EXIT89: An Evacuation Model for High-Rise Buildings

RITA F. FAHY
Fire Analysis and Research Division
National Fire Protection Association
1 Batterymarch Park, Quincy, Massachusetts 02269-9101, USA

ABSTRACT

EXIT89 is an evacuation model designed to handle the evacuation of a large population of individuals from a high-rise building. It has the ability to track the location of individuals as they move through the building so that the output from this model can be used as input to a toxicity model that will accumulate occupant exposures to combustion products. EXIT89 uses occupant densities in building spaces to compute each occupant's walking speed. In this way, queueing effects can be modeled.

One possible future use for EXIT89 is as the evacuation module of Hazard I, allowing that software package to extend its use to larger, more complex buildings. The model described in this paper was designed to use the smoke movement data generated by one component of Hazard I and to provide the occupant location data required by the tenability model incorporated in Hazard I.

The program has been tested using data from a fire drill in a high-rise office building with 700 occupants. It is written in FORTRAN.

KEYWORDS: evacuation model

BACKGROUND

EXIT89 was developed to meet the need for an evacuation model that could track large populations of individuals in high-rise buildings. Existing evacuation models are either behavioral or network flow models. The first type can be used to track individuals in small buildings such as dwellings, but they do not address queueing. The second type can handle large buildings but use queueing methods that cannot treat occupants individually.

This paper describes an evacuation model for high-rise buildings that can track the movement of individuals from time of awareness of a fire until escape from the building, or entrapment. It was originally written in BASIC in order to run on a personal computer but its size has forced its translation into FORTRAN.

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INTRODUCTION

EXIT89 was originally developed for use as part of a software package called Hazard I. Hazard I, which was developed by the National Institute of Standards and Technology Center for Fire Research (NIST/CFR), includes programs that model fire growth and smoke spread in a building, the evacuation of occupants, and the impact of combustion products on the occupants as they move through the building. This package's applicability is limited to one- and two-family dwellings at least in part because of the limitations of the evacuation model currently used [1].

The need for a model that can handle the evacuation of a high-rise became obvious during some other project work being done at NFPA. Some of the capabilities of Hazard I's evacuation model, especially its ability to track individuals along their routes out of the building, needed to be available in the high-rise model.

Hazard I can be used as a tool to evaluate the fire hazard of a dwelling. The components of Hazard I that relate to building evacuation are FAST, EXITT and TENAB. FAST, which stands for Fire and Smoke Transport, models the conditions throughout a dwelling during a user-specified fire. Inputs to the model include the geometry of the rooms, the size and location of connections between rooms, the burning properties of the walls, floors and ceilings, the burning rate of the fire and generation rates for combustion products. The output from the model includes the changes in temperature and levels of combustion products throughout the building during the fire.

EXITT, which was written by Bernard M. Levin, formerly of NIST/CFR, is the evacuation model used in Hazard I. It requires for input a network description of the building, the geometry of the rooms, and descriptions of the occupants (age, sex, awake/asleep, dependent on assistance, etc.). EXITT takes into consideration the behavioral characteristics of the occupants. It attempts to realistically reflect the actions of family members including investigation of the fire by capable adults, the rescue of small children by adult females and the varying degree of difficulty waking sleeping adults. The movement of people, however, is deterministic. All individuals within an occupant class will behave in the same way and at the same speeds. Actions of occupants will not vary from run to run, or from individual to individual, as they would in a probabilistic model. EXITT's output includes the actions and locations of the occupants as they evacuate along optimal escape routes. The model is currently limited to 12 rooms and 35 nodes.

TENAB uses output from FAST and EXITT to estimate the hazard to occupants of their exposure to combustion products from the fire as they move along their escape routes. When those hazards reach certain levels defined for each combustion product, the person is considered incapacitated or dead.

Hazard I is the best tool available for evaluating the fire risk of a building but EXITT is of limited use beyond dwelling fires. Aside from the fact that it is limited to 12 rooms, it requires so much bookkeeping to keep track of each individual's characteristics, capabilities, location and motivation for his or her actions that it can run very slowly. It requires too much detail on each individual to be used in an analysis of high-rise evacuation. It also recalculates escape routes throughout the entire building each time a room or node is blocked by smoke, which would be an extremely time-consuming exercise for a large building. In addition, it has no provision for queueing effects, which would be a requirement for any model applicable to large buildings.

The model described in this paper was designed to use the same smoke input as EXITT and to output the information needed by TENAB so as to function as a replacement module for EXITT. It was specifically designed to handle high-rise buildings with large occupant populations. It does not explicitly include the detailed behavioral considerations included in EXITT, but these are not believed to be as relevant in the more impersonal settings of offices and hotels as in homes.

PROGRAM DESCRIPTION

EXIT89 requires as input a network description of the building, geometrical data for each room and for openings between rooms and smoke data if the effect of smoke blockages is to be considered. The model will be described in detail in this paper, but the following is a brief overview.

It first calculates the shortest route from each building location to a location of safety (usually outside). It moves people along the calculated routes until a location is blocked by smoke. Affected exit routes are recalculated and people movement continues until the next blockage occurs or until everyone who can escape has reached the outside.

Evacuation can begin for all occupants at time 0 or can be delayed. Smoke data can be used to predict when the activation of a smoke detector would occur and evacuation will begin then or after some user-defined delay beyond that time. The program was written originally in BASIC.

CHARACTERISTICS AND ASSUMPTIONS OF EXIT89

At a minimum, an evacuation model that could serve as a substitute for EXITT in high-rise applications needs: 1) to be able to handle a large occupant population; 2) to be able to recalculate exit paths after rooms or nodes become blocked by smoke; 3) to track individuals as they move through the building by recording each occupant's location at set time intervals during the fire; and 4) to vary travel speeds as a function of the changing crowdedness of spaces during the evacuation, i.e., queueing effects.

The size of the building and its population that can be handled by EXIT89 can be expanded by modifying the size of the data arrays used by the program. The dimensions of the storage arrays currently allow for up to 700 occupants in a total of 80 nodes or building spaces over 100 10-second time intervals. These can be changed by the user to handle larger problems. Due to the naming convention for nodes that the program relies on, each floor can have up to 89 nodes and the building can have up to 10 stairways.

The model has a local perspective rather than a global one. People will move to what looks like the closest exit, even though the total length of the path to the outside might be longer than through another exit door. For example, an occupant of a hotel stepping out of his room will head to the closest stairwell even though it may be five flights down to grade level while another stairwell a slightly greater distance from his room might be only three flights from grade level. A model with a global perspective would move him along the truly shortest path, but that route would not be realistic for a hotel guest who would be unfamiliar with the layout of the building.

Another assumption is that once people enter a stairwell, they will follow it all the way down to the outside unless it becomes blocked by the fire's progress, in which case they will move out of the stairs and onto the nearest floor. In real situations, people may head for the roof or leave the stairs to go onto lower floors for no apparent reason.

EXIT89 does not explicitly include the behavioral considerations that are included in EXITT. These behaviors include investigation of the fire, rescue of small children, alerting or waking other capable adults and assisting other occupants who may require help. The population of high-rise buildings is too large to handle so much detail for each individual, and behaviors such as investigation or rescue of other occupants are not as relevant in larger, more impersonal, buildings. The model calculates walking speed as a function of density. This calculation will be discussed in more detail later.

MODEL INPUTS

The input to the model includes a network description of the building. Nodes can be rooms or sections of rooms or corridors, whichever will result in the most realistic travel paths. The nodes defined, though, should correspond to the rooms described in FAST, if FAST output will be used as the smoke data input for EXIT89.

The definition of each node includes its useable floor area, the height of the ceiling, its initial occupant load, and the number of seconds the original occupants of that room will delay before beginning evacuation. The definition of each arc includes the distance between nodes and the width of the opening between the nodes. Arcs are bidirectional, so a connection between the nodes only has to be described once.

USING THE MODEL

EXIT89 can be used in two different ways. The user can input the names of nodes that become blocked by smoke and the time those blockages occur. Or, the user can take the smoke data output from FAST as input to the model. FAST will calculate and write to a disk file the optical density of the hot upper layer at each node at each time interval and the height from the floor of the cooler lower layer. In the first version, evacuation begins simultaneously throughout the building at time 0, plus any delay time specified at nodes by the user. In the second version, evacuation begins throughout the building when the smoke level reaches that defined for smoke detector activation, plus any delay time specified at nodes by the user. By using the first version and not specifying any blockages, the user can model emergency evacuation of a building with no fire occurring.

The program will print out the movement of each occupant from node to node. It also records the location of each occupant at each time interval so that the output can be used as input to TENAB. TENAB will calculate the hazards to which each occupant was exposed using FAST output for combustion products and will determine when incapacitation or death occurs.

SHORTEST ROUTE CALCULATIONS

Shortest routes are calculated for each floor, from each node to the stairways or to the outside. The shortest route algorithm used is that described by Hillier and Lieberman as the shortest and simplest of those they reviewed [2]. The algorithm begins by identifying the origin of a network and then fans out from the origin, identifying the shortest routes to all the other nodes until the destination is reached.

The adapted version of the algorithm used in the model is described below. The model calculates the shortest routes on each floor to the stairways or the outside or other locations of safety. Locations of safety can include horizontal exits or areas on the other side of fire doors. In order for the model to recognize these locations of safety, the user identifies them as part of the building description input data. These nodes are referred to as intermediate exits (IE) in the following discussion. An array is created that consists of the connected node that occupants at a given node will move to in evacuating the building. For example, if the path from node 102 to the outside goes through nodes 104 and 107, then the connected node for 102 is 104, the connected node for 104 is 107 and the connected node for 107 is the outside.

The route down each stairway is then established by defining the connected node for each stairway node as the one below it.

The shortest route subroutine begins by identifying all the IE's on a floor of the building. These nodes are placed on the list of "solved nodes."

Step 1 Identify all unsolved nodes connected to the solved nodes.

Step 2 Add the distance between the solved and unsolved nodes to the distance from the solved node to its closest IE.

Step 3 The unsolved node with the shortest distance to the IE is added to the list of solved nodes, its connected node is that solved node and its distance to the IE is stored.

Return to Step 1 until all nodes are solved.
This is repeated for each floor.

One advantage of the approach used in EXIT89 is that the blocking of a node by smoke will only require the recalculation of the routes on that floor, rather than all routes throughout the building. If a stairway node is blocked by fire, the routes on that floor and the floor above will be recalculated. This will cause occupants in the stairway on higher floors to move out of the stairway when they reach the node above the smoke-blocked node.

Another advantage of this approach is that it more closely approximates the local perspective of an occupant in the building. Other shortest route routines "see" all possible routes to the outside and so they make decisions based on information not available to a real person.

CALCULATION OF WALKING SPEEDS

Walking speeds are incorporated in models in various ways. Some, like EVACNET+, use constant values [3]. Some, like EXITT, use different discrete values based on fire conditions. EXITT uses a basic speed of 1.3 m/s. If the occupant believes the fire to be serious, walking speed increases by 30 percent. If an occupant has to assist another, walking speed is cut in half. Crawling reduces speed by 40 percent. Crawling while assisting reduces speed by 60 percent.

In EVACNET+, the user specifies a level of crowdedness for corridors and stairways and the average flow volume associated with that level of crowdedness is used throughout the model. These are based on Fruin's work [4], which defines levels of service for areas in terms of occupancy area for each pedestrian. A range of average flow volumes is associated with each level of service. The level of service chosen by the user does not vary over the course of the evacuation.

The method chosen for EXIT89 uses walking speeds calculated as a function of density based on formulas from Predtechenskii and Milinskii [5]. Body size is included in their density calculations. Using dimensions of people (adults, youths, and children) in various types of dress, both empty-handed or encumbered with packages, knapsacks, baggage or babies, they calculated the area of horizontal projection of a person. This measure is the area of an ellipse whose axes correspond to the width of a person at shoulder level and breadth at chest level. Tables of mean values for different age groups and types of dress are given in the text. Their formula for density of a stream of people, D, is:

$$D = Nf/wL \quad (m^2/m^2) \qquad (1)$$

where N = number of people in the stream
f = the area of horizontal projection of a person
w = width of the stream
L = length of the stream.

Their model established an optimal density of 0.92. Although a higher density can be observed in real situations, 0.92 is the maximum they used in empirical expressions for walking speeds. Based on their observations recorded in thousands of situations, they developed the following equations for normal circumstances. For the mean values of velocity as a function of density for horizontal paths:

$$V = 112\,D^4 - 380\,D^3 + 434\,D^2 - 217\,D + 57 \quad \text{(m/min)} \tag{2}$$

$$\text{for } 0 < D \leq 0.92.$$

For movement through doors

$$V_o = Vm_o \quad \text{(m/min)} \tag{3}$$

$$\text{where } m_o = 1.17 + 0.13 \sin(6.03D_o - 0.12)$$

For movement down stairs

$$V_{\downarrow} = Vm_{\downarrow} \quad \text{(m/min)} \tag{4}$$

$$\text{where } m_{\downarrow} = 0.775 + 0.44\,e^{-0.39D_{\downarrow}} \cdot \sin(5.16\,D_{\downarrow} - 0.224)$$

Since the model does not move people up stairs, the values for travel up stairs is not shown.

In emergencies, such as earthquakes or fire, the fear that makes people try to flee danger raises the speed of movement at the same densities. Predtechenskii and Milinskii found the following relationship between the two velocities:

$$V_e = \mu_e \cdot v \tag{5}$$

where $\mu_e = 1.49 - 0.36\,D$ for horizontal paths and through openings
$\mu_e = 1.21$ for descending stairs.

Repeatedly calculating velocities using these equations for every occupant throughout a fire simulation would be extremely time-consuming. Fortunately, tables of velocities by density were given for normal, emergency and comfortable movement along horizontal paths, through openings and on stairs. EXIT89 originally assumed that people are aware of the fire emergency when they evacuate, so only the velocities for emergency movement were included in this model.

The area of horizontal projection of a person used in the calculation is 0.113 m^2 (1.22 ft^2) -- the mean dimensions of an adult in mid-season street dress. Velocities are calculated for both segments of the arc between two nodes, based on the different densities and floor areas for the two nodes. If a value for D greater than 0.92 is calculated, D is set equal to 0.92. The value calculated for D is used to look up the velocity from the tables. The tables hold velocities along horizontal paths and down stairs.

Initially, the program was coded the way the formulas were given; that is, the density was based on the area of the stream -- the width of the doorway by the length of the stream of people. This resulted in reduced velocities even when only two people were in a room, and could noticeably decrease walking speed when, say, six people were in even a fair-sized room. People do not necessarily line themselves up so closely when evacuating through rooms. They can spread out and so maintain a more rapid, free-flowing walking speed. The formulas used in the model now calculate densities based on the floor area of the nodes. For travel along corridors, the useable floor area and the area of the stream as calculated by Predtechenskii and Milinskii will be very close, if not identical.

EXIT89 does not yet simulate people crawling through smoke. First, a mechanism must be inserted in the code to detect conditions at a node where crawling would be necessary. The routes on that floor should be recalculated to move people away from that node. Then if moving through a smoky node is the only out of the building, the velocity would be adjusted.

SMOKE LEVELS

As mentioned above, there are two versions of this model. In the first, the user determines at what node and when blockages due to smoke will occur. In the second version, smoke densities and depths of smoke layers are read in from a file created by FAST. Using the same method as EXITT of calculating the psychological impact of smoke, S, the following equation is used:

$$S = 2 \cdot OD \cdot D/H \tag{6}$$

where OD is the optical density of the smoke in the upper layer
D is the depth of the upper layer, and
H is the height of the ceiling.

EXITT uses $S > 0.5$ to stop an occupant and $S > 0.4$ as a threshold to prevent entering a room, in both cases unless there is enough clear air in the lower layer to crawl. Since this model does not yet handle crawling, a value of $S > 0.5$ is used to block a node which traps everyone currently at that node.

Smoke detectors operate when $S \geq 0.015$ or the depth of the upper layer is greater than 0.15 meters (0.5 feet). The model currently assumes that notification of all occupants occurs when levels needed for smoke detector activation are reached at any node, and evacuation will begin after any user-specified delays. Refinement of the program to define the range of a smoke detector and to otherwise modify the rules determining the notification of occupants are important next steps in the development of EXIT89.

MOVING THE OCCUPANTS

The initial shortest routes throughout the building are calculated before any smoke data is read in. For the first version of the model, where the user enters the location and time of smoke blockages, notification to begin evacuation occurs at time 0. For the second version, the model reads in the smoke data and determines where and when blockages would occur and when smoke detector activation would occur and evacuation would begin.

The model begins by calculating, based on the initial distribution of occupants, how long it would take to travel from each occupied node to its connected node. Then for each occupant, it looks at how long that occupant has been at that node and how long it takes to traverse the arc. If the occupant has been waiting long enough to traverse the arc, the occupant is moved to the next node, and the waiting time at that node is set to 0. Waiting times are actually portions of the arc traversal times. If there are still occupants in the building, the model recalculates time to traverse arcs based on the updated densities at nodes.

The sequence is repeated until the time is reached when a node is blocked by smoke. At that point, the affected node is removed from the network, any occupants at that node are counted as trapped and shortest routes are recalculated for the affected floor (or floors if the node is in a stairway). People movement is then resumed until the next blockage or until everyone is either out of the building or trapped.

Queueing is handled by the decreased walking speeds that result from increased densities as more occupants move into a room or stairway. The program does not currently allow occupants to select less crowded routes. They simply join the queue at nodes along the shortest route.

MODEL VALIDATION

EXIT89 was originally written in BASIC and tested using floorplans designed to exercise specific aspects of the model as it was being developed. Because BASIC could not handle the large array sizes required for an actual high-rise building, it was necessary to translate the model into FORTRAN. This phase of the testing was done on NFPA's mainframe computer.

To validate the model, data from a fire drill in a nine-story office building was used. This building consists of seven floors of office space (floors 2 through 8). The ground floor consists of the lobby, a cafeteria and building services. There is a mechanical equipment penthouse on the top floor. Each of the office floors consists of approximately 1,950 square meters (21,000 square feet) of usable space. There are two stairwells in the central core of the building. Both discharge into the lobby.

At the time of the fire drill, there were approximately 100 workers on each office floor (a total of 700 occupants). Travel distances were measured from the center of each space to the center of the openings between connected spaces.

The model was run first using the emergency velocities from Predtechenskii and Milinskii described earlier. These resulted in an estimate of 5.6 minutes to evacuate the building, faster than the 7 minutes calculated during the drill. This may not be an unreasonable result, given that the occupants of the building during the drill would not have felt compelled to treat the situation as an emergency and would not have moved throughout the building as quickly as they would if they had felt threatened.

The program was modified to use the "normal" velocities computed by Predtechenskii and Milinskii. These velocities are from 14 percent to 32 percent slower than the emergency rates. When the model was rerun using the same floorplan and occupant distribution, the time to evacuate the building increased to 10 minutes. This now is slower than the 7 minutes calculated during the drill.

The model has been successful in meeting the objectives for which it was designed, such as handling individuals in a large occupant population, handling evacuation of a high-rise, and allowing for queueing. The times calculated by the model are not unrealistic, but some fine-tuning is still necessary. The next enhancement planned for the model is to have occupants move at either the emergency or normal velocities defined by Predtechenskii and Milinskii, depending on their location in relation to the fire.

LIMITATIONS OF THE MODEL

The model in its current form does not include any explicit behavioral considerations. Occupants who are aware of the fire do not assist other occupants or travel to other nodes to alert them. This may be realistic in an office environment where everyone should be awake but may be less so in a hotel. Once an occupant begins evacuation, s/he does not stop unless blocked by smoke. Behavioral considerations can be handled implicitly by incorporating time to perform investigation activities or to alert others before evacuating in the delay times that the user specifies for the occupants of each node. The model will be modified to allow occupants to be defined as "assisters" or "assistees." Due to the degree of impersonal-ness of large buildings, assistance will be limited to others at the same node, e.g., family groups in hotel rooms or a handicapped person's coworkers.

Another behavior that is not yet incorporated in the model is the tendency of able-bodied adults in the presence of other able-bodied adults to ignore early warnings of the presence of a fire. This diffusion of responsibility has been observed in actual incidents and needs to be added to this model.

Walking speeds are calculated as a function of densities and are based on tables of values from Predtechenskii and Milinskii. The model does not yet simulate crawling through smoky rooms by reducing walking speeds, or reversing direction where possible to use a less smoky, though longer escape route. These changes should not be difficult to incorporate.

One of the program's inputs is the capacity of nodes. The reason for including this value was to allow evacuees to avoid nodes that were already crowded if alternate routes are available. This would prevent occupants from queueing at one stairway while the other section or sections of the floor emptied out into less busy stairways. That logic also has not yet been written.

CONCLUSION

EXIT89 is still in a developmental stage. Additional testing and validation of the model are required. Some of the current limitations of the model, and the actions needed to address them, have been presented. The structure of this model allows those changes to be incorporated, eventually resulting in a model that will be able to substitute for EXITT in Hazard I and still include essential human behaviors and interactions, but be able to handle much larger buildings efficiently and realistically.

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