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CLEAR
(CALCULATES LOGICAL EVACUATION AND RESPONSE) -

A GENERIC TRANSPORTATION NETWORK MODEL FOR THE CALCULATION OF EVACUATION TIME ESTIMATES

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INTRODUCTION

Following the accident at Three Mile Island, the U.S. Nuclear Regulatory Commission (NRC) required that each nuclear reactor operator submit an evacuation time estimate for an area with a radius about 10 miles surrounding the plant.[1] Previously, such estimates were prepared only for low-population zones (LPZ), which generally extended from only 1 to 6 miles from the reactor. Because of the small area and number of people involved, evacuation time estimates could, therefore, be performed using relatively simple models. When NRC increased the area subject to evacuation, these simple models frequently proved inadequate.[2] Consequently, an unbiased generic model was needed to estimate evacuation times for relatively large areas and to accurately represent the road network, terrain, and specific characteristics and problems posed by each power plant and the surrounding region.

This paper describes a computer model, designated CLEAR (Calculates Logical Evacuation And Response), developed to simulate vehicle departure and movement on a transportation network to determine time estimates for an emergency evacuation. NRC requested and sponsored the development of the CLEAR model to facilitate a viable means of verifying the evaluation time estimates submitted by the licensees. To date, the CLEAR model has been used primarily as an analytical tool for simulating an emergency evacuation

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1 The letter, dated 29 November 1979, from Brian Grimes, Director of Emergency Preparedness Task Group, requested estimates of evacuation times for ten sectors within a radius of about ten miles. Factors to be considered in the analyses included population (permanent, transient, and special facilities), weather conditions, warning times, response times and preparation times.

2 Analysis of Techniques for Estimating Evacuation Times for Emergency Planning Zones. T. Urbanik, A. Desrosiers, M. Lindell, C. Schuller NUREG/CR-L745 BHARC-40L/80-OL7 November 1980.

following an accident at a nuclear power plant. The methodology is, however, equally applicable to simulate evacuations following other types of accidents such as toxic waste spills, toxic gas leaks, fires, or other natural or man-made accidents.

In order to test the model, evacuation time estimates for a power reactor facility and the surrounding area were calculated and compared with the time estimates from three other studies. The site chosen for this test was the Beaver Valley Nuclear Power Plant in Pennsylvania. The time estimates use for comparison were prepared by Wilber Smith and Associates under contract for the Federal Emergency Management Agency (FEMA), the utility company, Duquesne Light, as requested by NRC, and the Pennsylvania Emergency Management Agency (PEMA).

METHODOLOGY

An explanation of the methodology of the computer model includes a discussion of all functions, subroutines, and algorithms used to simulate behavior during an evacuation involving a specific transportation network. The order in which the events of the evacuation proceed, as well as the handling of all necessary and arbitrary decisions, constitute the theory of the evacuation plan.

The methodology used in CLEAR satisfies the requirements outlined by the NRC in NUREG-0654 Revision 1. The NRC report recommends that the transportation network and population information be specific to the evacuation site. Information on assumptions, such as automobile occupancy factors, method of determining roadway capacities, and method of estimating populations should also be available for analysis. In addition, a description of the method of analyzing the evacuation times should be provided.

The NRC recommends that three potential population groups be considered: permanent residents, transients, and persons in special facilities. Permanent residents are all people having residence in the emergency planning zone (EPZ), but not in institutions. The transient population includes tourists, employees not residing in the area, or other groups that may visit within the EPZ. Finally, special facility residents include those confined to institutions such as hospitals and nursing homes. The school population should also be included in this group.[3]

[3] Criteria for Preparati... ...d Evaluation of Radiological Emergency Response Plans and Preparedness ... Support of Nuclear Power Plants. U.S. Nuclear Regulatory Commission NUREG-0654 FEMA-REP-1 Rev. 1 November 1980.

The criteria for the zone sub-areas in the EPZ is described in NUREG-0654 Revision 1. The sub-areas for which evacuation time estimates are required must encompass the entire area within the plume exposure EPZ. Furthermore, evacuation time estimates are also considered for simultaneous evacuation of the entire plume exposure pathway. Evacuation time analysis considers more than the four 90° sectors out to about two miles, the four 90° sectors from the two mile radius to about five miles, the four 90° sectors from the five mile radius to about ten miles, and the entire EPZ.[4]

According to NRC requirements, a map showing the transportation network used as evacuation routes is included with the time estimates. Each road segment is numbered for reference. In addition, a table listing the characteristics of each road segment is included.[5]

The reported calculations can include evacuation times estimated for two conditions: normal and adverse.[6] Adverse conditions would depend on the characteristics of a specific site and could include flooding, snow, ice, fog, or rain. The affects of adverse weather on a specific EPZ used in the analysis are to be severe enough to have an impact on the events modeled in the evacuation. These conditions will affect both travel times and capacity. Since adverse conditions may affect an EPZ differently depending upon season or time of day, it may be necessary to consider more than one type of adverse condition.[7]

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4 Ibid.
5 Ibid.
6 Ibid.
7 Ibid.

To date, the CLEAR calculations have not considered adverse weather conditions. Although this is within the model capabilities, there exists significant uncertainty concerning the assumptions necessary to model adverse weather. Until reasonable estimates are available for these assumptions, the CLEAR model will be used primarily for normal conditions.

The text accompanying a table of evacuation time estimates shall clearly indicate the critical assumptions which underlie the calculations. This might include day versus night, workday versus weekend, peak transient versus off-peak transient, and evacuation on adjacent sectors versus nonevacuation. The relative significance of alternative assumptions shall be analyzed, especially with regard to time-dependent traffic loading of the transportation network segments.[8]

The NRC recommends two methods for calculating evacuation time estimates. The simplest approach is to assume that events are sequential, i.e., that no one begins to evacuate until all persons within the EPZ have been warned and are prepared to leave. The time is then estimated by simply adding the maximum time for each stage (warning, preparation, and evacuation). This approach tends to lead to an overestimate of the evacuation time.[9]

The second approach, which is used in CLEAR, is more complex. It incorporates functions to simulate the stages of the evacuation occuring simultaneously. For example, at a given moment some persons may be in the preparation stage while others are in the response stage. This integrated system for estimating the evacuation process can result in reduced time

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8 Ibid.
9 Ibid.

estimates due to more realistic assumptions. The NRC notes that some functions must be based on the judgment of the estimators.[10]

The computer evacuation model adheres to many of the basic axioms of traffic monitoring theory by including several functions that handle the vital conditions and consequences of traffic flow. These include handling vehicles at road segment intersections, determining the speed of travel on a road segment as a function of vehicle density, simulating the delay of vehicles in traffic jams or congestion, and advancing vehicles on the transportation network.

While some of the methodology is dictated by traffic simulation theory and NRC requirements, several aspects of the evacuation plan which are unique to the model. For example, the theories for determining the number of vehicles assigned to a road segment and the initial positions from which they are being evacuated, as well as the method for randomly initiating a vehicle's movement, have all been developed specifically for this computer model. The method of output, which includes vehicle population as a function of radial distance from the site of the emergency, is unique to this code.

In order to represent the evacuation accurately, the computer model allows events to occur similtaneously in a continuous time format. By calculating all occurrences on all roads during an increment of time, the model snaps a picture of how vehicles have progressed within this small time period.

The size of the time increment is determined by the shortest road in the transportation network. Since no vehicle may pass over more than one road

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10 NUREG-0654 Rev. 1, Page 3-3.

segment during single increment of time, the time increment is equal to 99% of the shortest road segment's length (meters) times the road segment's nominal velocity (meters per second). Consequently, the time increment is small enough not to have any significant effect on the evacuation time estimates while hopefully being large enough to make the program run efficiently.

Description of Input

The input of data at the beginning of the program enables the generic computer model to be used to calculate evacuation time estimates for a specific transportation network and population distribution. Because these data are critical to the computer model's calculations, any assumptions, utilizations, or transformations pertaining to these numbers are significant.

In order to discuss the input of the transportation network and population data, it is first necessary to describe the division and identification of the area surrounding a nuclear reactor facility. The area is divided into twenty-four zones with eight equal zones from the reactor to the 2-mile radius, eight more from the 2-mile radius to the 5-mile radius and finally, eight more equal zones from the 5-mile radius to about the 10-mile radius.

The twenty-four zones are identified by eight polar directions. The three rings of eight zones are lined up so that three zones compose each of the eight geographical directions: north, northeast, east, southeast, south, soutwest, west and northwest.

The zones have been established in this manner for two reasons. First, this arrangement complies with NRC's guidelines[5], and second, it provides greater flexibility and accuracy in determining the evacuation time estimates.

With the zone network defined, an estimation of the population density for each zone is obtained from current U.S. Bureau of Census reports, as well as from the data provided by the licensees in their response to the NRC's request for evacuation time estimates. In cases where the data from these two sources do not agree, best efforts are made to establish the population on the basis of supplementary information. For example, when known population statistics cover an area in more than one zone or extending beyond the EPZ, the population can be considered to be evenly distributed over the area or may be weighed according to the location of specific townships.

In addition to representing the general population distribution, the computer code also includes an independent special traffic generator which models schools, factories, hospitals, prisons, and other large population contributors. By enabling specific population densities to be modelled accurately, this routine ensures that NRC's requirement that special facilities be represented in the evacuation time estimates is satisfied.

In conjunction with the precise representation of the population information, the transportation network around a nuclear reactor is also modelled accurately. Characteristics of a road segment that affect the evacuation time are input as data for a specific site. This information includes the road segment's length, number of lanes, nominal vehicle rate of

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[5] Brian Grimes letter dated 29 November 1979, requested as a minimum two 180° zones in the two mile radius, four 90° zones in the five mile radius, and four 90° zones out to about ten miles.

travel, relative position is terms of radial distance, from the next roadway segment on which the vehicles travel (link), and possible intersecting routes. The utilization of these data enables the program to model the transportation network as an interactive homologous system.

As each section of roadway is numbered and has its own specific parameters, a description of the criteria for establishing a road segment is useful. A road segment ends and another begins where two or more road segments intersect. Furthermore, for the purpose of tracking population density, a road segment ends at the boundary of one zone and another begins in the next sector. Similarly, when a roadway continues for a long stretch in one zone without being intersected, it may be divided into a few road segments in order to accurately track population versus radial distance. In order to run the program efficiently, the maximum length of a road segment is approximately 3600 meters while the minimum length is 300 meters.

The initial step in preparing a transportation network is to construct a map of the roadways in the EPZ area surrounding the nuclear power plant. The twenty-four zone network is then placed over the map. The road segments are defined and assigned their length, nominal velocity of travel, relative position as radial distance, and finally, given a direction for evacuation. Once completed, the number of outbound lanes is assigned to each segment. In addition, the entire EPZ transportation network can now be divided into evacuation trees.

Each evacuation tree is a system of interacting road segments with at least one exit from the EPZ. Every road segment in the evacuation tree is dependent upon or interacts only with other road segments in the system. The evacuation time estimate calculated for a single evacuation tree may or may not determine the evacuation time estimate for an entire EPZ.

The evacuation tree may contain roads from a number of zones. It is not necessary that a tree contain all the road segments in a zone, but rather those road segments that interact together. The evacuation time estimate for a particular zone may be determined by analyzing all evacuation trees containing road segments in that zone.

When an evacuation tree has been isolated, the remaining road segment parameters can be determined. Each road segment is given a number for identification. The input for an evacuation tree, therefore, has become a numerical system. The link and possible intersecting road segments of a road segment are input as numbers.

An evacuation path for each road segment will be determined on a shortest distance estimate and will later be established by determining the traffic routes for the quickest evacuation. Since it is necessary to have an evacuation path programmed into the computer model, the first such path is determined by a "shortest route" approach. In effect, each road segment usually has one shortest path distance out of the ten mile radius and this path becomes the initial input route. If two or more equally short evacuation routes exist for a road segment, then one is arbitrarily chosen. It is significant that after the intial run of the computer model, the programmer will have a better knowledge of where difficulties or slow spots arise in the evacuation plan. It is then possible to reduce the traffic on a slow road segment by distributing vehicles to alternative routes. Eventually, precise information on each road segment will be available.

After data on the population and the transportation network for a particular zone in an evacuation tree have been entered into the program, the number of persons assigned to each road segment can be calculated. Dividing the length of a specific road segment by the length of all road segments in the zone determines the fraction of zone's population that road segment may service. Following this pattern, a conservative estimate of the road segment's initial vehicle population is calculated as follows:

$$\text{Initial Vehicle Population Assigned to the Road Segment} = \frac{\text{Total Population of Zone} * \text{Fraction of Total Road Length}}{\text{Persons Per Vehicle}}$$

In an effort to represent accurately the starting positions of vehicles on the roadway network, the distribution of vehicles on a road segment is determined by its length. Because the bulk of the population will probably depart from residential streets, which have few lanes and relatively low vehicle capacities, the number of vehicles assigned to each road segment is based solely on the road segment's length. If the population were distributed by each road segment's vehicle capacity, then the major roads and highways would begin with large vehicle populations.

After the vehicle population of a road segment has been determined, the vehicles are assigned a departure position along the road segment. This procedure fulfills two important purposes. First, it ensures an even population distribution over the road segment, and second, it incorporates a random number generator to facilitate a stochastically unbiased evacuation process.

This method divides the length of the road segment by the number of vehicles assigned to the road segment. The result is a unit length or incremental distance which will separate the vehicles, starting with a vehicle at the beginning of the road segment. The random number generator arbitrarily selects a loading position where a specific number is assigned. The vehicles would appear evenly spaced from the beginning of the road segment, although numbered in a random order.

The method for advancing vehicles along the transportation network is critical to the calculation of evacuation time estimates. After the data for the road network and population distribution have been entered into the program, the number of vehicles per road segment determined and their positions assigned, and time increment established, the CLEAR model begins to simulate the evacuation process.

The CLEAR model analyzes one road in a zone at a time. When all the road segments in a particular zone have been processed, the road segments in the next zone are analyzed. The zones are processed in order beginning with the inner eight zones (within 2 miles), then the middle eight zones (between 2 and 5 miles), and finally, the outer eight zones (from 5 miles to the end of the EPZ). In other words, all zones within the two mile radius having road segments in the evacuation tree are processed first. Next, all zones comprising the area from the two mile radius to the five mile radius containing road segments in the evacuation tree are processed. Similarly, the remaining zones in the EPZ, comprising the area from the five mile radius to the about ten mile radius with road segments in the evacuation tree are processed. As a result of this method, each road segment in the evacuation tree is processed only once during each increment of time.

Having selected a road segment in a particular zone, the CLEAR program begins preparing for vehicle movement. At this point, a new term of significance is the phrase "loaded". Because the first decision block determines whether the link of the current road segment being processed has been loaded for this increment of time, an explanation of the term is necessary. A road segment is loaded when the number of vehicles scheduled to begin their evacuation movement during a particular time increment command a position and occupy space on the segment. This must not be confused with when a vehicle is advancing through the transportation network. For a road segment to be loaded for an increment of time, a specified number of vehicles assume their starting position and occupy space on the road segment. Only later, will these vehicles move on the transportation network. The number of vehicles scheduled for departure is in accordance with the loading function which simulates the departure rate for a population during an evacuation condition.

There are several stages before a population group is ready to begin their evacuation. While the evacuation time represents the interval of time from the detection of an incident which ultimately requires evacuation to the end of the period required for individuals to physically move out of the area, there exist components of evacuation time which are helpful to determine a loading function. Decision time is the amount of time elapsed from detection of an incident until a decision is made by an authority competent to order an evacuation. The time required to notify all individuals in the specified area or EPZ of the need to evacuate is called the notification time. The preparation time is that which is required for individuals to prepare to evacuate from the EPZ. Finally, these components together with response time, the time necessary for individuals to physically move out of the EPZ, constitute the evacuation time.[12]

In an area designated for evacuation, there is a distribution of times for each of the components of evacuation times previously described. For the purpose of simulating the departure rate of the evacuees, the loading function in the CLEAR model determines a percentage of the population initiating their evacuation during a given increment of time based upon the curve estimating notification and preparation times in NUREG-0654 Revision 1. The evacuation time estimates for the CLEAR model are, therefore, a calculation of the notification, preparation, and response times added to an estimate for the decision time.

The loading function in the computer model allows for two input variables to determine the rate of departure of the vehicles. The first variable estimates the overall time period for all individuals to begin evacuating by establishing a maximum departure time. This represents the maximum notification time plus the slowest preparation time for any individual.

The second variable used in the loading function determines the rate and distribution at which individuals begin their evacuation within the maximum departure time. The variable represents the percentage of the population within the entire EPZ who begin their evacuation before one-fourth of the maximum departure time has transpired. According to this method which describes a histograph function, of the remaining population 25 percent leaves during the second quarter of the maximum departure time, 50 percent departs

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12 Analysis of Techniques for Estimating Evacuation Times for Emergency Planning Zones, Page 2,3.

during the third quarter, and finally, 25 percent leave during the last quarter. Therefore, the function with a variable fraction equal to one-tenth would be represented as the following histogram. (See figure 1)

In order to represent several stages of the evacuation occuring simultaneously, it is necessary that the link of a road segment be loaded before the road segment itself. Because the loading of all road segments during an increment of time occurs simultaneously in theory, it is preferable that the model simulate events under similar conditions. If a road segment were loaded during a increment of time and the same vehicles advanced along the transportation network, then some of these vehicles could continue onto the link of the road segment. Under these assumptions, later in the model when the link is loaded for the same increment of time, there now exist new vehicles on the link (coming from the road segment) which would have been loading at the same time during the evacuation as the vehicles presently being loaded onto the link. Since the loading of vehicles on these two road segments actually occurs simultaneously, no vehicles from the road segment should already be on the link when it is being loaded for the same increment of time. Since vehicles compete for available space on a road segment, to load the road segment before the link would give an unfair and inaccurate advantage to vehicles on the road segment. The link of the road segment is, therefore, loaded before the road. As mentioned previously, when vehicles are loaded on the link they assume a starting position and occupy space on the road segment, but they are not advanced along the transportation network until the link is processed as a road segment.

When the link has not been loaded for the currentent of time, the program tests to determine if the elapsed time is greater than the maximum departure

time. Since all vehicles have been loaded by the maximum departure time, the loading procedure is not used after that point because there are no vehicles remaining to be loaded.

During an increment of time preceeding the maximum departure time when the link has not been loaded, the number of vehicles scheduled to load are transferred from the random queue into the loading queue. The random queue lists the vehicles on a road segment with a random starting position. The loading queue is, therefore, a list of the vehicles which have been loaded but have not begun their movement on the transportation network. The selection of which vehicle should leave is unbiased because the vehicles are selected in order from the random queue. Vehicles in the random queue have a position of departure from the road segment which was randomly chosen.

When vehicles are being positioned on a road segment, it is necessary to analyze their vehicle length and its significance. The basic figure for vehicle length was determined using a free flow rate of 1700 vehicles per lane hour at 40 miles per hour and the hypothesis that vehicles begin to jam or queue at 15 miles per hour. The base vehicle length is 5.68 meters (18.64 feet).

The effective vehicle length is the space occupied by a vehicle on a road segment. The length necessary for a vehicle increases as the velocity of travel on a road segment increases to allow for additional spacing between vehicles at greater speeds. The effective vehicle length is calculated by summing 5.68 meters for a vehicle and an additional 5.68 meters for every ten miles per hour the vehicle is travelling. The smallest effective vehicle length of 14.20 meters (46.59 feet) occurs at the minimum velocity of travel on a road segment of 15 miles per hour.

The back-up queue system in the CLEAR model for representing a traffic jam due to an excessive number of vehicles on a road segment is based on effective vehicle length. When the addition of one effective vehicle length for a vehicle to the total of effective vehicle length for all vehicles on a road segment exceeds the length of the road segment, then the vehicle is placed in a back-up queue. This simulates when the addition of a single vehicle to a road segment would cause the volume of traffic to exceed the total capacity for the road segment. The vehicle is placed in a back-up queue at the beginning of the road segment and will not continue its evacuation until there is adequate space on the road segment for it.

Returning to the program run, a combined list of vehicles is formed for a road segment during each increment of time from those in the loading queue and those that may exist in a back-up queue. This combined list, or total queue, is used to add vehicles to a road segment. A decision block tests whether the addition of one vehicle from the total queue would exceed the total capacity of the road segment. If there is not adequate space on the road segment, then the vehicle remains in its orginal loading or back-up queue and will be included in the total queue formed during the next increment of time.

This denial of a vehicle to advance on the transportation network is the second type of delaying queue. In contrast to the single position of all vehicles in the back-up queue, the vehicles remaining in the loading queue retain their assigned positions of entry onto the road segment. In this case, therefore, the model holds the vehicle where it is until a suitable opening appears on the road segment.

During the formation of the total queue, a priority for loading or continuing the evacuation movement is established in the total queue. Since a traffic jam on a road segment disperses from the front to the back and the vehicles in the loading queue are ahead of those in the back-up queue, the vehicles in the loading queue are given priority to advance on the road segment when an adequate opening develops. Therefore, the total queue lists vehicles in a specific order. Vehicles from the loading queue listed chronologically in order to placement into that queue followed by vehicles in the back-up queue. Although vehicles are transferred from the random queue to the loading queue only before the end of maximum departure time, during each increment of time the CLEAR model attempts to add queued vehicles to the transportation network.

Before adding vehicles to the link, a decision block tests whether the addition of one more vehicle would exceed the maximum flow rate of the segment. The maximum flow rate of a segment is calculated using the 15 mile per hour minimum velocity. Since 15 miles per hour is assumed to be the slowest rate of travel occurring on the transportation network, the effective vehicle length at that velocity is the minimum space a vehicle could ever occupy. The total capacity of a road segment is calculated, therefore, by dividing the road segment's total length (meters) times number of lanes by a vehicle's effective length at 15 mph (14.20 meters). The truncated result is the total capacity of the road segment.

If there is room on a road segment for the addition of one more vehicle, then the first vehicle in the road segment's total queue is added to the road segment's list of moving vehicles. The list of moving vehicles contains all those advancing on the road segment. After the vehicle is moving then it is deleted from the total queue and the list from which it originated, either the loading or back-up queue.

A subsequent test is made to determine if there are any vehicles remaining in the total queue. If there are, then the code determine if the addition of yet another vehicle to the road segment would exceed its capacity. Vehicles will continue to be added to the road segment's list of moving vehicles until either the capacity of the road segment is full or the total queue is empty.

Because the addition, as well as deletion, of vehicles from a road segment alters the volume of traffic, it also affects the velocity of travel on the road segment. With the addition of a vehicle to a road segment, the velocity of travel for the road segment must be recalculated according to its current volume of traffic. This is accomplished using a speed versus volume function.

The speed versus volume function may increase or decrease the optimum rate of travel for vehicles on a road segment in accordance with a change in the number of vehicles on the road segment. Several specific characteristics of a road segment that are essential in determining the speed versus volume relationship include length, number of lanes, nominal or free flow velocity, and the capacity of the road segment.

The subroutine changes the velocity of movement on the road segment after the number of vehicles on the road segment exceeds some percentage of the maximum rate of flow. Until the volume of traffic reaches that point, t velocity of travel is assumed to be constant at the free flow or nominal value. The percentage used represents the point at which free flow is no longer possible on the road segment. In other words, the volume of traffic on the road segment does not interfere with the velocity of movement until the

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volume of traffic exceeds that point. Once reached, the speed decreases as a linear function to intersect the maximum density at the minimum speed of 15 miles per hour. When the volume of traffic reaches the maximum volume, any additional vehicles are placed in a back-up queue at the beginning of the road segment. Vehicles in this back-up queue will continue their evacuation when there is adequate space on the road segment for them. (See figure 2)

According to the function, the velocity of travel on a roadway segment is either the free flow or nominal speed, on the decreasing linear function, or the minimum speed of 15 miles per hour. For a given road segment, the velocity of travel along the decreasing linear function can be calculated as follows:

$$\text{Velocity of travel} = \left(\frac{\text{Free Flow}}{\text{Rate*}} \times \frac{\text{Number}}{\text{of Lanes}} \times \frac{\text{Length}}{\text{of Road}}\right) \div \frac{\text{Current Number}}{\text{of vehicles}}$$

* Assumed to be 1700 vehicles per hour on one lane.

For example, the speed of vehicles on a specific segment of roadway would equal:

$$\left(\frac{\text{Autos}}{\text{Lane-hour}} \times \text{Lanes} \times \text{Miles}\right) \div \text{Autos} \rightarrow \frac{\text{Miles}}{\text{Hour}}$$

or

$$\left(\frac{\text{Autos}}{\text{Lane-Hour}} \times \text{Lanes} \times \text{Meters}\right) \div \text{Autos} \rightarrow \frac{\text{Meters}}{\text{Second}}$$

After the velocity of travel on the link segment is calculated for the new volume of traffic, it is time to load the current road segment being processed. The procedure for setting vehicles in motion on the road segment is the same as that which has been described for its link. Since it is possible that the current road segment is the link for another road segment that may have already been processed, it is important to check if the road segment has already been processed for this increment of time.

Upon completion of the loading sequence for both the link and road segment, the CLEAR model is prepared to simulate the advancement of vehicles through the transportation network. The moving vehicles on each road segment are listed in a queue with their specific position on the road segment. Every vehicle will be processed in an attempt to advance it along the network once during each increment of time.

Because a vehicle may advance from a road segment to its link during a increment of time, the first decision block for advancing vehicles tests whether the current vehicle has already been moved, advanced, and processed during the present increment of time.

If the vehicle has already been processed for this increment of time, then the next vehicle in the list of moving vehicles is tested providing there is another vehicle in the queue. When all vehicles on a road segment have been advanced, then that road segment is processed completely. Consequently, the code increments to the next road segment.

Since each vehicle is advanced once during a increment of time, there will be many cases when a vehicle has not been processed. In these cases, the next step is to calculate how far the vehicle will travel during the increment of time.

The subsequent decision block tests if the vehicle will pass beyond the boundary of the road segment and travel onto the its link. If the vehicle stays on the road segment, then its new position is recorded and the next vehicle is incremented. When the vehicle has sufficient time to advance onto the road segment's link, the vehicle is advanced to the beginning of the link and several conditions are tested. If another road intersects where the road segment becomes the link, then a function is used to allocate openings on the link according to the demand of the intersecting roads.

In an effort to represent the flow of traffic along a transportation network accurately, the CLEAR model simulates the movement and delay of vehicles at intersecting road segments. The CLEAR model attempts to represent three types of intersections, a stop sign, a traffic light and a merge with a function that is unique to this model.

The CLEAR model's method of representing intersections depends on the number of vehicles present on the intersecting road segments. In order to allocate space for the advancement of vehicles onto the link beyond an intersection, the relative vehicle densities of the two intersecting road segments are compared. In other words, the volume of vehicles on the intersecting road segments versus their relative capacities is compared. It is believed that this difference is proportional to the priority for advancement given one road segment over another.

While the density of each road segment is used to determine the traffic behavior at the intersection, it is still the capacity of the link beyond the intersection which ultimately controls the flow of traffic. The number of openings available on the link is determined by subtracting the number of moving vehicles from the capacity of the link. A percentage of the number of openings on the link for the two segments is allocated to each according to their relative priorities.

According to traffic monitoring theory, the type of control at an intersection is determined according to the relative priorities of the intersecting road segments. In the case where most vehicles are advanced from one of the intersecting road segments of greater density, although some vehicles from the smaller road segment will continue onto the link, there is usually a stop sign where the smaller road segment intersects the larger one at the link. When there is less of a difference between intersecting road segments, often a traffic light controls the intersection according to the relative demands of the intersecting segments. When two road segments in a transportation network come together and continue as a single road segment, it is called a merge. Sometimes a merge occurs between road segments of similar density and at other times it occurs among road segments of very different density.

The CLEAR model calculates the advancement of vehicles through an intersection according to the density of the road segments rather than the type of control. Because the type of control at an intersection in the transportation network for any EPZ is frequently chosen according to the relative priority of the road segments which is based on their relative densities, the CLEAR model attempts to simulate the theory behind the selection of a controlling device. It does not, however, model a specific control at an intersection in the EPZ.

There will be times during an evacuation when one road segment at an intersection served by a traffic light will have no vehicles or when a traffic officer is monitoring the vehicle flow. In both cases, the control will be analyzing the demands of the intersecting road segments according to density. Late in an evacuation, it would not be inconceivable for a vehicle operator to stop and then advance through a red light to continue his exit if few vehicles are travelling on the intersecting road segment. Furthermore, it is expected that traffic management personnel may assist vehicle flow at difficult intersections by advancing vehicles according to the relative density of the intersecting road segments.

The CLEAR model handles an intersection of three or more road segments by analyzing just two at a time. Although this could allow slightly more vehicles to advance from the road segment processed first, the number of vehicles advancing onto the link will still not be any greater. Because the capacity of the link is the limiting parameter controlling the advancement of vehicles through an intersection, this method will not increase the rate at which vehicles are advanced to the link.

If there is sufficient space on the road segment for another vehicle and it should advance through the intersection during this increment of time, then a new position on the link is calculated for the vehicle. The advancement of the vehicle along the link is determined according to its original position on the road segment. In addition, the model keeps track of the vehicle so that it will not be processed again during this same increment of time.

There are two situations in which a vehicle reaches the beginning of a link before the end of a increment of time, but will be unable to advance onto the road segment. It can occur when there is insufficient room on the link or when the addition of a vehicle would exceed the number of vehicles allocated to the road segment according to the intersection condition.

The advancement of each moving vehicle on the road segment is analyzed individually. Since a vehicle may leave the road segment and proceed onto its link, the speed on the road segment is recalculated according to the remaining number of moving vehicles on the road segment.

After the velocity of travel on the road segment has been recalculated for this increment of time, the road segment has been processed completely for this time interval. Consequently, the code increments to the next road segment scheduled to be processed for this increment of time. Should there not be any more road segments in the zone currently being processed, the code increments to the next zone. When the moving vehicles on the road segments in all zones have been processed during the current increment of time, vehicle information flags specific to this increment of time are removed. This includes all loading and advancing markers.

The output from the CLEAR model can be printed at a variable increment of time. Since increment of time may be relatively small (~12 seconds), it can be more desirable to print out a status report on the advancement of vehicles over a longer period of time, perhaps every five minutes.

The output from the CLEAR model registers the position and state of all vehicles in the EPZ for that instant. In essence, the output is a picture of the vehicles on the transporation network at that one moment. The output begins with the initial vehicle population for the EPZ and the total time elapsed in seconds, as well as in hours, minutes, and seconds. The output continues with the vehicle population on each road segment in the evacuation tree within each of the eight possible zones composing the area within the two mile radius. After the vehicle population has been recorded for each road segment in a zone, the total vehicle population is listed for that zone. When the information for all zones within the two mile radius containing road segment of the evacuation tree has been recorded in this manner, the total vehicle population for these zones is printed as the vehicle population within the two mile radius.

The vehicle population is registered in this manner for the road segment and zones comprising the entire EPZ. The vehicle population within the five mile radius is the total in the eight zones comprising the area from the two mile radius to the five mile radius and the total vehicle population within the two mile radius. Similarly, the total vehicle population in the EPZ is the sum in the eight zones between the five mile radius and about the ten mile radius and the total vehicle population within the five mile radius.

The output also includes a table of the vehicle population as a function of radial distance in mile increments. Therefore, the approximate vehicle population in each of the ten one mile wide doughnuts comprising the EPZ is recorded. In addition, the output includes the percentage of vehicles contained in each radial increment relative to the vehicle population remaining in the EPZ. Finally, the output registers the remaining vehicle population and initial population for comparison.

When the vehicle population within the ten mile radius is zero, the evacuation has been completed and the current time is the evacuation time estimate. If the population within the ten mile radius is not zero, however, a time increment is added to the present time and the code returns to process the road segments in all zones for another increment of time.

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RESULTS

CLEAR was used to calculate evacuation time estimates for an EPZ of radius ten miles surrounding the Beaver Valley Nuclear Power Plant in Pennsylvania. In order to calculate these estimates, the transportation network and population in the EPZ were prepared as input data.

The population information was compiled from two sources. The study by Wilber Smith and Associates listed a figure for the total population in the EPZ. The report submitted to the NRC by Duquesne Light included a map of population densities by zones. Because the zones did not correspond exactly to those used in CLEAR, the population information was altered slightly to fit the input format for CLEAR. A population figure was used for each of the twenty-four zones in the Beaver Valley EPZ.

The transportation network in the Beaver Valley EPZ was developed for input into CLEAR using 7.5 minute (1-24,000) U.S. Geological Survey Maps of the area. Once the segments and their direction of evacuation had been identified and defined, the roadways were assigned parameters including length, number of lanes, radial distance, link, and possible intersecting segments. In addition, the USGS maps presented a complete picture of the transportation system enabling the network to be divided up into evacuation trees according to interacting segments. (See figures 3-7)

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evacuation time estimate calculated by CLEAR for a 10 mile radius EPZ the Beaver Valley Nuclear Power Plant is 235 minutes. The slowest tree which has tremendous demands placed on one major intersection estimate of 205 minutes (3 hours, 25 minutes) plus the 30 minute results in the overall evacuation time. Evacuation time for the other 17 trees range from 120 to 200 minutes.

calculated time estimates for an evacuation of two and five miles EPZ. The estimate for an area with a radius two miles around the is 145 minutes. Some zones in this area have evacuation time ranging from 120 to 125 minutes. The area of radius five miles Beaver Valley plant has an evacuation time estimate of 150 Other areas in the five mile radius have evacuation estimates from 120 to 140 minutes.

rding to the data most evacuation trees in the Beaver Valley EPZ tersections which cause a delay in the evacuation process. In two- the trees, however, the traffic delays at intersections or on small dissipated before the maximum departure time. In most of the zones, ion time is the sum of the notification time (30 minutes), the paration time (90 minutes), and the transportatio time (5-

Although queues developed and dissipated prior to the end of on time in a majority of the trees, they did increase evacuation to 125 minutes in one-third of the zones. (See Page 35)

The 10 mile - 360° EPZ evacuation time estimate calculated by CLEAR proved to be within 5% of that reported by Wilber Smith and Associates. The FEMA contractor estimated an evacuation time of 243 minutes for the Beaver Valley EPZ.

The CLEAR calculations were also compared to those prepared recently by the State of Pennsylvania in developing their own evacuation time estimates. The Pennsylvania Emergency Management Agency (PEMA) interviewed numerous local policemen and officials, State policemen, and State traffic engineers to determine the troublesome areas in the Beaver Valley EPZ. In addition, PEMA conducted onsite field studies to determine the evacuation rate. After equating several variables used to determine evacuation time estimates, PEMA and CLEAR time estimates also proved to be within 5%.

One assumed variable that originally differed between the PEMA calculations and the Battelle CLEAR evacuation times estimates was the number of vehicles per lane hour. According to calculations prepared by Tom Urbanik, a traffic engineer at the Texas Transportation Institute, approximately 1700 vehicles can pass over one lane routing within one hour. PEMA used an extremely conservative figure of 750 vehicles per lane hour. The 950 vehicles difference between the CLEAR figure and the Pennsylvania State figure resulted in the evacuation time estimates initially being significantly different. Upon adjusting for the vehicle flow, the Battelle CLEAR evacuation time estimates agreed within 5% of those developed by the Pennsylvania State Emergency Management Agency.

Other variables that potentially caused differences in the evacuation time estimates include the manner of inputting population, the pathways used in the road network, the function used to initiate vehicular movement, and the relative velocity of the travel on a road segment. The differences in vehicular movement resulted primarily from inaccurate resources available to the Battelle researchers to accurately identify the population in the zones. The total population used in all models, however, was within 10%. The input of road network pathways was an arbitrary decision, although it was calculated based upon the best information available.

The primary transportation network differences resulted from various interpretations of the U.S. Geological Survey map. There were, however, no serious omissions or differences in the road network input. One difference in the estimates centered on when vehicles would begin their movement on to the road networks. In contrast to the Battelle model, PEMA's effort lacked a notification and preparation time period. PEMA considered all populations leaving concurrently at time t=0 and, therefore, they did not stagger vehicle departure as did the Battelle CLEAR model. Similarily, the PEMA calculations held the velocity of travel on all roadways fixed at 35 miles per hour throughout the entire evacuation. This differed from the Battelle CLEAR model which used a function to constantly adjust the speed versus density relationship.

The Battelle CLEAR model identified correctly the two major intersections within the EPZ that caused significant delay. Based on their interviews with traffic engineers, the Pennsylvania State Emergency Management Agency reached the conclusion that these two intersections would be troublesome. During their evacuation calculation, they corroborated this theory by indicating that a significantly large number of vehicles would pass through these intersections and cause a serious delay. Although the Pennsylvania group was able to make these predictions, only the Battelle model was able to calculate the size and duration of the potential traffic holdups.

In comparison to the 243 minute evacuation time CLEAR calculated, the licensee reported a time estimate of 345 minutes. A lack of documentation prevents a detailed comparison of the results of CLEAR and Dusquesne Light[13]. One speculation as to the 102 minute time difference concerns the population being evacuated. If the licensee considered the evacuation incomplete until all hospitals had been evacuated from the EPZ, their final time estimate would be significantly higher than CLEAR. Since the hospital patients are the slowest evacuees, an evacuation time estimate dependent upon their departure will be much larger than that for the general public. Because the CLEAR time estimates are based on the general public or about 100% of the total EPZ population, it is not unrealistic for the CLEAR estimates to be lower.

While the evacuation time estimates calculated by CLEAR for Beaver Valley agree with the results reported by FEMA and the Pennsylvania Emergency Management Agency, further calculations were made to determine the significance of assumptions used in network evacuation models. In order to test the sensitivity of the evacuation time estimate to assumed preparation time, an evacuation time was calculated for the critical (235 minute) tree using maximum preparation times of 10, 40, and 90 minutes. The resulting evacuation times were 135, 135, and 235 minutes, respectively. An analyses of the assumed preparation times on the flow of traffic indicate the significance of vehicle density and traffic queues. The evacuation times for a maximum

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13 "An Analysis of Evacuation Time Estimates Around 52 Nuclear Power Plant Sites, Volume I," T. Urbanik, NUREG/CR 1956, December, 1980.

departure time of 10 and 40 minutes reflects the effectiveness of traffic queues in delaying traffic flow. It is apparent that although the maximum departure times differed by 30 minutes, the evacuation times were the same because the vehicles were delayed in preparation time in the one case and in traffic queues in the other. For the 235 minute evacuation, it would appear that vehicles were delayed in both the preparation stage and later in traffic queues. This trend would be quite significant if it were generally applicable to evacuation times for other EPZs.

The evacuation time estimates for some of the more heavily populated evacuation trees were calculated by using a random sample rather than the entire population. The conversion of CLEAR from a total population model to a random sample calculation is accomplished by changing the effective length of an evacuating vehicle. When the number of individuals per vehicle is enlarged beyond the actual figure, the same percentage increase of the effective vehicle length will have a cancelling effect. It is possible, therefore, to calculate the evacuation time estimate for the total population by analyzing a fractional random sample equal to the suggested persons per vehicle number divided by the actual number used. For the critical evacuation tree tested the evacuation time estimate did not change until the random sample was less than 16.67 percent or 1/6 of the total population.

The validation of the CLEAR code lies not only in its calculation of time estimates, but also in its ability to identify troublesome areas in the EPZ. The corroboration of CLEAR's results by Wilber Smith and Associates for FEMA and by the Pennsylvania Emergency Management Agency are testimony to the verification of the CLEAR model.

The CLEAR model is intended to be a realistic calculation of evacuation time estimates. While the licensees and others may be cautious and conservative in their estimation of evacuation times, the CLEAR code utilizes the most realistic hypothesizes in traffic simulation theory. The CLEAR time estimates may initially appear slightly less than others due to this realistic versus conservative approach.

It is important that the CLEAR model presents a realistic calculation of evacuation time estimates. The licensee of a plant may wish to present a conservative figure to the public to ensure that their time estimates would not be less than that actually occurring in the event of an evacuation. In terms of selecting alternative sites, reviewing existing plants, and estimating the consequences to an evacuating population, a realistic estimate is essential. An anology may be made to a source term release. While the licensee may present a higher, conservative figure to the public as to the amount released, it is better to take a realistic figure to calculate the actual effect on the population.

One advantage of the Battelle computer evacuation model is its ability to model an entire EPZ population or just a random sample. The tremendous benefit lies in its effectiveness on a small (<380 K words) computer. This means that the CLEAR model should be relatively inexpensive to run since it does not necessarily require large memory space.

CONCLUSIONS

While the CLEAR model has demonstrated its ability to calculate evacuation time estimates, the results have also shown that the assumptions on critical parameters have a significant effect on the estimates of evacuation times. Although the notification and preparation function incorporated in CLEAR simulates those outlined by FEMA, there still remain uncertainties surrounding these critical variables.[16] At present, because the notification and preparation times are much greater than the travel time, the accuracy of the evacuation estimates depend heavily on assumptions.

The Beaver Valley results reveal the need for more work to establish criteria for acceptable models. Until there is some uniformity in assumptions, comparisons of evacuation time estimates from different models is difficult. Some guidance is needed to determine appropriate values for vehicle speed at specific densities, the number of persons per vehicle, and notification and preparation times. Until this work is done, all evacuation models and calculations are largely dependent on the assumptions used.

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[16] NUREG-0654 Revision 1, Appendix 4, Page 4-14.