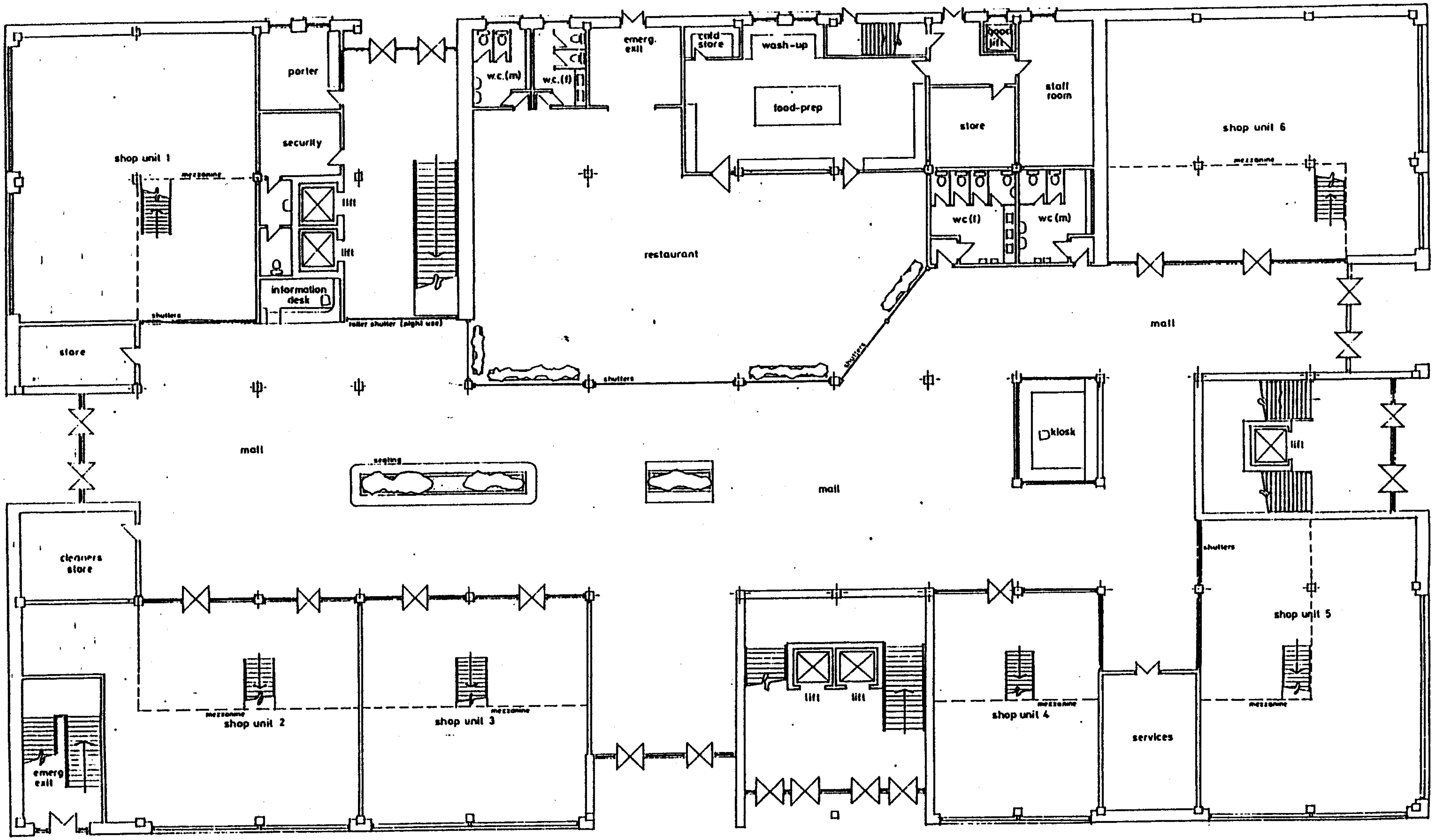
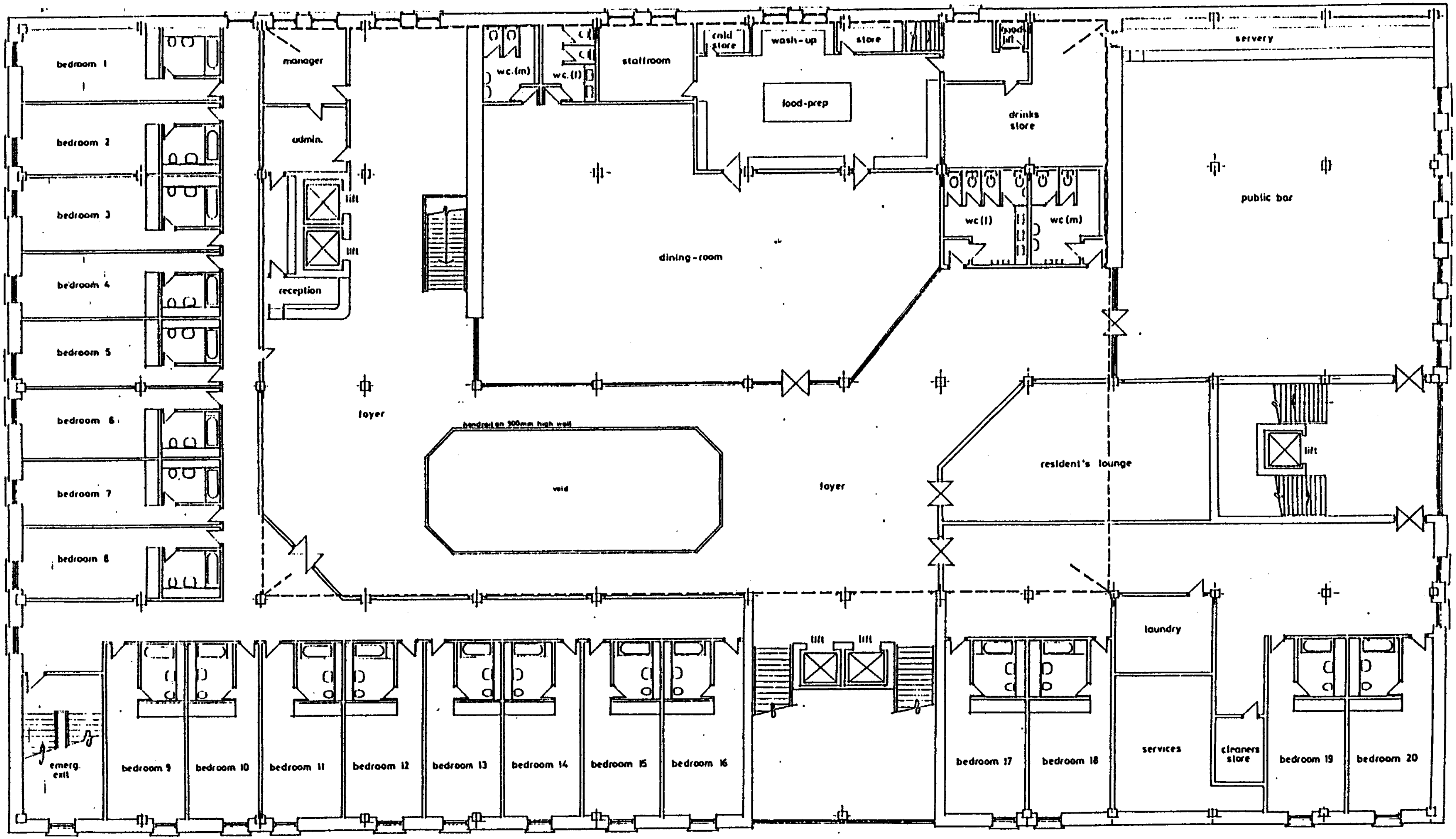
APPENDIX A



GROUND FLOOR PLAN 1:100

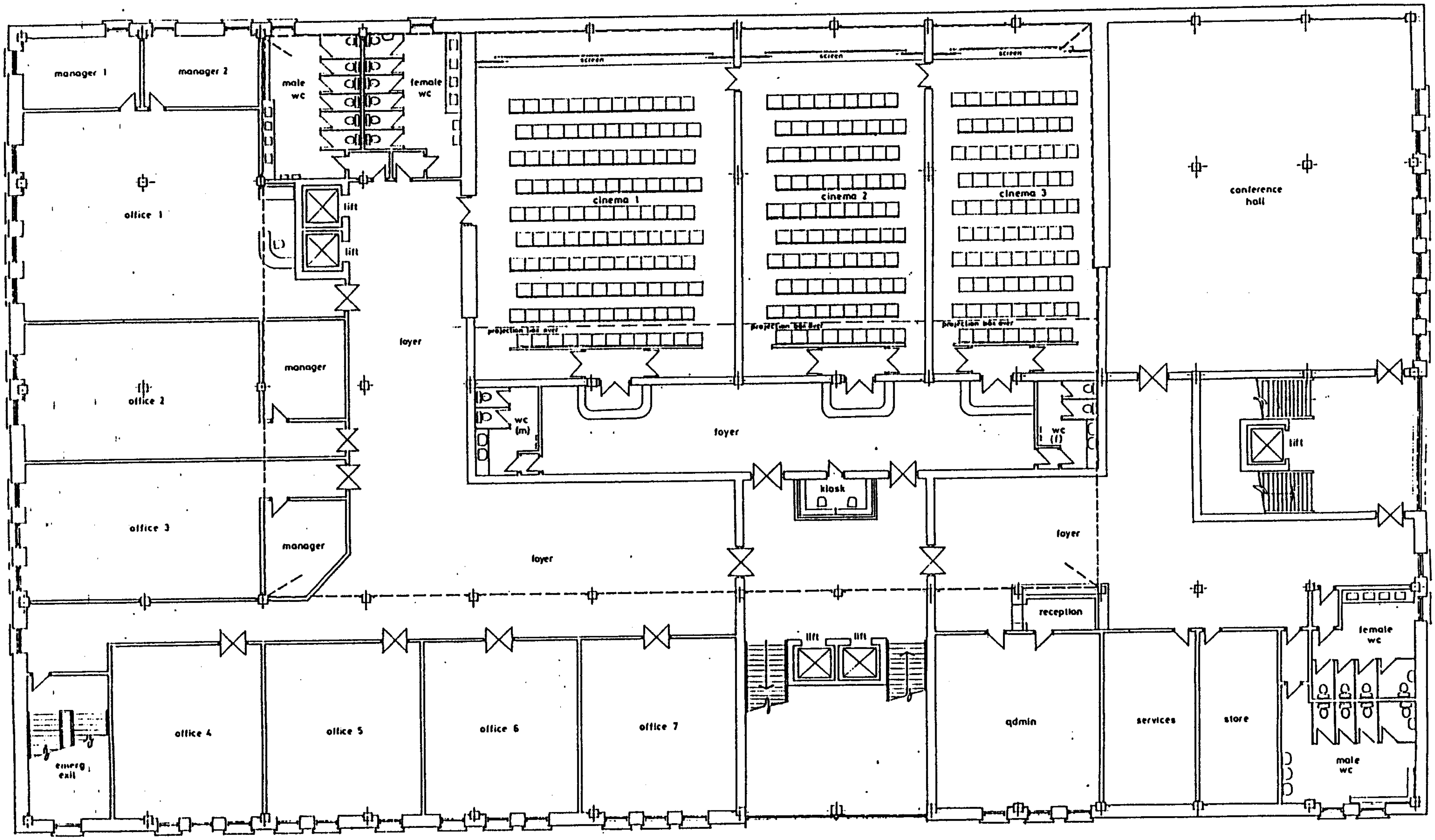
Figure A-1



FIRST FLOOR PLAN 1:100

⬚ indicates area of new reinforced concrete floor

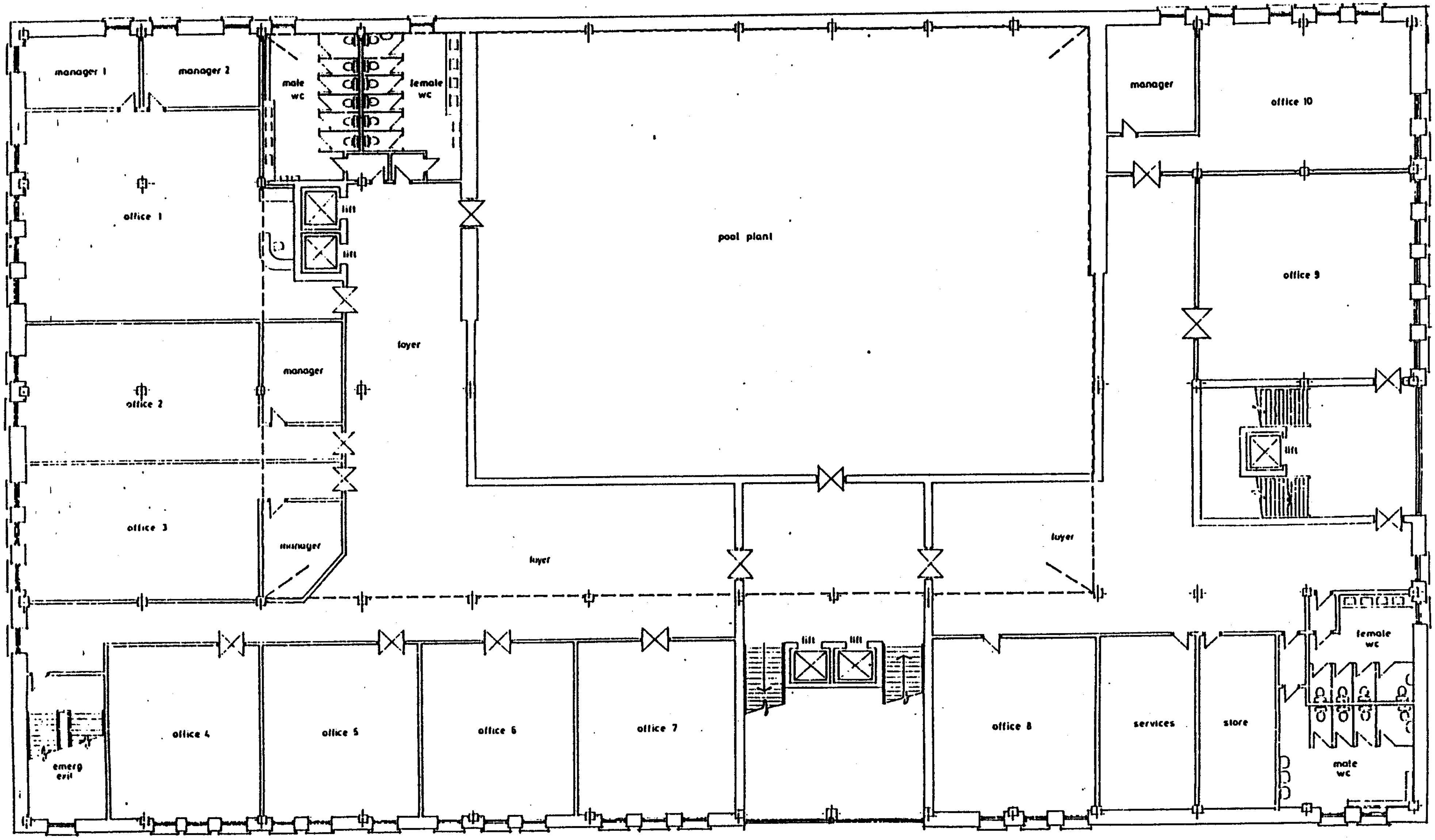
Figure A-2



SECOND FLOOR PLAN 1:100

Figure A-3

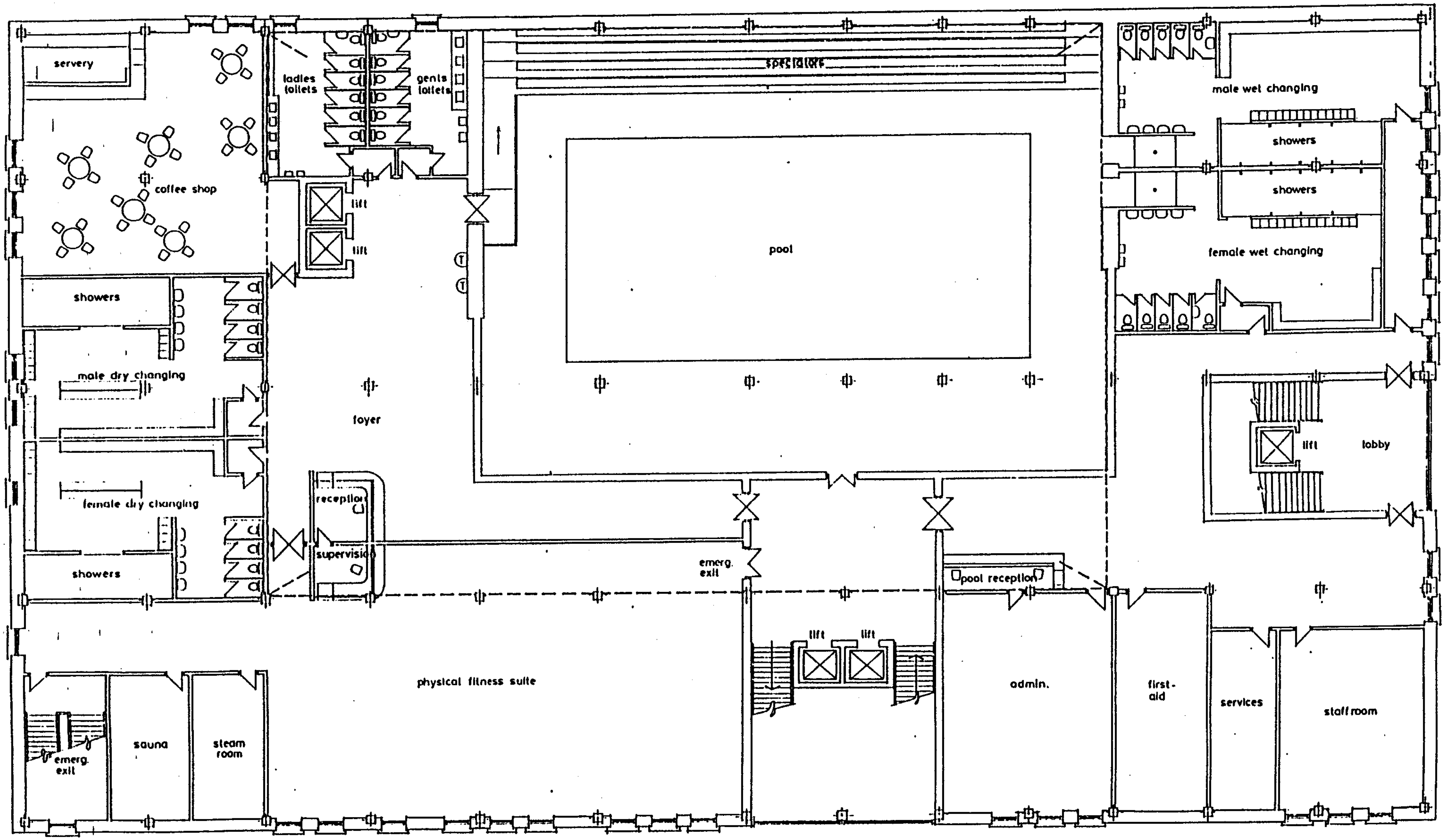
⬚ indicates area of new reinforced concrete floor



THIRD FLOOR PLAN 1:100

indicates area of new reinforced concrete floor

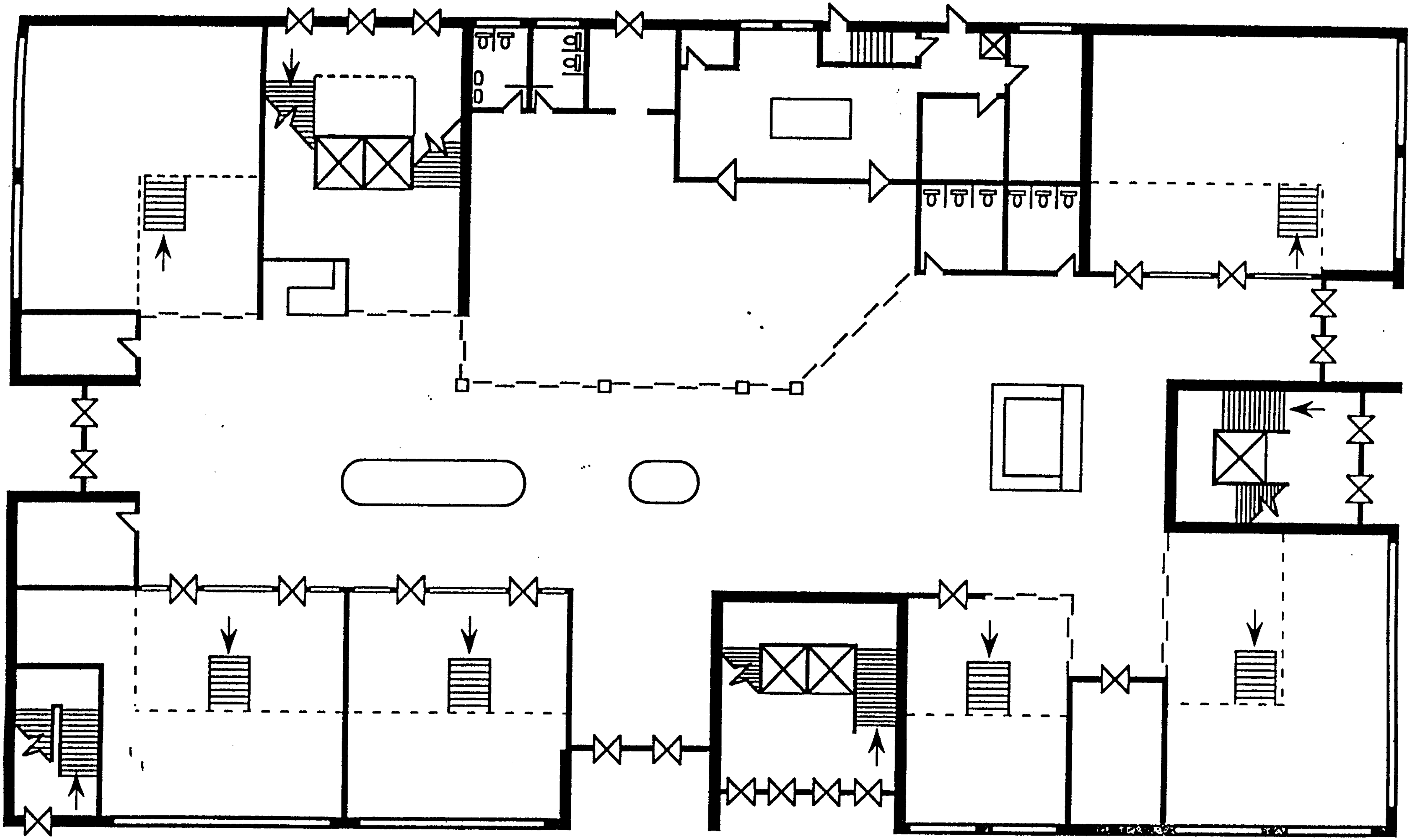
Figure A-4



FOURTH FLOOR PLAN 1:100

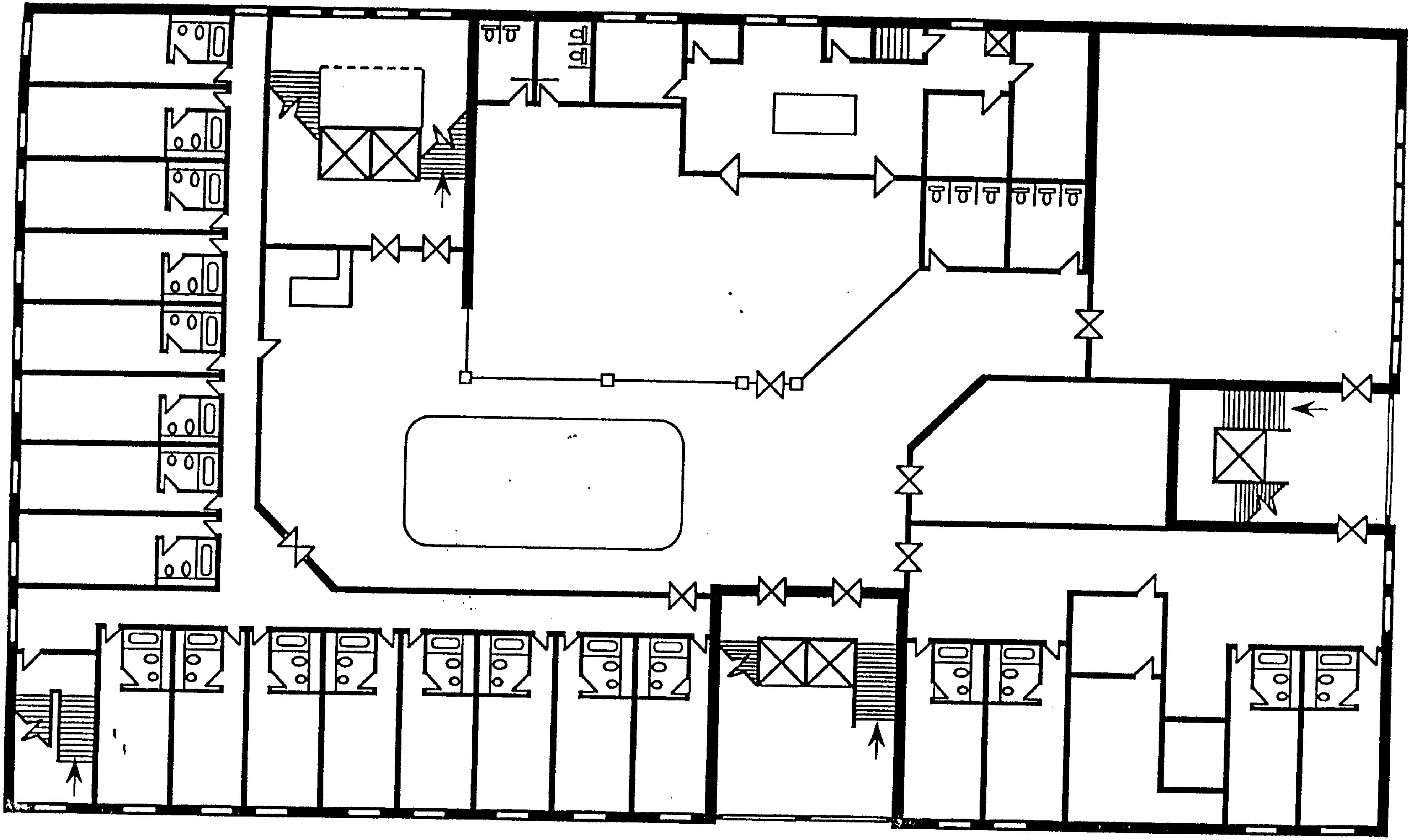
Figure A-5

⬚ indicates area of new reinforced concrete floor



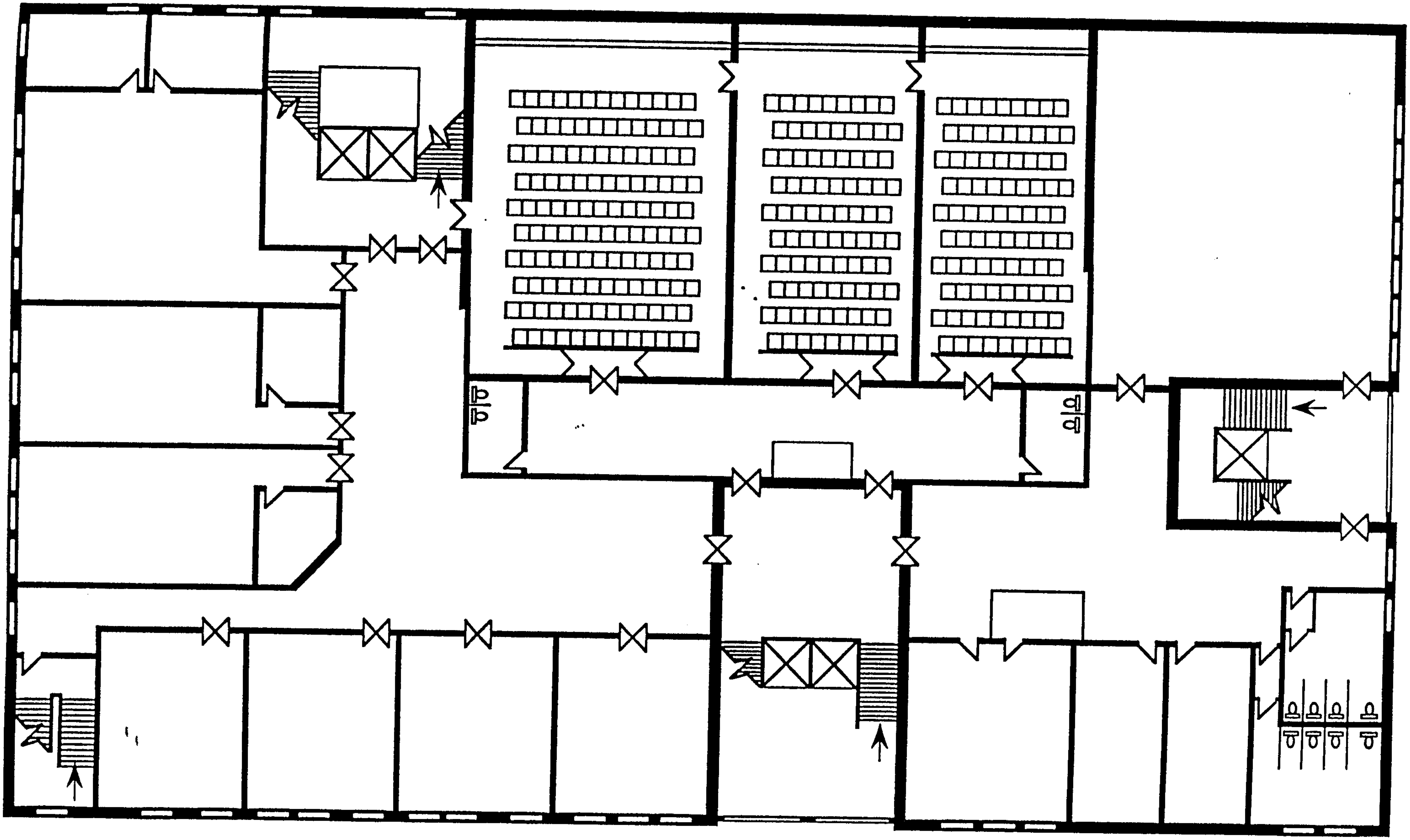
Ground Floor

Figure A-6



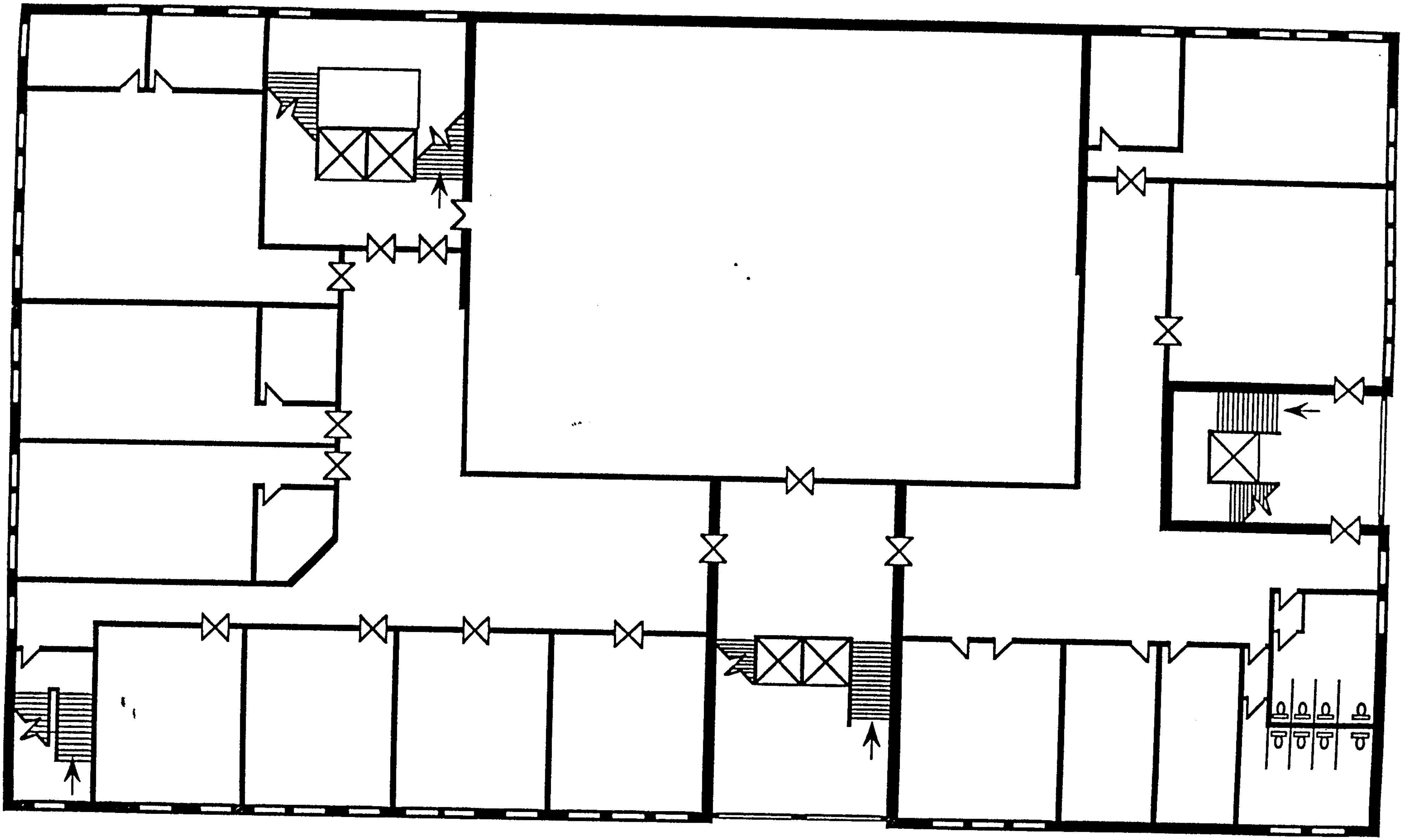
First Floor

Figure A-7



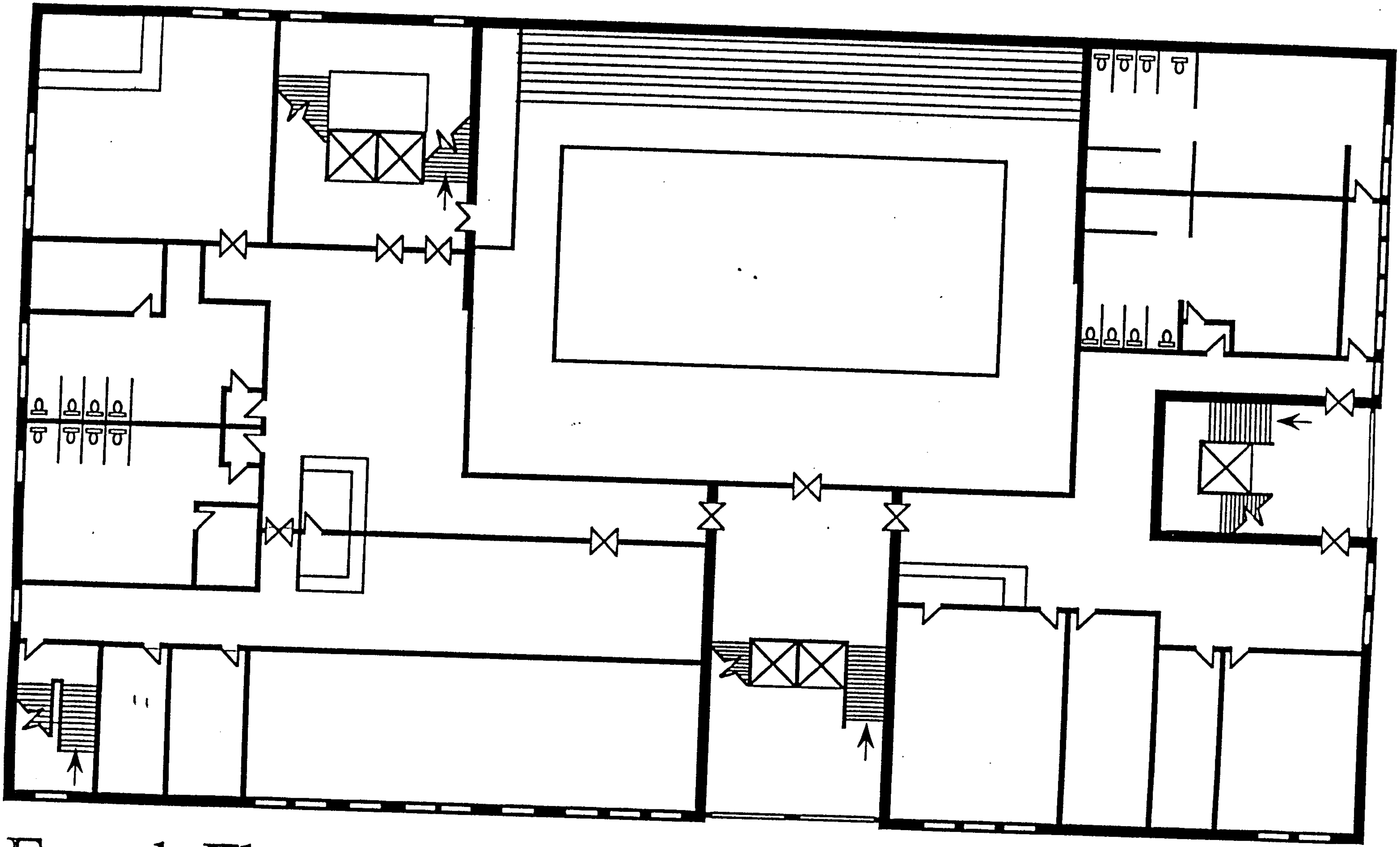
Second Floor

Figure A-8



Third Floor

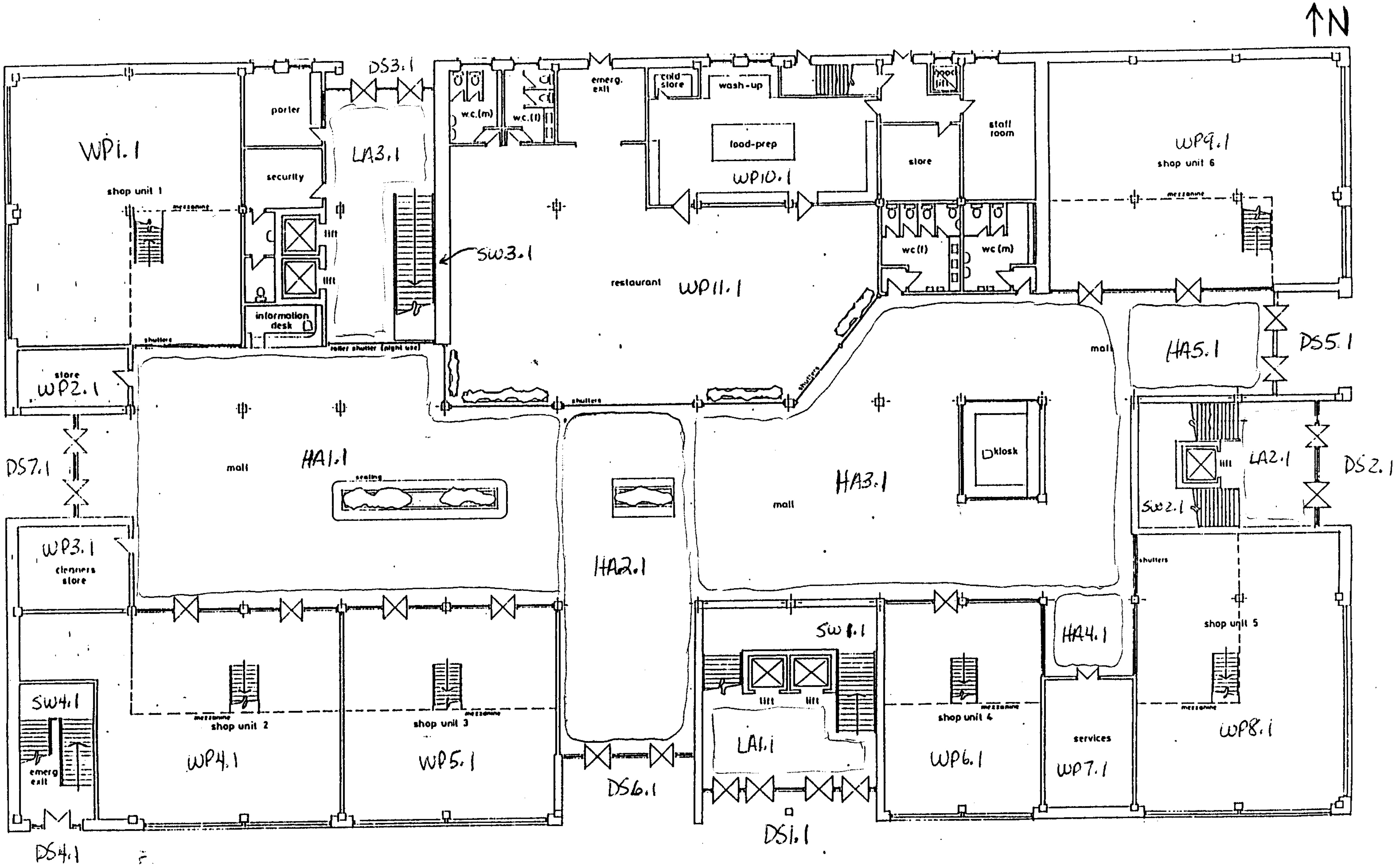
Figure A-9



Fourth Floor

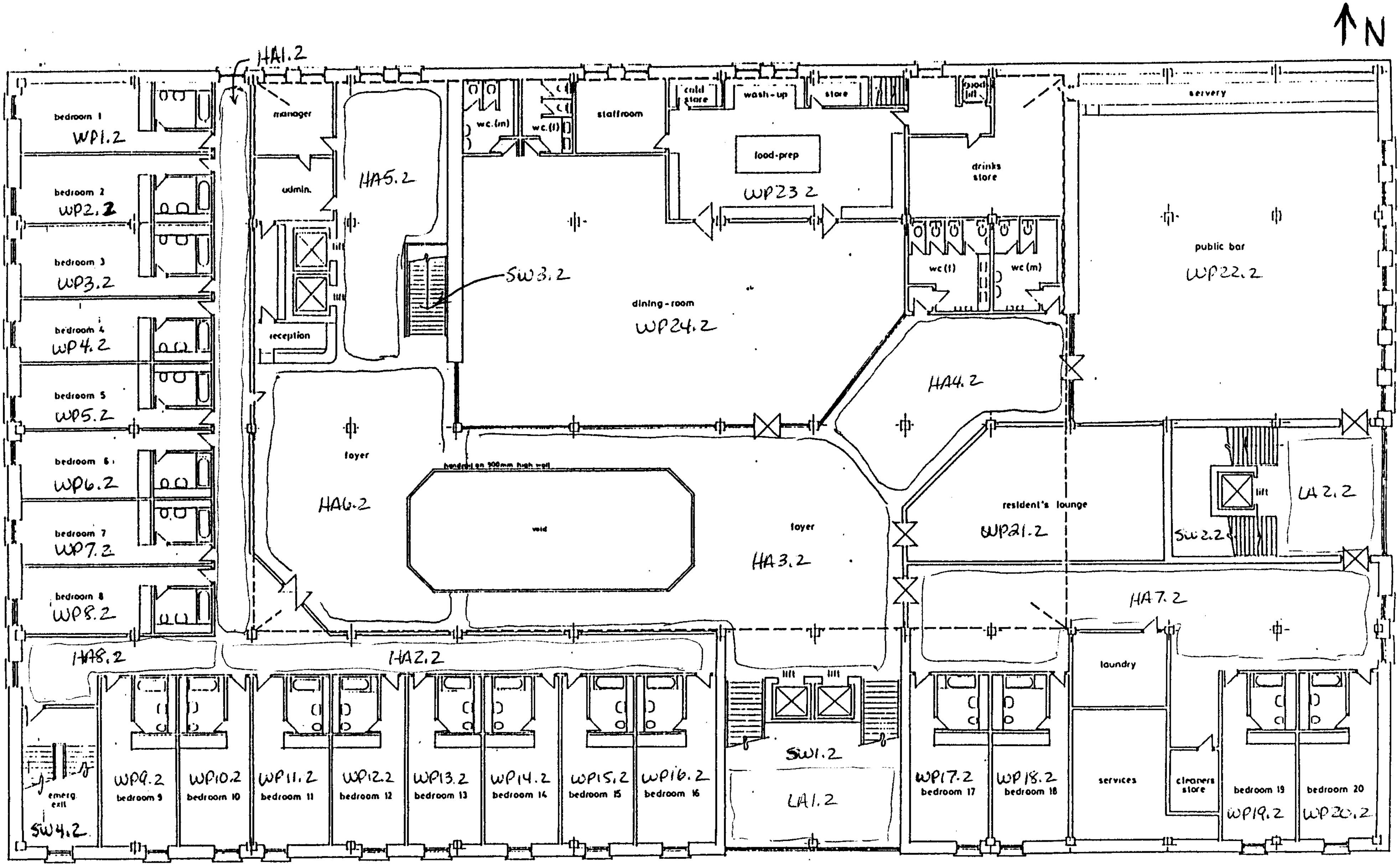
Figure A-10

APPENDIX B



GROUND FLOOR PLAN 1:100

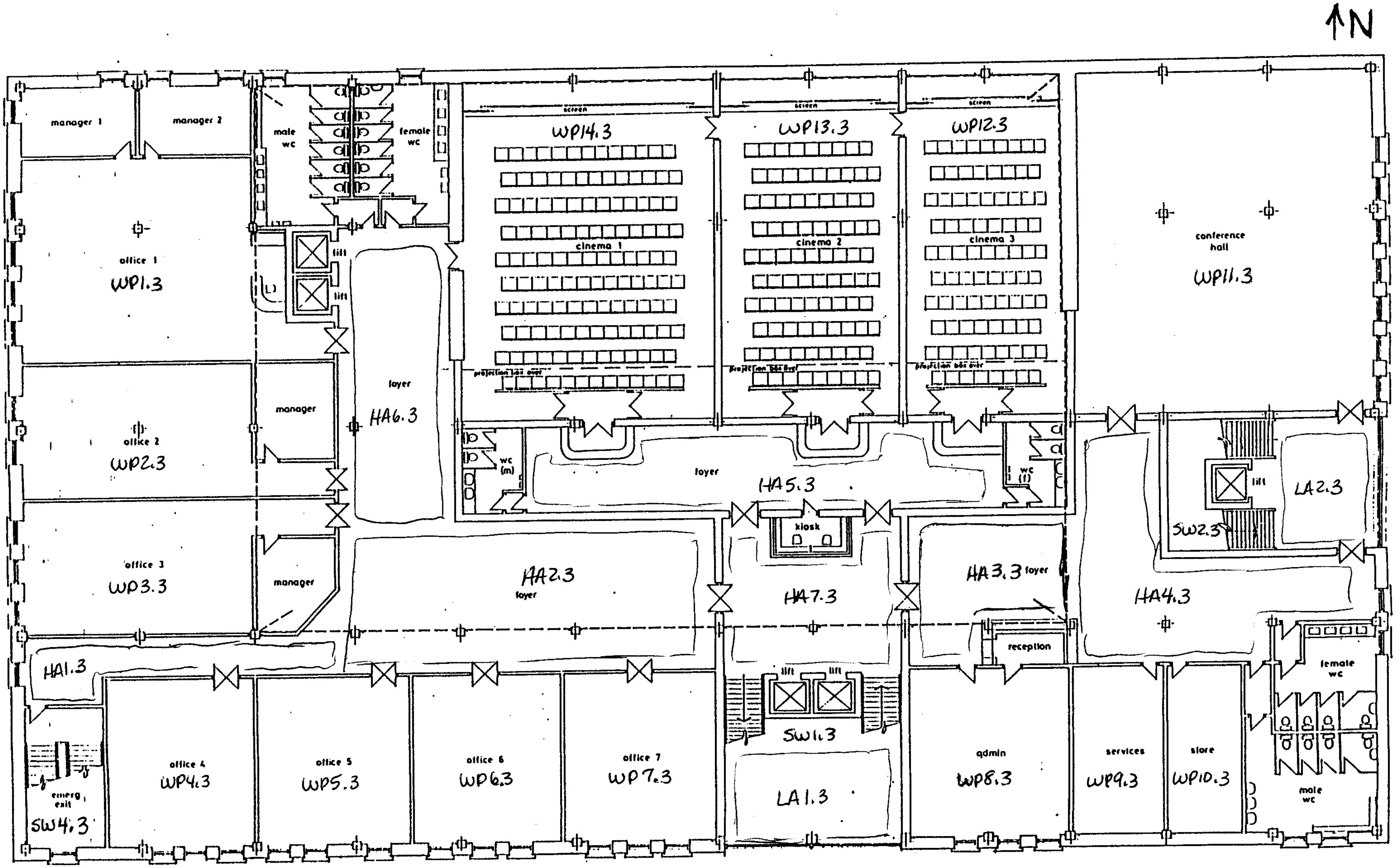
Figure B-1



FIRST FLOOR PLAN 1:100

⬚ indicates area of new reinforced concrete floor

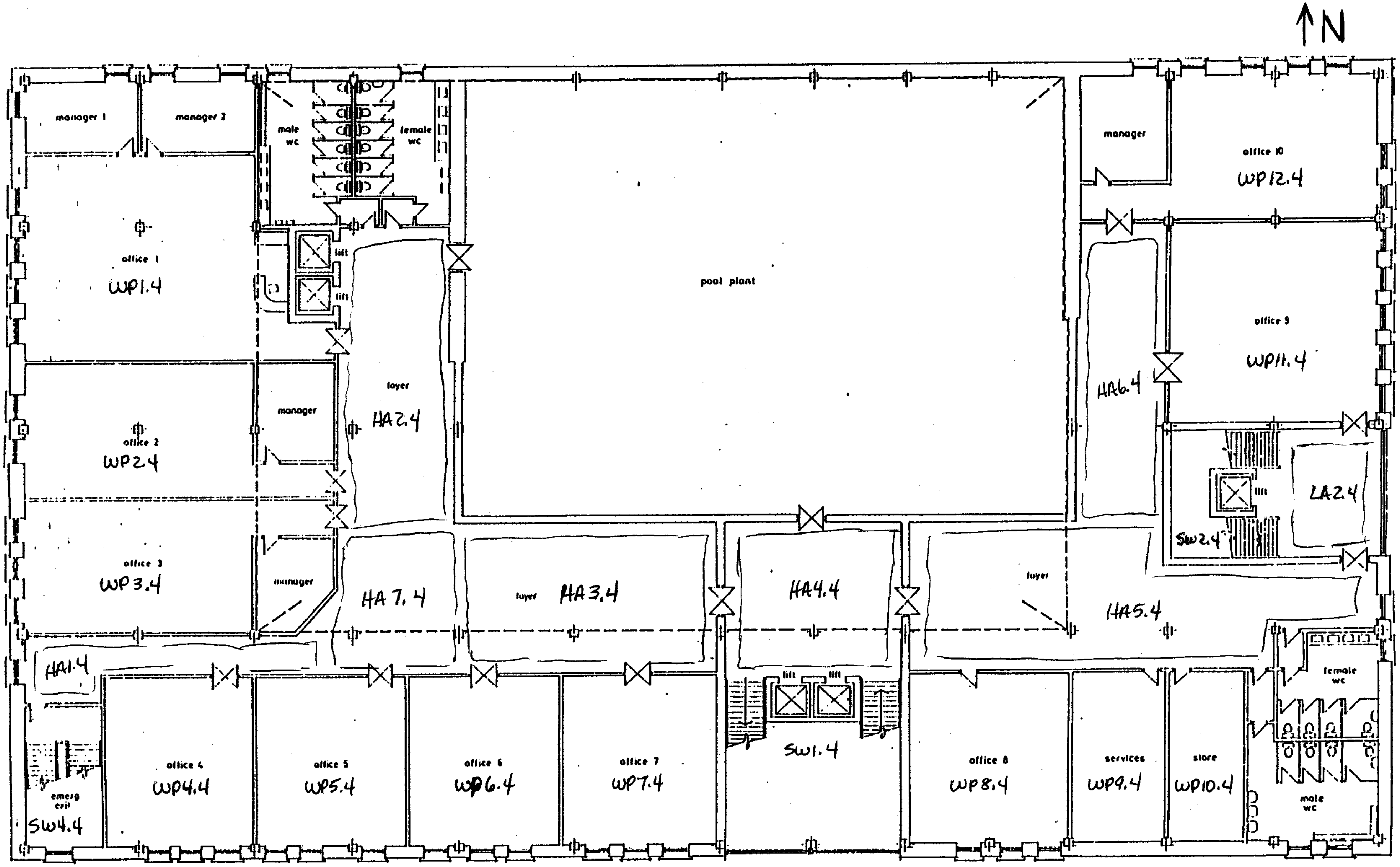
Figure B-2



SECOND FLOOR PLAN 1:100

⬚ indicates area of new reinforced concrete floor

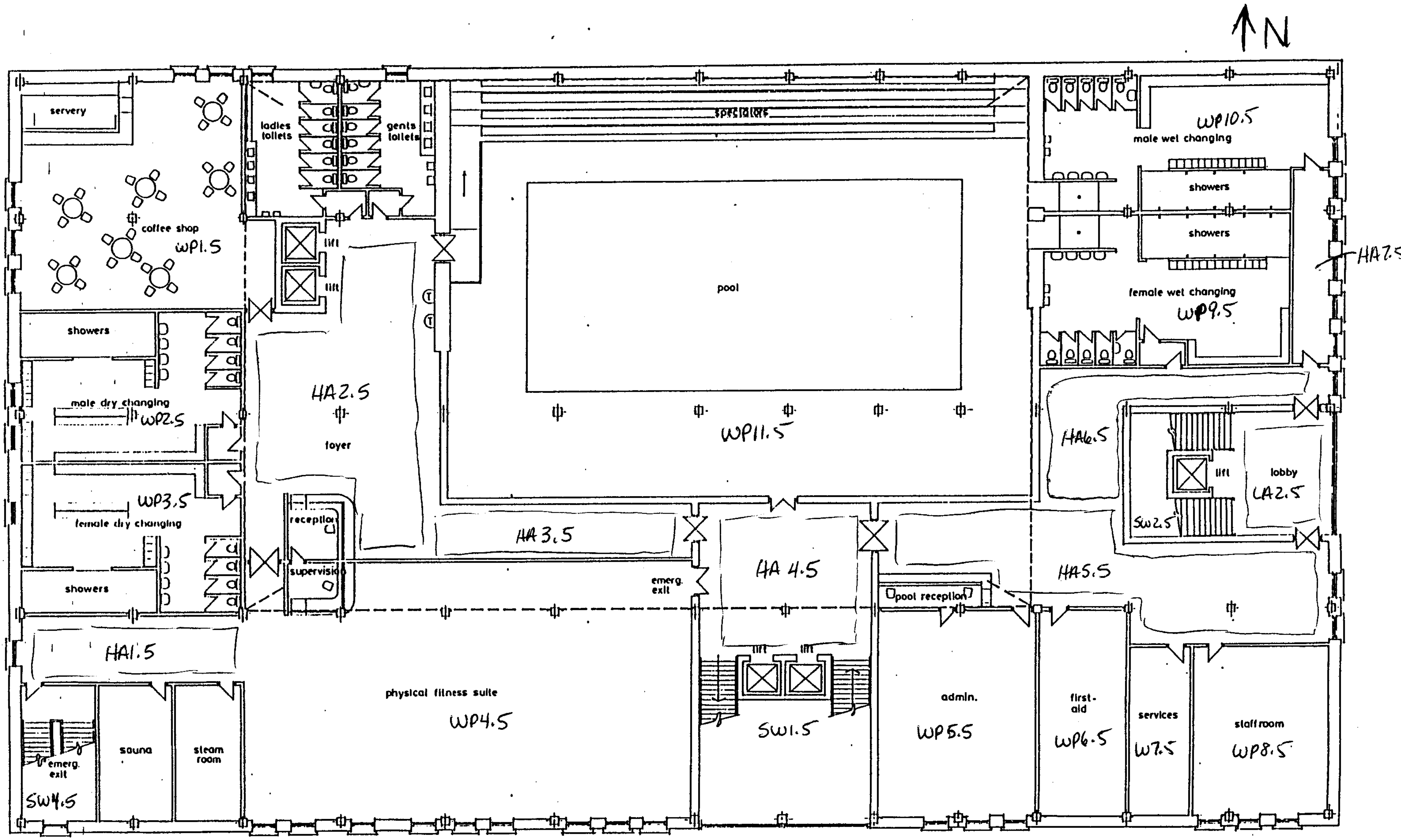
Figure B-3



THIRD FLOOR PLAN 1:100

▨ indicates area of new reinforced concrete floor

Figure B-4



FOURTH FLOOR PLAN 1:100

indicates area of new reinforced concrete floor

Figure B-5

Table B-1: Node Data

NODE	UA	APAD	NC	IC
WP1.1	1951	30	65	50
WP4.1	1711.4	30	57	50
WP5.1	1361.6	30	45	45
WP6.1	1006.4	30	34	34
WP8.1	1776	30	59	50
WP9.1	2002	30	67	50
WP10.1	710.4	15	47	47
WP11.1	5295.6	15	353	100
HA1.1	3116.2	15	208	45
HA2.1	1394	15	93	30
HA3.1	2588.7	15	173	30
HA4.1	193.8	15	13	8
HA5.1	444	15	30	5
LA1.1	538.2	12	45	0
LA2.1	280	12	23	0
LA3.1	699.7	12	58	0
SW1.1	344.4	10	34	2
SW2.1	269.1	10	27	2
SW3.1	172	10	17	2
SW4.1	204.5	10	20	0
DS1.1				
DS2.1				
DS3.1				
DS4.1				
DS5.1				

NODE	UA	APAD	NC	IC
DS6.1				
DS7.1				
WP21.2	882.6	15	59	50
WP22.2	2586	3	862	200
WP23.2	710.4	15	47	47
WP24.2	5295.6	15	353	50
HA1.2	602.8	15	40	10
HA2.2	538.2	15	36	10
HA3.2	1663	15	111	2
HA4.2	740	15	49	5
HA6.2	1073.7	15	72	2
HA7.2	1033.4	15	69	6
HA8.2	236.8	15	16	2
LA2.2	384.8	12	32	0
SW1.2	344.4	10	34	2
SW2.2	269.1	10	27	2
SW3.2	172	10	17	2
SW4.2	204.5	10	20	0
WP1.3	1555.4	100	16	16
WP11.3	3003.1	15	200	150
WP12.3	1377.8		85	85
WP13.3	1550		90	90
WP14.3	2238.9		130	130
HA1.3	355.2	15	24	7

NODE	UA	APAD	NC	IC
HA2.3	1636.1	15	109	40
HA3.3	567.8	15	38	24
HA4.3	1256.7	15	84	11
HA5.3	1134	15	76	5
HA6.3	968.8	15	65	1
HA7.3	688.9	15	46	1
LA2.3	349.8	12	29	0
SW1.3	344.4	10	34	2
SW2.3	269.1	10	27	2
SW4.3	204.5	10	20	0
WP1.4	1555.4	100	16	16
WP2.4	1065.6	100	11	11
WP3.4	1065.6	100	11	11
WP6.4	775	100	8	8
WP11.4	1243.2	100	12	12
HA1.4	355.2	15	24	8
HA2.4	968.8	15	65	13
HA3.4	1119.4	15	75	26
HA4.4	775	15	52	0
HA5.4	1371.5	15	91	10
HA6.4	750.8	15	50	11
HA7.4	516.7	15	34	2
LA2.4	349.8	12	29	0
SW1.4	344.4	10	34	2
SW2.4	269.1	10	27	2

NODE	UA	APAD	NC	IC
SW4.4	204.5	10	20	0
WP1.5	1646.8	15	110	30
WP4.5	3487.5	15	233	70
WP5.5	1066.4	100	11	11
WP11.5	4772.7		200	150
HA1.5	452.1	15	30	0
HA2.5	1711.5	15	114	22
HA3.5	435.9	15	29	2
HA4.5	775	15	52	2
HA5.5	1420.8	15	95	37
LA2.5	349.8	12	29	0
SW1.5	344.4	10	34	2
SW2.5	269.1	10	27	2
SW4.5	204.5	10	20	0
			Total	**1964**

Table B-2: Most Optimistic Time Arc Data

ARCS	SPTP	AFV	AS	DC	TT
WP1.1-HA1.1	10	18	200	59	1
WP4.1-HA1.1	10	18	120	26	2
WP5.1-HA1.1	10	17	120	24	2
WP6.1-HA3.1	10	17	120	7	2
WP8.1-HA3.1	10	18	200	71	1
WP9.1-HA5.1	10	18	120	26	2
WP10.1-WP11.1	10	15	120	7	1
WP11.1-HA2.1	10	18	170	69	2
WP11.1-HA3.1	10	18	170	69	2
HA1.1-DS7.1	10	17	120	24	4
HA1.1-HA2.1	10	20	250	109	1
HA2.1-DS6.1	10	17	120	24	3
HA3.1-HA2.1	10	20	250	109	1
HA3.1-HA5.1	10	20	250	60	1
HA4.1-HA3.1	10	20	250	49	0
HA5.1-DS5.1	10	17	120	24	1
LA1.1-DS1.1	10	15	120	59	1
LA2.1-DS2.1	10	15	120	21	1
LA3.1-DS3.1	10	15	120	21	1
SW1.1-LA1.1	10	13	100	14	3
SW2.1-LA2.1	10	13	100	14	2
SW3.1-LA3.1	10	13	100	14	2
SW4.1-DS4.1	10	13	100	14	2
WP21.2-HA3.2	10	18	120	13	2

ARCS	SPTP	AFV	AS	DC	TT
WP22.2-LA2.2	10	15	100	11	4
WP22.2-HA4.2	10	15	100	11	4
WP23.2-WP24.2	10	15	120	7	1
WP24.2-HA3.2	10	15	120	11	3
HA1.2-HA8.2	10	15	250	16	2
HA1.2-HA6.2	10	15	120	7	2
HA2.2-HA8.2	10	15	250	16	2
HA8.2-SW4.2	10	15	150	7	2
HA3.2-SW1.2	10	15	120	16	3
HA4.2-HA3.2	10	20	250	66	1
HA6.2-HA8.2	10	15	120	11	3
HA6.2-SW3.2	10	15	150	16	1
HA3.2-HA6.2	10	15	150	16	3
HA7.2-LA2.2	10	15	120	11	4
HA7.2-HA3.2	10	15	120	11	4
LA2.2-SW2.2	10	15	120	16	1
SW1.2-SW1.1	10	12	100	13	3
SW2.2-SW2.1	10	12	100	13	2
SW3.2-SW3.1	10	12	100	13	2
SW4.2-SW4.1	10	12	100	13	2
WP1.3-HA6.3	10	17	120	12	3
WP11.3-HA4.3	10	15	120	11	3
WP11.3-LA2.3	10	15	120	11	3
WP12.3-HA5.3	10	10	60	9	5
WP13.3-HA5.3	10	10	60	9	5

ARCS	SPTP	AFV	AS	DC	TT
WP14.3-HA5.3	10	10	60	9	5
HA1.3-SW4.3	10	15	120	7	3
HA2.3-HA1.3	10	15	250	16	1
HA2.3-HA7.3	10	15	120	11	3
HA3.3-HA7.3	10	15	120	11	1
HA4.3-LA2.3	10	15	120	11	2
HA5.3-HA7.3	10	15	120	21	2
HA6.3-HA2.3	10	18	250	59	1
HA7.3-SW1.3	10	15	100	16	2
LA2.3-SW2.3	10	15	120	16	1
SW1.3-SW1.2	10	12	100	13	3
SW2.3-SW2.2	10	12	100	13	2
SW4.3-SW4.2	10	12	100	13	2
WP1.4-HA2.4	10	17	120	12	3
WP2.4-HA2.4	10	17	120	12	3
WP3.4-HA2.4	10	17	120	12	3
WP6.4-HA3.4	10	17	120	12	1
WP11.4-LA2.4	10	17	120	12	2
WP11.4-HA6.4	10	17	120	12	2
HA1.4-SW4.4	10	15	120	7	3
HA2.4-HA7.4	10	20	250	66	1
HA7.4-HA1.4	10	15	250	16	0
HA7.4-HA3.4	10	20	250	87	0
HA3.4-HA4.4	10	15	120	11	2
HA3.4-HA7.4	10	20	250	66	1

ARCS	SPTP	AFV	AS	DC	TT
HA4.4-SW1.4	10	15	120	16	1
HA5.4-HA4.4	10	15	120	11	3
HA5.4-LA2.4	10	15	120	11	3
HA6.4-HA5.4	10	18	250	44	1
LA2.4-SW2.4	10	15	120	16	1
SW1.4-SW1.3	10	12	100	13	3
SW2.4-SW2.3	10	12	100	13	2
SW4.4-SW4.3	10	12	100	13	2
WP1.5-HA2.5	10	15	120	11	2
WP4.5-HA1.5	10	17	150	33	2
WP4.5-HA4.5	10	15	120	11	2
WP5.5-HA5.5	10	15	120	7	2
WP11.5-HA4.5	10	15	120	11	3
WP11.5-HA2.5	10	15	120	11	3
HA1.5-SW4.5	10	15	120	7	2
HA2.5-HA3.5	10	18	150	30	2
HA2.5-WP4.5	10	15	120	11	3
HA3.5-HA4.5	10	15	120	11	2
HA4.5-SW1.5	10	15	120	16	1
HA5.5-HA4.5	10	15	120	11	4
HA5.5-LA2.5	10	15	120	11	4
LA2.5-SW2.5	10	15	120	16	1
SW1.5-SW1.4	10	12	100	13	3
SW2.5-SW2.4	10	12	100	13	2
SW4.5-SW4.4	10	12	100	13	2

Table B-3: Most Reasonable Time Arc Data

ARCS	SPTP	AFV	AS	DC	TT
WP1.1-HA1.1	10	18	180	59	2
WP4.1-HA1.1	10	18	100	26	2
WP5.1-HA1.1	10	17	100	24	2
WP6.1-HA3.1	10	17	100	7	2
WP8.1-HA3.1	10	18	180	71	2
WP9.1-HA5.1	10	18	100	26	3
WP10.1-WP11.1	10	15	100	7	1
WP11.1-HA2.1	10	18	150	69	2
WP11.1-HA3.1	10	18	150	69	2
HA1.1-DS7.1	10	17	100	24	5
HA1.1-HA2.1	10	20	230	109	1
HA2.1-DS6.1	10	17	100	24	4
HA3.1-HA2.1	10	20	230	109	2
HA3.1-HA5.1	10	20	230	60	2
HA4.1-HA3.1	10	20	230	49	0
HA5.1-DS5.1	10	17	100	24	1
LA1.1-DS1.1	10	15	100	59	1
LA2.1-DS2.1	10	15	100	21	1
LA3.1-DS3.1	10	15	100	21	1
SW1.1-LA1.1	10	13	80	14	4
SW2.1-LA2.1	10	13	80	14	3
SW3.1-LA3.1	10	13	80	14	2
SW4.1-DS4.1	10	13	80	14	2
WP21.2-HA3.2	10	18	100	13	3

ARCS	SPTP	AFV	AS	DC	TT
WP22.2-LA2.2	10	15	80	11	4
WP22.2-HA4.2	10	15	80	11	4
WP23.2-WP24.2	10	15	100	7	1
WP24.2-HA3.2	10	15	100	11	4
HA1.2-HA8.2	10	15	230	16	2
HA1.2-HA6.2	10	15	100	7	3
HA2.2-HA8.2	10	15	230	16	2
HA8.2-SW4.2	10	15	130	7	2
HA3.2-SW1.2	10	15	100	16	4
HA4.2-HA3.2	10	20	230	66	1
HA6.2-HA8.2	10	15	100	11	4
HA6.2-SW3.2	10	15	130	16	2
HA3.2-HA6.2	10	15	130	16	3
HA7.2-LA2.2	10	15	100	11	5
HA7.2-HA3.2	10	15	100	11	5
LA2.2-SW2.2	10	15	100	16	1
SW1.2-SW1.1	10	12	80	13	4
SW2.2-SW2.1	10	12	80	13	3
SW3.2-SW3.1	10	12	80	13	2
SW4.2-SW4.1	10	12	80	13	2
WP1.3-HA6.3	10	17	100	12	3
WP11.3-HA4.3	10	15	100	11	3
WP11.3-LA2.3	10	15	100	11	3
WP12.3-HA5.3	10	10	50	9	6
WP13.3-HA5.3	10	10	50	9	6

ARCS	SPTP	AFV	AS	DC	TT
WP14.3-HA5.3	10	10	50	9	6
HA1.3-SW4.3	10	15	100	7	4
HA2.3-HA1.3	10	15	230	16	2
HA2.3-HA7.3	10	15	100	11	4
HA3.3-HA7.3	10	15	100	11	2
HA4.3-LA2.3	10	15	100	11	2
HA5.3-HA7.3	10	15	100	21	2
HA6.3-HA2.3	10	18	230	59	1
HA7.3-SW1.3	10	15	80	16	2
LA2.3-SW2.3	10	15	100	16	1
SW1.3-SW1.2	10	12	80	13	4
SW2.3-SW2.2	10	12	80	13	3
SW4.3-SW4.2	10	12	80	13	2
WP1.4-HA2.4	10	17	100	12	3
WP2.4-HA2.4	10	17	100	12	3
WP3.4-HA2.4	10	17	100	12	3
WP6.4-HA3.4	10	17	100	12	2
WP11.4-LA2.4	10	17	100	12	2
WP11.4-HA6.4	10	17	100	12	2
HA1.4-SW4.4	10	15	100	7	4
HA2.4-HA7.4	10	20	230	66	1
HA7.4-HA1.4	10	15	230	16	1
HA7.4-HA3.4	10	20	230	87	1
HA3.4-HA4.4	10	15	100	11	3
HA3.4-HA7.4	10	20	230	66	1

ARCS	SPTP	AFV	AS	DC	TT
HA4.4-SW1.4	10	15	100	16	2
HA5.4-HA4.4	10	15	100	11	4
HA5.4-LA2.4	10	15	100	11	4
HA6.4-HA5.4	10	18	230	44	1
LA2.4-SW2.4	10	15	100	16	1
SW1.4-SW1.3	10	12	80	13	4
SW2.4-SW2.3	10	12	80	13	3
SW4.4-SW4.3	10	12	80	13	2
WP1.5-HA2.5	10	15	100	11	2
WP4.5-HA1.5	10	17	130	33	2
WP4.5-HA4.5	10	15	100	11	3
WP5.5-HA5.5	10	15	100	7	2
WP11.5-HA4.5	10	15	100	11	4
WP11.5-HA2.5	10	15	100	11	4
HA1.5-SW4.5	10	15	100	7	2
HA2.5-HA3.5	10	18	130	30	3
HA2.5-WP4.5	10	15	100	11	4
HA3.5-HA4.5	10	15	100	11	3
HA4.5-SW1.5	10	15	100	16	2
HA5.5-HA4.5	10	15	100	11	5
HA5.5-LA2.5	10	15	100	11	5
LA2.5-SW2.5	10	15	100	16	1
SW1.5-SW1.4	10	12	80	13	4
SW2.5-SW2.4	10	12	80	13	3
SW4.5-SW4.4	10	12	80	13	2

Table B-4: Most Pessimistic Time Arc Data

ARCS	SPTP	AFV	AS	DC	TT
WP1.1-HA1.1	10	18	170	59	2
WP4.1-HA1.1	10	18	90	26	2
WP5.1-HA1.1	10	17	90	24	2
WP6.1-HA3.1	10	17	90	7	2
WP8.1-HA3.1	10	18	170	71	2
WP9.1-HA5.1	10	18	90	26	3
WP10.1-WP11.1	10	15	90	7	1
WP11.1-HA2.1	10	18	140	69	2
WP11.1-HA3.1	10	18	140	69	2
HA1.1-DS7.1	10	17	90	24	5
HA1.1-HA2.1	10	20	220	109	1
HA2.1-DS6.1	10	17	90	24	4
HA3.1-HA2.1	10	20	220	109	2
HA3.1-HA5.1	10	20	220	60	2
HA4.1-HA3.1	10	20	220	49	0
HA5.1-DS5.1	10	17	90	24	2
LA1.1-DS1.1	10	15	90	59	1
LA2.1-DS2.1	10	15	90	21	1
LA3.1-DS3.1	10	15	90	21	1
SW1.1-LA1.1	10	13	70	14	4
SW2.1-LA2.1	10	13	70	14	4
SW3.1-LA3.1	10	13	70	14	2
SW4.1-DS4.1	10	13	70	14	3
WP21.2-HA3.2	10	18	90	13	3

ARCS	SPTP	AFV	AS	DC	TT
WP22.2-LA2.2	10	15	70	11	5
WP22.2-HA4.2	10	15	70	11	5
WP23.2-WP24.2	10	15	90	7	1
WP24.2-HA3.2	10	15	90	11	4
HA1.2-HA8.2	10	15	220	16	3
HA1.2-HA6.2	10	15	90	7	3
HA2.2-HA8.2	10	15	220	16	2
HA8.2-SW4.2	10	15	120	7	2
HA3.2-SW1.2	10	15	90	16	4
HA4.2-HA3.2	10	20	220	66	1
HA6.2-HA8.2	10	15	90	11	4
HA6.2-SW3.2	10	15	120	16	2
HA3.2-HA6.2	10	15	120	16	3
HA7.2-LA2.2	10	15	90	11	5
HA7.2-HA3.2	10	15	90	11	5
LA2.2-SW2.2	10	15	90	16	1
SW1.2-SW1.1	10	12	70	13	4
SW2.2-SW2.1	10	12	70	13	4
SW3.2-SW3.1	10	12	70	13	2
SW4.2-SW4.1	10	12	70	13	3
WP1.3-HA6.3	10	17	90	12	4
WP11.3-HA4.3	10	15	90	11	3
WP11.3-LA2.3	10	15	90	11	3
WP12.3-HA5.3	10	10	40	9	8
WP13.3-HA5.3	10	10	40	9	8

ARCS	SPTP	AFV	AS	DC	TT
WP14.3-HA5.3	10	10	40	9	8
HA1.3-SW4.3	10	15	90	7	4
HA2.3-HA1.3	10	15	220	16	2
HA2.3-HA7.3	10	15	90	11	4
HA3.3-HA7.3	10	15	90	11	2
HA4.3-LA2.3	10	15	90	11	3
HA5.3-HA7.3	10	15	90	21	2
HA6.3-HA2.3	10	18	220	59	1
HA7.3-SW1.3	10	15	70	16	3
LA2.3-SW2.3	10	15	90	16	1
SW1.3-SW1.2	10	12	70	13	4
SW2.3-SW2.2	10	12	70	13	4
SW4.3-SW4.2	10	12	70	13	3
WP1.4-HA2.4	10	17	90	12	4
WP2.4-HA2.4	10	17	90	12	4
WP3.4-HA2.4	10	17	90	12	4
WP6.4-HA3.4	10	17	90	12	2
WP11.4-LA2.4	10	17	90	12	2
WP11.4-HA6.4	10	17	90	12	2
HA1.4-SW4.4	10	15	90	7	4
HA2.4-HA7.4	10	20	220	66	1
HA7.4-HA1.4	10	15	220	16	1
HA7.4-HA3.4	10	20	220	87	1
HA3.4-HA4.4	10	15	90	11	3
HA3.4-HA7.4	10	20	220	66	1

ARCS	SPTP	AFV	AS	DC	TT
HA4.4-SW1.4	10	15	90	16	2
HA5.4-HA4.4	10	15	90	11	4
HA5.4-LA2.4	10	15	90	11	4
HA6.4-HA5.4	10	18	220	44	1
LA2.4-SW2.4	10	15	90	16	1
SW1.4-SW1.3	10	12	70	13	4
SW2.4-SW2.3	10	12	70	13	4
SW4.4-SW4.3	10	12	70	13	3
WP1.5-HA2.5	10	15	90	11	3
WP4.5-HA1.5	10	17	120	33	2
WP4.5-HA4.5	10	15	90	11	3
WP5.5-HA5.5	10	15	90	7	2
WP11.5-HA4.5	10	15	90	11	4
WP11.5-HA2.5	10	15	90	11	4
HA1.5-SW4.5	10	15	90	7	3
HA2.5-HA3.5	10	18	120	30	3
HA2.5-WP4.5	10	15	90	11	4
HA3.5-HA4.5	10	15	90	11	3
HA4.5-SW1.5	10	15	90	16	2
HA5.5-HA4.5	10	15	90	11	5
HA5.5-LA2.5	10	15	90	11	5
LA2.5-SW2.5	10	15	90	16	1
SW1.5-SW1.4	10	12	70	13	4
SW2.5-SW2.4	10	12	70	13	4
SW4.5-SW4.4	10	12	70	13	3

```
EVACNET+ SUMMARY OF RESULTS FOR MODEL ID 'THS-01-OPTIMUM     (5/16/94)  '

    46  TIME PERIODS TO EVACUATE BUILDING (  460 SECONDS)

    19  TIME PERIODS FOR UNCONGESTED BUILDING EVACUATION ( 190 SECONDS)

   2.4  CONGESTION FACTOR (RATIO OF BUILDING EVACUATION TIME TO
        UNCONGESTED BUILDING EVACUATION TIME)

  19.1  AVERAGE # OF PERIODS FOR AN EVACUEE TO EVACUATE ( 191 SECONDS)

  42.7  AVERAGE NUMBER OF EVACUEES PER TIME PERIOD

  1964  NUMBER OF SUCCESSFUL EVACUEES

    60  MAXIMUM # OF TIME PERIODS ALLOWED FOR EVACUATION ( 600 SECONDS)

    14  UNNECESSARY TIME PERIODS ( 140 SECONDS)
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A

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                         NODE CONTENTS PROFILE:
PEOPLE WAITING AT END OF TIME PERIOD, BY TIME PERIOD FOR NODE SW01.003
                      FOR MODEL ID 'THS-01-OPTIMUM      (5/16/94)  '

               (CAPACITY=   34,   INITIAL CONTENTS=    2)

 TIME     NODE          EACH * REPRESENTS   5 PERSON(S)
PERIOD  CONTENTS   ----|----|----|----|----|----|----|----|----|----|
   5         3     *
  10         3     *
  11         6     **
  12         9     **
  13        12     ***
  14        15     ***
  15        18     ****
  16        21     *****
  17        24     *****
  18        27     ******
  19        30     ******
  20        31     *******
  21        34     *******
  22        34     *******
  23        34     *******
  24        31     *******
  25        34     *******
  26        34     *******
  27        34     *******
  28        31     *******
  29        34     *******
  30        32     *******
  31        22     *****
  32        22     *****
  33         9     **
  34         9     **

NOTE:  CONTENTS ARE ZERO FOR UNLISTED TIME PERIODS
                         NODE CONTENTS PROFILE:
PEOPLE WAITING AT END OF TIME PERIOD, BY TIME PERIOD FOR NODE HA07.003
                      FOR MODEL ID 'THS-01-OPTIMUM      (5/16/94)  '

               (CAPACITY=   46,   INITIAL CONTENTS=    1)

 TIME     NODE          EACH * REPRESENTS   5 PERSON(S)
PERIOD  CONTENTS   ----|----|----|----|----|----|----|----|----|----|
   4         3     *
   5         3     *
   8         5     *
   9        10     **
  10        15     ***
  11        20     ****
  12        25     *****
  13        30     ******
  14        35     *******
  15        40     ********
  16        45     *********
  17        46     **********
  18        46     **********

  19        31     *******
  20        39     ********
  21        26     ******
  22        37     ********
  23        21     *****
  24        29     ******
  25        16     ****
  26        27     ******
  27        11     ***

NOTE:  CONTENTS ARE ZERO FOR UNLISTED TIME PERIODS
```

```
EVACNET+ SUMMARY OF RESULTS FOR MODEL ID 'THS-02-REASONABLE  (5/19/94)  '

    48  TIME PERIODS TO EVACUATE BUILDING (  480 SECONDS)

    26  TIME PERIODS FOR UNCONGESTED BUILDING EVACUATION ( 260 SECONDS)

   1.8  CONGESTION FACTOR (RATIO OF BUILDING EVACUATION TIME TO
        UNCONGESTED BUILDING EVACUATION TIME)

  21.1  AVERAGE # OF PERIODS FOR AN EVACUEE TO EVACUATE ( 211 SECONDS)

  40.9  AVERAGE NUMBER OF EVACUEES PER TIME PERIOD

  1964  NUMBER OF SUCCESSFUL EVACUEES

    60  MAXIMUM # OF TIME PERIODS ALLOWED FOR EVACUATION ( 600 SECONDS)

    12  UNNECESSARY TIME PERIODS ( 120 SECONDS)
```

```
                              NODE CONTENTS PROFILE:
 PEOPLE WAITING AT END OF TIME PERIOD, BY TIME PERIOD FOR NODE SW01.003
                            FOR MODEL ID 'THS-02-REASONABLE   (5/19/94)  '

                     (CAPACITY=   34,    INITIAL CONTENTS=     2)

  TIME      NODE           EACH * REPRESENTS    5 PERSON(S)
 PERIOD   CONTENTS   ----|----|----|----|----|----|----|----|----|----|
   11         3      *
   12         6      **
   13         9      **
   14        12      ***
   15        15      ***
   16        18      ****
   17        21      *****
   18        16      ****
   19        19      ****
   20        22      *****
   21        25      *****
   22        28      ******
   23        31      *******
   24        28      ******
   25        31      *******
   26        34      *******
   27        31      *******
   28        34      *******
   29        34      *******
   30        34      *******
   31        34      *******
   32        34      *******
   33        23      *****
   34        10      **
   35        13      ***

NOTE:   CONTENTS ARE ZERO FOR UNLISTED TIME PERIODS

                              NODE CONTENTS PROFILE:
PEOPLE WAITING AT END OF TIME PERIOD, BY TIME PERIOD FOR NODE HA07.003
                           FOR MODEL ID 'THS-02-REASONABLE   (5/19/94)  '

                     (CAPACITY=   46,    INITIAL CONTENTS=     1)

  TIME      NODE           EACH * REPRESENTS    5 PERSON(S)
 PERIOD   CONTENTS   ----|----|----|----|----|----|----|----|----|----|
    4        11      ***
    5        18      ****
    6        13      ***
    7         2      *
    9         5      *
   10        10      **
   11        15      ***
   12        20      ****
   13        25      *****
   14        30      ******
   15        35      *******
   16        46      **********
   17        46      **********
   18        46      **********
   19        46      **********
   20        30      ******
   21        35      *******
   22        46      **********
   23        46      **********
   24        46      **********
   25        46      **********
   26        42      *********
   27        29      ******
   28        29      ******
   29        29      ******
   30        16      ****
   31        16      ****
   32        16      ****

NOTE:   CONTENTS ARE ZERO FOR UNLISTED TIME PERIODS
```

```
EVACNET+ SUMMARY OF RESULTS FOR MODEL ID 'THS-03-PESSIMISTIC  (7/21/94  '

    57  TIME PERIODS TO EVACUATE BUILDING (  570 SECONDS)

    33  TIME PERIODS FOR UNCONGESTED BUILDING EVACUATION ( 330 SECONDS)

   1.7  CONGESTION FACTOR (RATIO OF BUILDING EVACUATION TIME TO
        UNCONGESTED BUILDING EVACUATION TIME)

  27.3  AVERAGE # OF PERIODS FOR AN EVACUEE TO EVACUATE ( 273 SECONDS)

  34.5  AVERAGE NUMBER OF EVACUEES PER TIME PERIOD

  1964  NUMBER OF SUCCESSFUL EVACUEES

    60  MAXIMUM # OF TIME PERIODS ALLOWED FOR EVACUATION ( 600 SECONDS)

     3  UNNECESSARY TIME PERIODS (   30 SECONDS)
```

```
                             NODE CONTENTS PROFILE:
PEOPLE WAITING AT END OF TIME PERIOD, BY TIME PERIOD FOR NODE SW01.003
                            FOR MODEL ID 'THS-03-PESSIMISTIC  (7/21/94  '

                  (CAPACITY=   34,   INITIAL CONTENTS=    2)

 TIME     NODE          EACH * REPRESENTS   5 PERSON(S)
PERIOD  CONTENTS  ----|----|----|----|----|----|----|----|----|----|
   7        3     *
  10       10     **
  15        3     *
  16        6     **
  17        9     **
  18       12     ***
  19       15     ***
  20       18     ****
  21       31     *******
  22       34     *******
  23       34     *******
  24       34     *******
  25       31     *******
  26       34     *******
  27       34     *******
  28       34     *******
  29       34     *******
  30       34     *******
  31       34     *******
  32       34     *******
  33       34     *******
  34       34     *******
  35       34     *******
  36       34     *******
  37       26     ******
  38       26     ******
  39       13     ***

NOTE:  CONTENTS ARE ZERO FOR UNLISTED TIME PERIODS
                             NODE CONTENTS PROFILE:
PEOPLE WAITING AT END OF TIME PERIOD, BY TIME PERIOD FOR NODE HA07.003
                            FOR MODEL ID 'THS-03-PESSIMISTIC  (7/21/94  '

                  (CAPACITY=   46,   INITIAL CONTENTS=    1)

 TIME     NODE          EACH * REPRESENTS   5 PERSON(S)
PERIOD  CONTENTS  ----|----|----|----|----|----|----|----|----|----|
   8        2     *
  12        5     *
  13       10     **
  14       15     ***
  15       20     ****
  16       25     *****
  17       30     ******
  18       37     ********
  19       35     *******
  20       22     *****
  21       30     ******
  22       41     *********
  23       46     **********
  24       38     ********
  25       46     **********
  26       46     **********
  27       33     *******
  28       41     *********
  29       28     ******
  30       23     *****
  31       10     **
  32       18     ****
  33        5     *

NOTE:  CONTENTS ARE ZERO FOR UNLISTED TIME PERIODS
```

APPENDIX C

INPUT FILE 1: High C/CO_2 ratio, Foyer Door Closed, Stairwell Door Closed

```
VERSN    2DESIGN FIRE;HIGH C/CO2
TIMES  1000   50   20   50   0
TAMB   300.  101300.    0.
EAMB   288.  101300.    0.
HI/F    0.00  0.00  0.00
WIDTH    7.80 25.91  9.14
DEPTH    8.69 12.34  18.29
HEIGH    3.05   3.05   9.14
HVENT   1  2  1   0.914   0.030   0.000
HVENT   2  3  1   0.914   0.030   0.000
HVENT   3  4  1   0.914   0.030   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CEILI CONCRETE  CONCRETE  CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI    16.    0.   6.0    18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS    1.17   1.17   0.00
FTIME     90.   120.   300.   330.   390.   420.   450.   510.   540.   670.  1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
0.00
FAREA    0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46
0.46
FQDOT  0.00      1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO     0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD     0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800
STPMAX  5.00
DUMPR TH_H1_CC.HI
DEVICE 1
WINDOW  0    0. -100. 1280. 1024. 1100.
GRAPH   1  100.   50.    0.  600.  475.   10.  3 TI HEIG
GRAPH   2  100.  550.    0.  600.  940.   10.  3 TI CELSI
GRAPH   3  720.   50.    0. 1250.  475.   10.  3 TI FIRE_SIZE(k
```

```
GRAPH   4  720.  550.    0. 1250.  940.    10.  3 TI O|D2|O(
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 2: High C/CO_2 ratio, Foyer Door Closed, Stairwell Door Open

```
VERSN    2DESIGN FIRE;HIGH C/CO2
TIMES  1000   50   20   50    0
TAMB  300.  101300.     0.
EAMB  288.  101300.     0.
HI/F    0.00  0.00  0.00
WIDTH    7.80  25.91   9.14
DEPTH    8.69  12.34  18.29
HEIGH    3.05   3.05   9.14
HVENT   1  2  1   0.914   0.030   0.000
HVENT   2  3  1   0.914   2.134   0.000
HVENT   3  4  1   0.914   0.030   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CEILI CONCRETE   CONCRETE   CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI    16.    0.   6.0    18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS    1.17   1.17   0.00
FTIME     90.   120.   300.   330.   390.   420.   450.   510.   540.   670.  1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
0.00
FAREA    0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46
0.46
FQDOT  0.00     1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800
STPMAX  5.00
DUMPR TH_H1_CO.HI
DEVICE 1
WINDOW  0    0. -100.  1280.  1024.  1100.
GRAPH   1  100.   50.    0.  600.  475.   10.  3 TI HEIG
GRAPH   2  100.  550.    0.  600.  940.   10.  3 TI CELSI
GRAPH   3  720.   50.    0. 1250.  475.   10.  3 TI FIRE_SIZE(k
```

```
GRAPH   4  720.  550.    0. 1250.  940.   10.  3 TI O|D2|O(
HEAT   0 0 0 0 3  1 U
HEAT   0 0 0 0 3  2 U
HEAT   0 0 0 0 3  3 U
HEAT   0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 3: High C/CO_2 ratio, Foyer Door Open, Stairwell Door Closed

```
VERSN   2DESIGN FIRE;HIGH C/CO2
TIMES  1000   50   20   50   0
TAMB  300.  101300.     0.
EAMB  288.  101300.     0.
HI/F   0.00  0.00  0.00
WIDTH   7.80  25.91  9.14
DEPTH   8.69  12.34  18.29
HEIGH   3.05   3.05   9.14
HVENT  1  2  1   0.914   2.134   0.000
HVENT  2  3  1   0.914   0.030   0.000
HVENT  3  4  1   0.914   0.030   0.000   0.000
CVENT  1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00  1.00
CVENT  2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00  1.00
CVENT  3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00  1.00
CEILI CONCRETE  CONCRETE  CONCRETE
WALLS GYPSUM   GYPSUM   GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI   16.   0.   6.0   18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS   1.17   1.17   0.00
FTIME    90.   120.   300.   330.   390.   420.   450.   510.   540.   670.  1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
0.00
FAREA    0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46
0.46
FQDOT  0.00     1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800
STPMAX  5.00
DUMPR TH_H1_OC.HI
DEVICE 1
WINDOW  0    0. -100. 1280. 1024. 1100.
GRAPH   1  100.   50.    0.  600.  475.   10.  3 TIME HEIGHT
GRAPH   2  100.  550.    0.  600.  940.   10.  3 TIME CELSIUS
GRAPH   3  720.   50.    0. 1250.  475.   10.  3 TIME FIRE_SIZE(kW)
```

```
GRAPH   4  720.  550.    0. 1250.  940.   10.  3 TIME O|D2|O(%)
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 4: High C/CO$_2$ ratio, Foyer Door Open, Stairwell Door Open

```
VERSN    2DESIGN FIRE;HIGH C/CO2
TIMES  1000   50   20   50    0
TAMB  300.  101300.     0.
EAMB  288.  101300.     0.
HI/F   0.00  0.00  0.00
WIDTH    7.80  25.91   9.14
DEPTH    8.69  12.34  18.29
HEIGH    3.05   3.05   9.14
HVENT   1  2  1   0.914   2.134   0.000
HVENT   2  3  1   0.914   2.134   0.000
HVENT   3  4  1   0.914   0.030   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CEILI CONCRETE  CONCRETE  CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI    16.    0.   6.0    18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS    1.17   1.17   0.00
FTIME     90.   120.   300.   330.   390.   420.   450.   510.   540.   670.  1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
0.00
FAREA    0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46
0.46
FQDOT  0.00      1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800 0.800
STPMAX  5.00
DUMPR TH_H1_OO.HI
DEVICE 1
WINDOW  0    0. -100.  1280.  1024.  1100.
GRAPH   1  100.   50.    0.  600.  475.   10.  3 TIME HEIGHT
GRAPH   2  100.  550.    0.  600.  940.   10.  3 TIME CELSIUS
GRAPH   3  720.   50.    0. 1250.  475.   10.  3 TIME FIRE_SIZE(kW)
```

```
GRAPH   4  720.  550.    0. 1250.  940.   10.  3 TIME O|D2|O(%)
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 5: Low C/CO$_2$ ratio, Foyer Door Closed, Stairwell Door Closed

```
VERSN    2DESIGN FIRE;LOW C/CO2
TIMES  1000    50    20    50     0
TAMB   300.  101300.      0.
EAMB   288.  101300.      0.
HI/F    0.00   0.00   0.00
WIDTH    7.80  25.91   9.14
DEPTH    8.69  12.34  18.29
HEIGH    3.05   3.05   9.14
HVENT   1  2  1   0.914   0.030   0.000
HVENT   2  3  1   0.914   0.030   0.000
HVENT   3  4  1   0.914   0.030   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CEILI CONCRETE   CONCRETE   CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI    16.    0.   6.0    18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS    1.17    1.17    0.00
FTIME     90.    120.    300.    330.    390.    420.    450.    510.    540.    670.   1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
0.00
FAREA    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46
0.46
FQDOT  0.00      1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR TH_L1_CC.HI
DEVICE 1
WINDOW  0    0. -100.  1280.  1024.  1100.
GRAPH   1  100.    50.     0.   600.   475.    10.   3 TIME HEIGHT
GRAPH   2  100.   550.     0.   600.   940.    10.   3 TIME CELSIUS
GRAPH   3  720.    50.     0.  1250.   475.    10.   3 TIME FIRE_SIZE(kW)
```

```
GRAPH   4  720.  550.    0. 1250.  940.   10.  3 TIME O|D2|O(%)
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 6: Low C/CO_2 ratio, Foyer Door Closed, Stairwell Door Open

```
VERSN    2DESIGN FIRE;LOW C/CO2
TIMES   1000    50    20    50     0
TAMB   300.  101300.      0.
EAMB   288.  101300.      0.
HI/F    0.00   0.00   0.00
WIDTH    7.80  25.91   9.14
DEPTH    8.69  12.34  18.29
HEIGH    3.05   3.05   9.14
HVENT   1  2  1   0.914   0.030   0.000
HVENT   2  3  1   0.914   2.134   0.000
HVENT   3  4  1   0.914   0.030   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CEILI CONCRETE   CONCRETE   CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI    16.    0.   6.0    18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS    1.17    1.17    0.00
FTIME     90.    120.    300.    330.    390.    420.    450.    510.    540.    670.   1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
0.00
FAREA    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46
0.46
FQDOT  0.00      1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR TH_L1_CO.HI
DEVICE 1
WINDOW  0    0. -100. 1280. 1024. 1100.
GRAPH   1  100.   50.    0.  600.  475.    10.  3 TIME HEIGHT
GRAPH   2  100.  550.    0.  600.  940.    10.  3 TIME CELSIUS
GRAPH   3  720.   50.    0. 1250.  475.    10.  3 TIME FIRE_SIZE(kW)
```

```
GRAPH   4  720.  550.    0. 1250.  940.   10.  3 TIME O|D2|O(%)
HEAT   0 0 0 0 3  1 U
HEAT   0 0 0 0 3  2 U
HEAT   0 0 0 0 3  3 U
HEAT   0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 7: Low C/CO_2 ratio, Foyer Door Open, Stairwell Door Closed

```
VERSN    2DESIGN FIRE;LOW C/CO2
TIMES   1000    50    20    50    0
TAMB   300.  101300.     0.
EAMB   288.  101300.     0.
HI/F    0.00   0.00   0.00
WIDTH    7.80  25.91   9.14
DEPTH    8.69  12.34  18.29
HEIGH    3.05   3.05   9.14
HVENT   1  2  1   0.914   2.134   0.000
HVENT   2  3  1   0.914   0.030   0.000
HVENT   3  4  1   0.914   0.030   0.000   0.000
CVENT   1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   2  3  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   3  4  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CEILI CONCRETE   CONCRETE   CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI    16.    0.   6.0    18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS    1.17    1.17    0.00
FTIME     90.   120.   300.   330.   390.   420.   450.   510.   540.   670.  1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
0.00
FAREA    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46    0.46
0.46
FQDOT  0.00      1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR TH_L1_OC.HI
DEVICE 1
WINDOW  0    0. -100. 1280. 1024. 1100.
GRAPH   1  100.   50.    0.  600.  475.   10.  3 TIME HEIGHT
GRAPH   2  100.  550.    0.  600.  940.   10.  3 TIME CELSIUS
GRAPH   3  720.   50.    0. 1250.  475.   10.  3 TIME FIRE_SIZE(kW)
```

```
GRAPH   4  720.  550.    0. 1250.  940.    10.  3 TIME O|D2|O(%)
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```

INPUT FILE 8: Low C/CO_2 ratio, Foyer Door Open, Stairwell Door Open

```
VERSN   2DESIGN FIRE;LOW C/CO2
TIMES  1000   50   20   50   0
TAMB  300.  101300.    0.
EAMB  288.  101300.    0.
HI/F   0.00  0.00  0.00
WIDTH   7.80 25.91  9.14
DEPTH   8.69 12.34 18.29
HEIGH   3.05  3.05  9.14
HVENT  1  2  1  0.914  2.134  0.000
HVENT  2  3  1  0.914  2.134  0.000
HVENT  3  4  1  0.914  0.030  0.000  0.000
CVENT  1  2  1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00
CVENT  2  3  1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00
CVENT  3  4  1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00
CEILI CONCRETE  CONCRETE  CONCRETE
WALLS GYPSUM    GYPSUM    GYPSUM
FLOOR CONCRETE  CONCRETE  CONCRETE
CHEMI   16.   0.   6.0   18000000.  300. 388.   0.
LFBO   1
LFBT   2
FPOS   1.17   1.17   0.00
FTIME    90.   120.   300.   330.   390.   420.   450.   510.   540.   670.  1000.
FMASS  0.0000 0.0006 0.0111 0.0083 0.0167 0.0389 0.0556 0.1389 0.2222 0.2223
0.2222 0.2222
FHIGH   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
0.00
FAREA   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46   0.46
0.46
FQDOT  0.00     1.00E+04 2.00E+05 1.50E+05 3.00E+05 7.00E+05 1.00E+06
2.50E+06 4.00E+06 4.00E+06 4.00E+06 4.00E+06
CJET OFF
HCR   0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333 0.333
CO    0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
OD    0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200 0.200
STPMAX  5.00
DUMPR TH_L1_OO.HI
DEVICE 1
WINDOW  0    0. -100. 1280. 1024. 1100.
GRAPH   1  100.   50.    0.  600.  475.   10.  3 TIME HEIGHT
GRAPH   2  100.  550.    0.  600.  940.   10.  3 TIME CELSIUS
GRAPH   3  720.   50.    0. 1250.  475.   10.  3 TIME FIRE_SIZE(kW)
```

```
GRAPH   4  720.  550.    0. 1250.  940.    10.  3 TIME O|D2|O(%)
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
INTER 0 0 0 0 1  4 U
O2    0 0 0 0 4  1 U
O2    0 0 0 0 4  2 U
O2    0 0 0 0 4  3 U
O2    0 0 0 0 4  4 U
```