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AN EVACUATION MODEL FOR MAJOR ACCIDENTS

by

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1. BACKGROUND

This paper summarises an approach to modelling the behaviour of people following a release of either toxic or radioactive material. Studies were carried out for both the Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer (VROM), Netherlands, and HM Nuclear Installations Inspectorate, U.K. to investigate the potential for developing and applying models of evacuation behaviour.

The need for modelling arose in two contexts:

- Probabilistic risk assessment: the incorporation of behavioural mitigation of the effects of toxic releases into a computerised assessment package.
- Decision-making aid: the calculation of evacuation times around nuclear power plants in the unlikely event of a radioactive release.

Only the model for the latter context will be described here, but relevant data obtained for the PRA application is also described.

2. OUTLINE OF METHOD OF MODEL DEVELOPMENT

In both contexts the method of model development was similar:

1. Detailed literature search, including:
   - o Accident reports
   - o Descriptions of models of evacuation
   - o Behavioural research literature on warning systems, evacuation and disaster responses
   - o Data bases containing evacuation information
2. Qualitative and quantitative data extraction
3. Identification of the major components of the evacuation process, their relationships, and the variables affecting each stage
4. Structuring of data for use in modelling applications
5. Applications testing

3. THE TIME MODEL

After detailed examination of both the toxic and nuclear accident and evacuation literature a very simple time model was developed as shown in Figure 1. A definition of each stage is given below:

Decision Time: This starts from the moment a threat is identified and continues to the point at which it is considered serious enough to issue a warning.

Notification Time: Begins when the decision to evacuate is made and ends when the last member of the target population has been notified. Notification has the following components:

- Delay in issuing warnings
- Time taken to notify people
- Further information seeking

Preparation Time: This commences from the point at which notified individuals decide to evacuate and begin preparations for leaving. It ends when evacuation commences.

Evacuation (Movement) Time: This starts once the process of actually leaving occurs and includes the time to exit from the evacuation zone. It ends when the evacuating population have left this zone.

The notification, preparation and movement phases overlap. However, by adding notification time and preparation time the theoretical maximum time to get the entire population on the move is estimated.

It is very difficult to estimate the extent of overlap. For this reason calculations of the total time to clear the evacuation zone are based on two components:

- Lag time after the decision to evacuate when no-one is moving
- Evacuation time as defined above

This is demonstrated in Figure 2 below (note that decision time is not included in the estimate of lag time).

FIGURE 1 : AN EVACUATION MODEL.

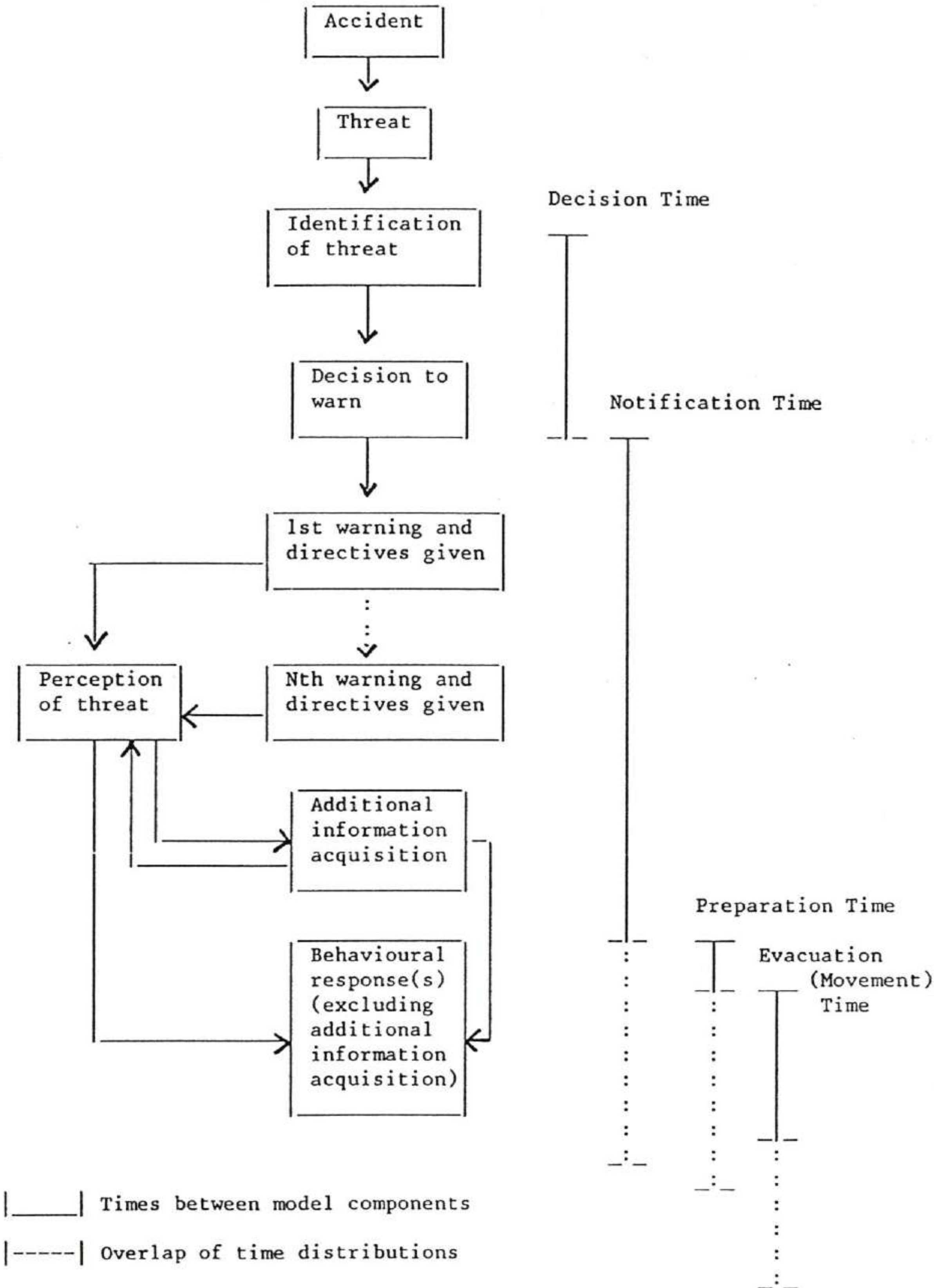
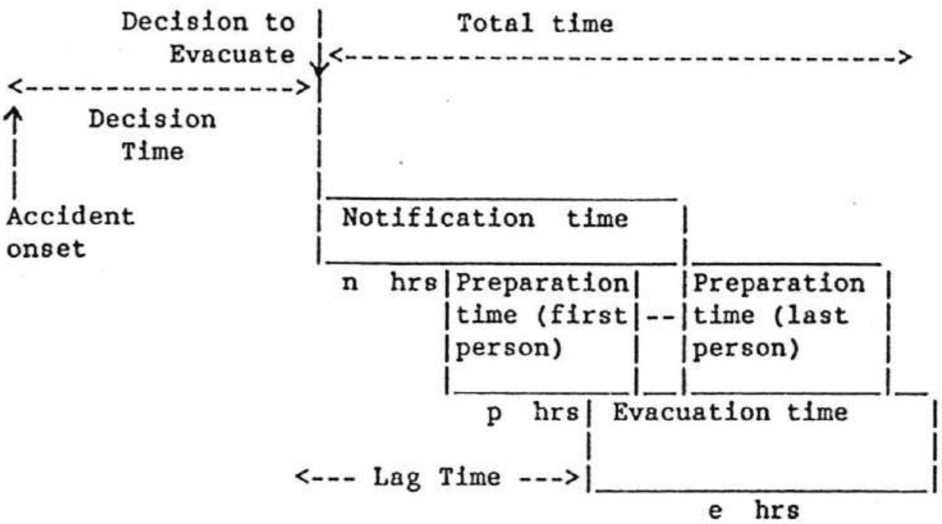


FIGURE 2 : OVERLAP BETWEEN DIFFERENT STAGES OF THE MODEL



Before describing the data used in the model and the way it can be applied, a brief resume of some of the characteristics of behaviour following toxic and nuclear accidents is given. Firstly, those variables which have been identified as having an effect on the time components are shown in Table 1.

TABLE 1 : TIME COMPONENTS AND THEIR VARIABLES

DECISION TIME	OFFICIAL NOTIFICATION & PUBLIC'S DECISION TIME	PREPARATION TIME	EVACUATION TIME
Threat characteristics/accident scenario Measurement resources	Warning media Warning content Sources of warnings Additional information acquisition Perception of threat (e.g. attitudes to nuclear power) Location of sectors of population Age characteristics of population	Children in family Location of members of household (together or not) Chosen destinations Instructions from authorities Intended mode of evacuation (e.g. official buses, private cars etc.) Work obligations (e.g. farm vs. home)	Availability of escape routes Resources for escape Resident and transient population numbers

4. BEHAVIOUR IN RESPONSE TO TOXIC INCIDENTS

The main characteristics of behaviour following toxic releases are summarised below:

4.1 Immediate Effect Zone

1. People close to the source of the release will almost certainly die if they are in the open air and directly in the path of the cloud. Running away will not be effective in high concentration clouds (see Figure 3).

2. Cars offer only short-lived protection

3. Buildings offer significant protection provided entry of vapours can be minimised. No deaths in buildings were identified.

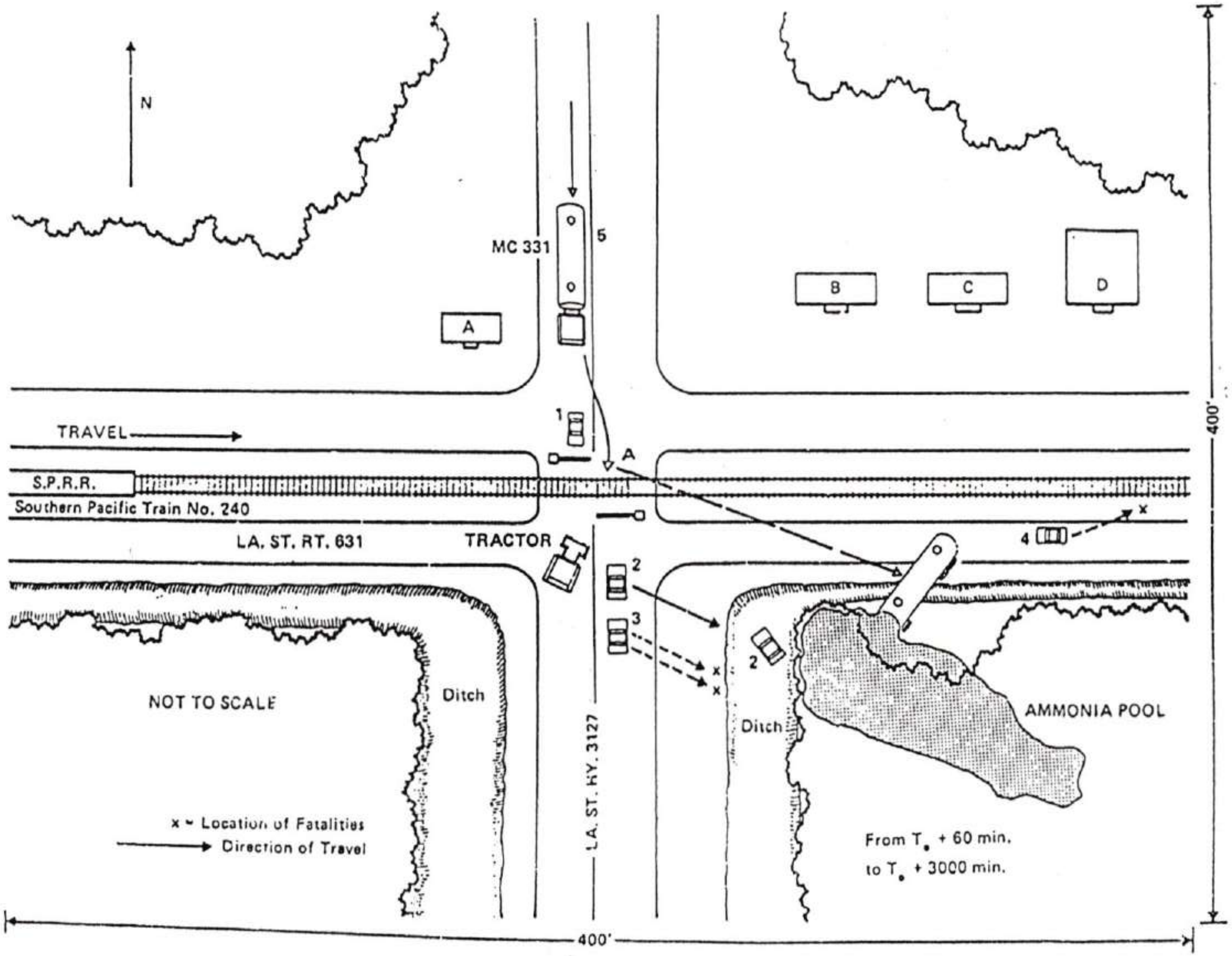


FIGURE 3 PATHS AND LOCATIONS OF FATALITIES IN THE BOUTTE, LOUISIANA AMMONIA ACCIDENT, 1978

4. The quickest and most effective warnings are provided by the incident itself.

5. The majority of people (80% estimate) in the immediate effect zone showed appropriate behaviour i.e. successful escape/mitigation.

6. No panic but some inappropriate behaviour such as leaving the safe haven of a building in order to use cars.

7. Official warnings are too late to help those in the immediate vicinity.

8. For US data, 15-30 minutes is about the minimum reported time for local emergency services to appear on the scene. In the UK, from the limited data available, this time appears to be shorter (an estimated 10 minutes from the accident being reported).

4.2 Distant Effect Zone

1. No deaths or injuries were identified in the distant effect zone.

2. A small percentage may evacuate before official warnings are given.

4.3 Evacuation Warnings

1. Official evacuation warnings occurred after a delay of 1.5 - 3.5 hrs (US data). 30 minutes was estimated for UK data.

2. The best official warnings in terms of initiating the appropriate response have the following characteristics:

   o Allow confirmation of threat (two-way communication)
   o Specify the danger, its imminence, and what to do about it
   o Are clear and unambiguous

4.4 Responses to Warnings

1. A response delay after receiving a warning is likely to occur due to:

   o Further information seeking (from media, police, neighbours, friends) which can result in jamming of communication lines
   o Preparation for evacuation (which may include waiting for official transportation)

2. People tend to behave as groups rather than individually. Also, families prefer to evacuate together.

3. The elderly are least likely to leave.

4. Non-evacuees varied between 2-74% of those warned, depending on the effectiveness of the warning system (a comparison of two incidents is shown in Figures 4 and 5).

5. If people have cars, they will tend to use them to evacuate.

5. BEHAVIOUR IN RESPONSE TO NUCLEAR ACCIDENTS

In many respects the behavioural response to nuclear accidents was similar to that of toxics. However, some important differences need to be highlighted:

5.1 Evacuation Warnings

1. At both the Three Mile Island (1979) and Chernobyl (1986) accidents there was considerable delay in deciding whether to issue warnings (11-52 hrs decision time estimate), particularly in comparison to toxics (typically 1 hr).

2. As well as official warnings, direct warnings from the accident itself is typical for toxics. For nuclear accidents the public is dependent on secondary warnings (word of mouth, official information).

5.2 Behavioural Response

1. While toxic accidents tend to result in an under-response of the threatened population following warnings, there appears to be a significant over-response in the event of a nuclear accident. This is referred to as the evacuation shadow phenomenon (Zeigler et al 1981). For example, the advisory at TMI indicated that 1% of the population in the 5 mile radius should leave, but 60% evacuated according to estimates. In addition, people were evacuating up to distances beyond 20 miles. A survey around the US Shoreham nuclear power plant, Long Island (Zeigler and Johnson 1984) showed that for a 5 mile advisory people up to 50 miles from the plant said they would evacuate.

2. Like toxics, a certain proportion of the population can be expected to stay (predominantly the elderly). It is difficult to estimate both the likelihood of this and the extent of the shadow phenomenon post-Chernobyl.

FIGURE 4 EVACUATION FROM A CONTINUOUS CHLORINE RELEASE AND THREATENED HCN RELEASE, FOLLOWING A WAREHOUSE FIRE IN OHBU JAPAN 1980

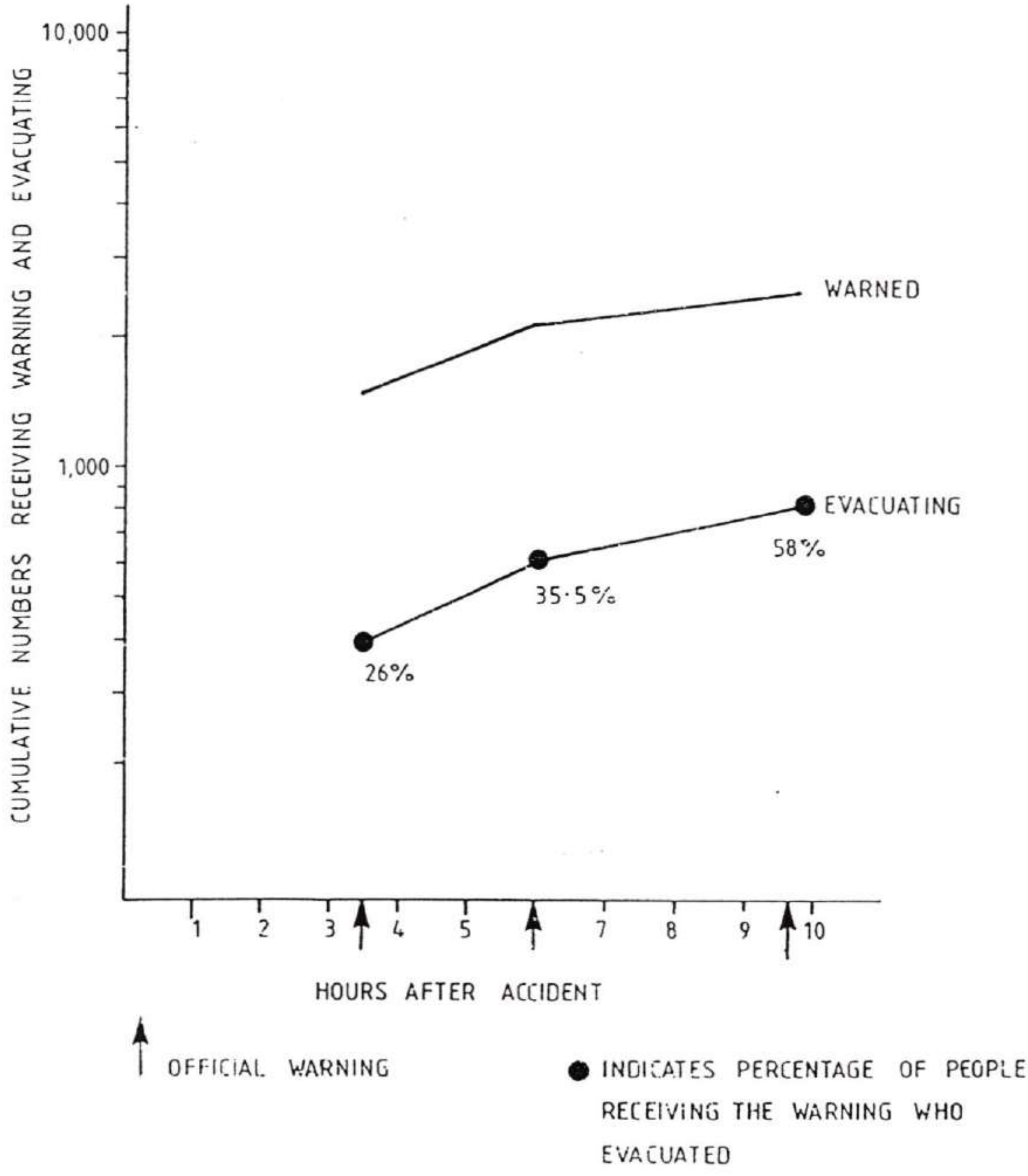
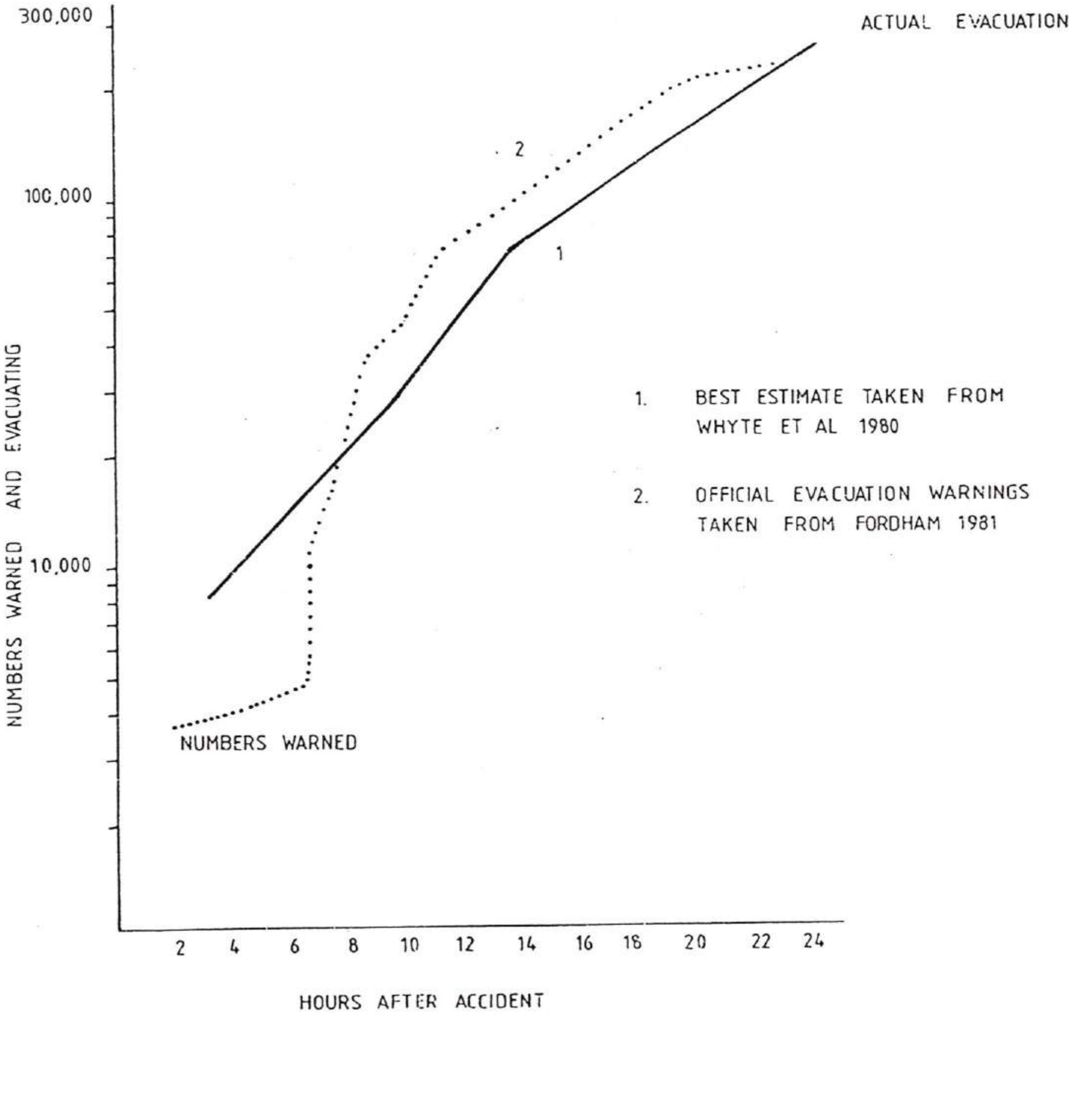


FIGURE 5 EVACUATION FROM AN INSTANTANEOUS CHLORINE RELEASE CAUSED BY A BLEVE AT MISSISSAUGA, CANADA 1979



6. EVALUATING EVACUATION (MOVEMENT) TIME

6.1 The Rates Equation

In estimating the time taken for a population to actually move out of an evacuation zone, a rate of evacuation was calculated, which is derived from the data base compiled during the Technica studies.

Rates which form the basis for the equation were derived by calculating the time from people starting to move (after being warned), to the time that the total evacuating population had evacuated. For example, if 5,000 people had been evacuated in $2^1/_2$ hours then the rate will be 2,000 per hour.

However, for some evacuations that were studied, it was not possible to calculate the precise time from people first starting to move. In some cases, the time from first official warnings had to be taken as the start point for rate calculations. Also, where evacuation was carried out in stages, or where some sectors of the population may have been kept waiting for official transport to a safe haven, there would inevitably be some adding in of dead time.

The fact that larger numbers of people will not generally be evacuated all at once is therefore implicit in the data.

Once the evacuation itself has started, it appears that the rate is dependent on the numbers evacuating.

Using the data in Technica's toxic incidents evacuation data base, the available U.K. data points, and also the data for nuclear incidents the points were plotted of rate against number evacuated on a log-log scale. It should be noted that the axes were drawn in such a way as to imply that rate of evacuation is dependent on numbers evacuating. It is possible, however, that the rate reflects resource availability and that this is the limiting factor for the numbers evacuating. However, as the number evacuating is the known variable, we have taken the rate as the dependent variable. We also have no evidence that we should accept the alternative.

A line of best fit was drawn using all of these data together (see Figure 6) using the method of least squares. In order to highlight the spread in the data, $\pm$ 1 standard deviation from the mean line is shown. 68% of the data fall between these lines.

It should be noted that 75% of the data used in the rates graph involved evacuating populations of less than 9000 people, and that little data exist for very large population evacuations.

Evacuation Rate is then given by:

$$y = 14.12\ (x)^{0.5}, \text{ where;}$$

x = the numbers to be evacuated
y = the evacuation rate (numbers per hour).

The values for + 1 S.D. are:

$$y = 30.49\ (x)^{0.5}$$

and for - 1 S.D.

$$y = 6.54\ (x)^{0.5}$$

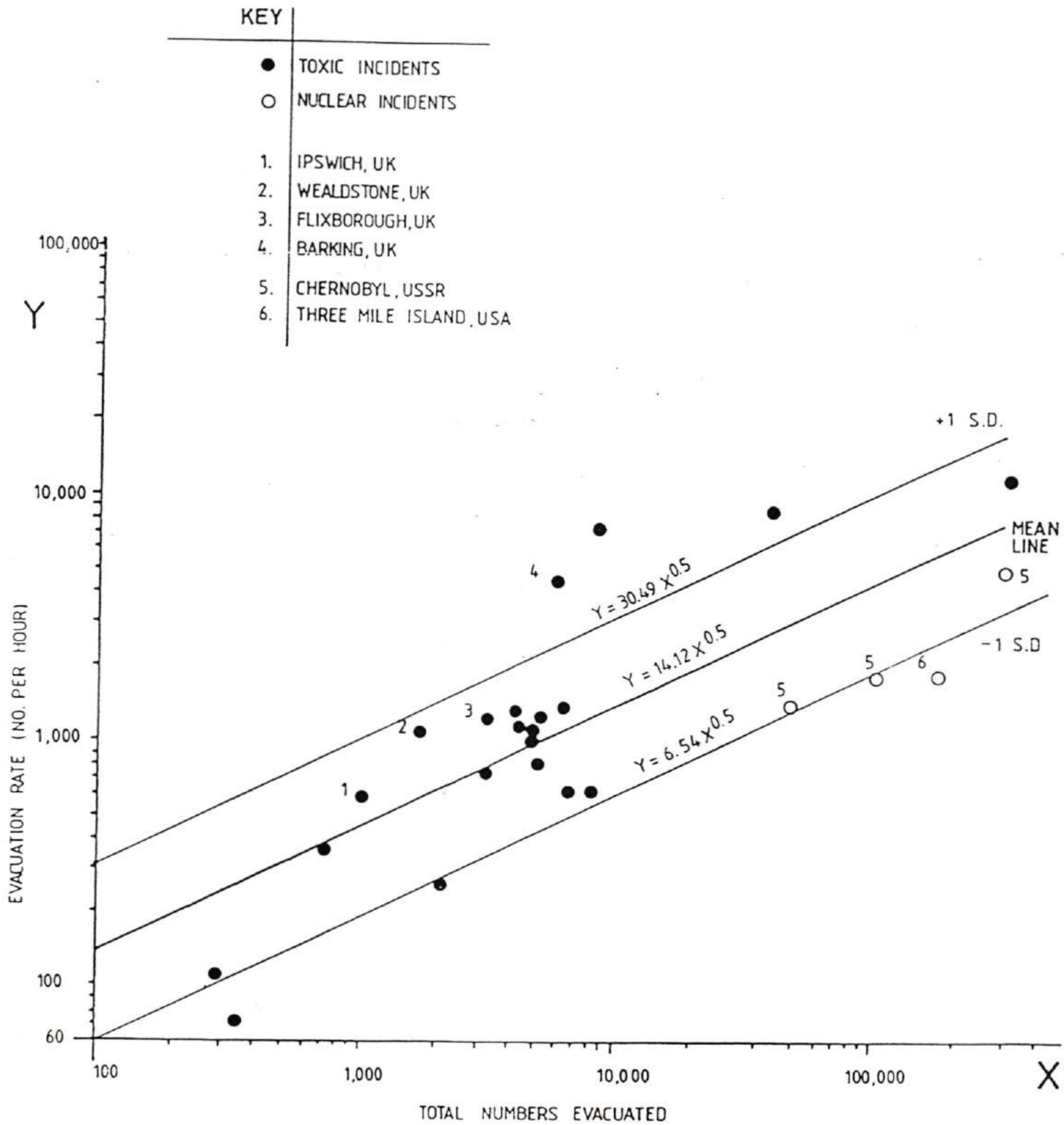
Note also that for 84% of evacuations, movement times will be slower than those given by the +1 standard deviation line and faster than those given by the -1 standard deviation line. This + 1 S.D. line, then, gives an indication of the fastest rate for the majority of evacuations, based on the data used in the rates graph.

6.2 Escape Route Networks

A calculated evacuation rate can be compared to road capacities, where such data are available, to estimate if such a rate is tolerable. Potential bottlenecks may be a problem, but apart from this it is the population numbers and flow rates that are important. Where it is assumed that the escape routes for evacuation are controlled, it is not necessary, according to the assumptions of the model, to consider time of day (e.g. rush hour traffic) or holiday makers travelling on major routes, for example. Both are also taken care of in calculations of transient and permanent population numbers.

In a more complex model, where more detailed information is needed, computer simulation of the use of escape routes may be desirable.

FIGURE 6 LINE OF BEST FIT THROUGH EVACUATION DATA POINTS



7. PROCEDURE FOR TIME CALCULATIONS

The procedure by which the time estimates are made is documented in the steps outlined below:

1. Divide area around site into sectors and radii of interest.

   Note that it is usual to divide an area into 30° sectors for the purposes of emergency planning. Although one would not expect a plume spread of 90°, we consider that quadrants are more appropriate for modelling nuclear accidents due to the evacuation shadow phenomenon.

2. Determine permanent population numbers for each sector and radius.

3. Determine transient population numbers from information provided and/or by examining maps for the locations of tourist attractions and factoring up the permanent population numbers.

4. Add permanent and transient population numbers for each sector and radius. This gives the values of x to be inserted into the rates equation.

5. Make an estimate of any delay that might be expected after the decision to warn the population and before notification actually begins.

6. Evaluate notification time for each sector and radius.

   Note that the availability of actual data is limited here. For the UK we would assume that beyond any zone where an emergency plan exists the main method of notification would be by the media. Otherwise we assume the use of tannoys, sirens and door-to-door knocking. A rough guide is shown in Table 2 for 90° sectors:

TABLE 2 : SCALE FOR ESTIMATING NOTIFICATION TIMES FOR 90° SECTORS

RADIUS	TIME TO COMPLETE NOTIFICATION (hrs)
1/2 mile	2 hours
2 miles	3 hours
5 miles	4 hours
10 miles	6 hours
15 miles	7 hours
20 miles	8 hours

7. Evaluate preparation time for each sector and radius.

Again, the availability of real data is limited and highly dependent upon the length of time of effect, imminence of threat and any necessity for shutting down farms, factories etc. Some gross estimates are shown in Table 3.

TABLE 3 : SCALE FOR PREPARATION TIMES

TIMES (Hrs)	COMMENT
1	No farms and institutions
2	Family effect, no farms or institutions
3	Farms and/or institutions

8. Calculate evacuation rate using the rates equation and the population calculated in step 4. It may be necessary to adjust the population estimates to account for non-evacuees. This is more important when small scale evacuations are being evaluated.

The decision as to whether to use the mean or standard deviation lines will depend on the scenario. For UK toxic accidents it is recommended that the +1 S.D. line is used. Lack of UK data for nuclear accidents suggests use of the mean line unless otherwise indicated.

9. Divide the population number by the rate calculated in step 8 to obtain evacuation (movement) time estimates.

10. Evaluate the extent of overlap of the stages to obtain lag time. A range of 30-150 mins is considered appropriate, with 30 minutes being used for UK small scale evacuations (few hundred people) where emergency plans exist and the population is in imminent danger.

11. By adding notification time and preparation time the theoretical maximum time to get the entire population on the move is estimated.

12. Lag time plus evacuation (movement) time calculated from the rates equation gives the total time to clear the entire sector radius.

8. EXAMPLE CALCULATION

A hypothetical example is used to demonstrate the model. A map of the area showing the radii and sectors around an imaginary nuclear power plant is given in Figure 7. The coastline has many sandy beaches and offers considerable attractions to tourists in this and surrounding areas. Beyond 5 miles of the plant there are farming areas.

The shape of the coastline is such that the plant is sited on a promentary fed by a single A road. This feeds into a motorway. In making the time estimates the decision making phase was not considered. Delay after the decision to evacuate was estimated as negligible for this example.

An estimate of lag time was 2 hours for the 2 mile radius and beyond, and 1 hour for areas within $^1/_2$ mile because here an emergency plan exists. These lags would have been shorter if a toxic or flammable incidents were being considered.

The results are shown in Table 4. It can be seen that evacuation is predicted to take between 5-44 hours depending on quadrant and radius for a mean rate of evacuations.

Figure 7 : Map of Area Around a Hypothetical NPP Site

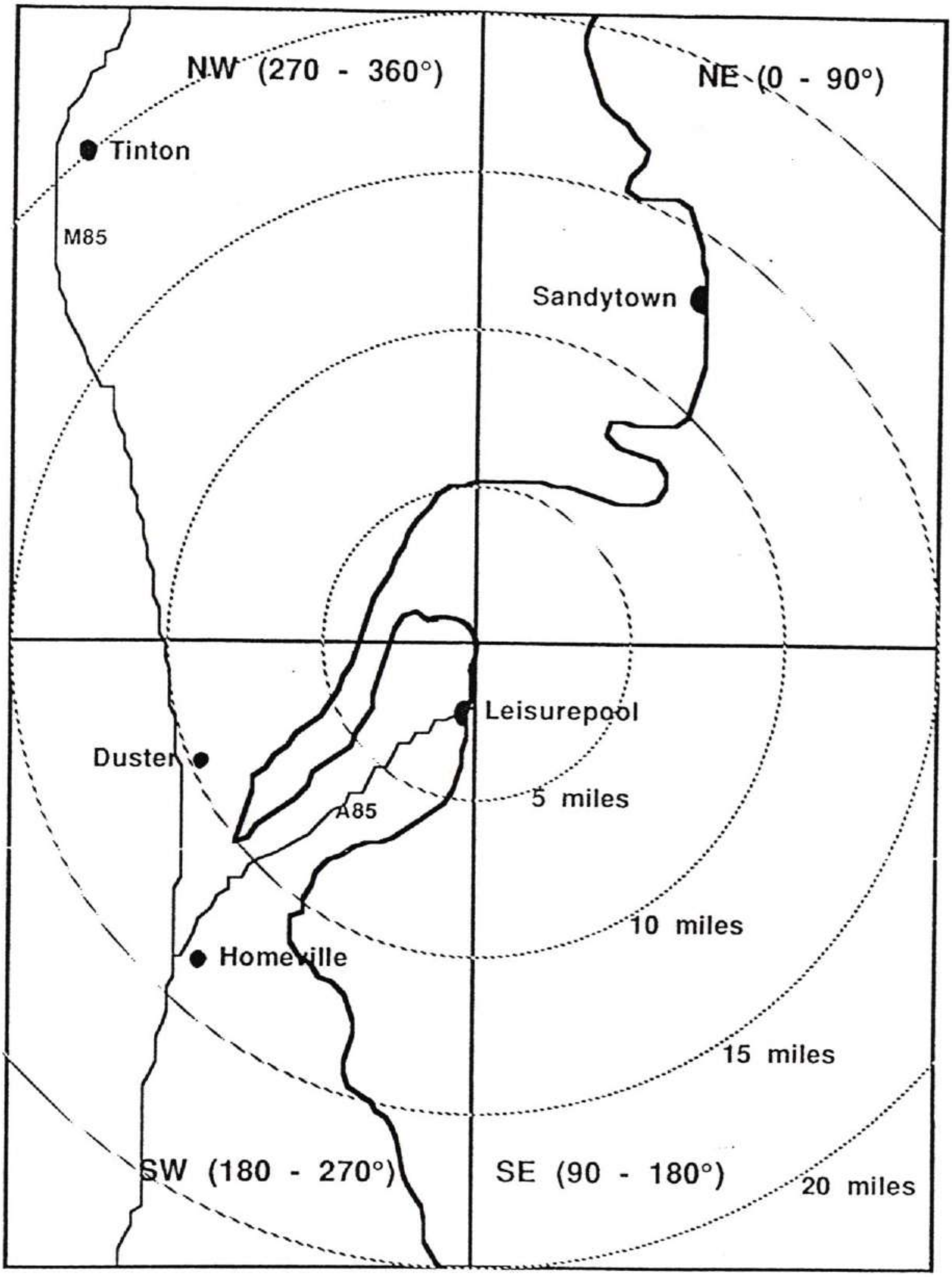


TABLE 4 : EVACUATION TIME ESTIMATES FOR LEISUREPOOL

QUADRANT (degrees from N)	DISTANCE (RADIUS)	PERMANENT POPULATION ESTIMATES	TRANSIENT POPULATION ESTIMATES	TOTAL POPULATION ESTIMATES	MAX. TIME TO GET POPULATION ON THE MOVE: NOTIFICATION TIME (Hrs)		MAX. TIME TO GET POPULATION ON THE MOVE	LAG TIME DERIVED FROM OVERLAP (Hrs)	MOVEMENT TIME		AVERAGE TIME TO CLEAR ZONE
					DELAY AFTER DECISION TO EVACUATE	ISSUING WARNING TO 100% OF POPULATION	MAX. PREPARATION TIME (Hrs)		MEAN (Hrs)	RANGE (Hrs)	TOTAL EVACUATION TIME (Hrs) (LAG TIME + MEAN MOVEMENT TIME)
180-270 (SW)	1/2 mile		3075	3075	0	2	1	1	4	1- 5	5
	2 miles	5734	4625	10359	0	3	2	2	7	3-12	9
Duster, Homeville,	5 miles	54767	+ 25%	71200	0	4	3	2	19	8-39	21
Leisurepool	10 miles	98900	+ 10%	108790	0	6	3	2	23	11-50	25
	15 miles	118821	+ 10%	130703	0	7	3	2	26	12-55	28
	20 miles	127505	+ 10%	140256	0	8	3	2	26	12-59	28
270-360 (NW)	1/2 mile		3075	3075	0	2	1	1	4	1- 7	5
	2 miles	530	4625	5155	0	3	2	2	5	2- 8	7
Sparsley populated,	5 miles	2421	+200%	7263	0	4	3	2	6	2-10	8
but with edge of	10 miles	13133	+ 45%	19043	0	6	3	2	10	4-20	12
Tinton	15 miles	29063	+ 25%	36329	0	7	3	2	13	6-27	15
	20 miles	66417	+ 15%	76380	0	8	3	2	20	9-41	22
0-90 (NE)	1/2 mile				NOTHING BUT SEA						
	2 miles										
Sandytown area	5 miles										
	10 miles	22373	+ 20%	26848	0	4	3	2	12	5-24	14
	15 miles	153005	+100%	306606	0	7	3	2	39	14-65	41
	20 miles	232506	+ 50%	348759	0	8	3	2	42	17-77	44
90-180 (SE)	NOTHING BUT SEA										

Rates can then be compared with escape route capacity. The promentary should clearly be examined as this has only a single escape road. By estimating the population figures just for the promentary, within the 5 mile radius, a rate of evacuation can be calculated for this area. The population data for the SW and NW sectors were added and the value of 78,463 persons put into the mean rates equation. This gives an evacuation rate of 3955 persons per hour.

If we assume 2 persons per car, then the rate of evacuation is 1977 cars per hour. Say the flow rate capacity of the hypothetical A85 is 2500 cars per hour; by dividing the road capacity by the evacuation rate, then:

$$\frac{2500 \text{ cars/hr}}{1977 \text{ cars/hr}} = 1.3$$

In other words, the escape system is only just able to cope with the estimated evacuation rate.

Finally, if one uses the + 1 S.D. formula, an evacuation rate of 8541 persons/hr or 4270 cars per/hr is obtained. then:

$$\frac{\text{Road flow rate}}{\text{Evacuation rate}} = 0.6$$

Thus, the evacuation rate is no longer within the escape route capacity. This is a potential condition for panic, where people may feel unable to escape from what they perceive as a high threat situation.

9. SUMMARY

The model that has been presented is extremely simple in that it can be very easily applied to any evacuation scenario with few data requirements. In this way it can provide some feel for the time it will take to move very large populations - an area where there is little practical experience or data. The real data on which the model is based has allowed such extreme cases to be evaluated.

A benchmark exercise carried out for two small U.K. evacuations showed that the model performed well. In fact, only a few minutes difference was obtained between actual data and that estimated using the model.

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TWO DAY CONFERENCE

SASTERS &
ERGENC

12TH-13TH APRIL 1988 · REGENT CREST HOTEL, LONDON W1

CHAIRMEN

SPEAKERS

INTRODUCTION

The effect of Chernobyl will be felt for a long time to come and the risks to Society and the environment posed by advanced technologies has increased public awareness. Tragic recent events in a quite different context again underline the need for preparedness.

Proper emergency planning can mitigate the worst, or even contain it, when the unthinkable happens, but emergency control must be planned and tested if it is to be effective. Indeed the fact that such plans have been made and tested is one way in which local and other authorities can play an important part in reassuring the public about the hazards of large scale industry.

This conference invites experts in all the fields who together can provide essential information for those who will be called upon to help should disaster strike.

CONFERENCE PROGRAMME

Day 1

TUESDAY, 12th APRIL, 1988

Chairman: **H. Lewis,**
Hazardous Substances Division,
Branch A, Health & Safety Executive

09.00 *Registration and Coffee*

09.30 **HISTORICAL UPDATE OF MAJOR HAZARD LEGISLATION**
The presentation consists of the background showing how the British Government Agencies for health and safety and land use control have evolved a legal framework for the regulation of potential major hazards.
Speaker: **P. Morgan,**
Hazardous Installations Policy Unit,
Health & Safety Executive

10.15 **THE HISTORICAL EXPERIENCE**
Definitions of disaster. Sources of information. The frequencies of natural and human caused disasters both for the world and for the UK. Winds, floods, and earthquakes. Transport, entertainment, power generation and mining as sources of disasters and emergencies. The nine sorts of harm which may follow disasters. Criteria of severity of disasters. The organisation of response; some international comparisons.
†EL3*Speaker:* **Dr V. C. Marshall,**
Honorary Fellow, Schools of Industrial Technology, University of Bradford

11.00 *Coffee*

11.30 **CHERNOBYL AND AFTER**
The Chernobyl reactor is described in outline and the sequence of events presented for both on-site and off-site situations. The on-site situations include immediate fire fighting, control of the reactor fire, first aid, and ventilation. The off-site situations include dose assessment, evacuation, control of foodstuffs, command structure and communications. The problems faced by other countries are then discussed, together with the responses of International bodies.

Finally, an indication is given of the current state of international and UK views on the steps needed to limit radiation exposures following a major nuclear accident.
Speaker: **J. Dunster,**
Former Director of National Radiological Protection Board

12.15 *Pre-Luncheon Drinks and Luncheon*

14.00 **THE CHEMICAL SCENE: WHAT CAN GO WRONG?**
The chemical scene to include the hydrocarbon fuel industries. Sources of information, including MHIDAS. Major Chemical Hazards primarily a problem of growth of scale. Discussion of the problems which arise from fires, explosions, and toxic releases including persistent toxic fall-out. Other MCH including water pollution. Particular problems of transport and of transit warehouses. The prediction of nature and level of casualties. Implications for emergency response arising from EEC requirements to inform the public and to generate on-site and off-site emergency plans.
Speaker: **Dr V. C. Marshall**

14.45 **EMERGENCY PLANNING: HOW BIG? HOW FAR?**
This paper discusses the information needed to formulate emergency plans and considers how far owners of hazardous materials should go in preparing for major (or minor) disasters and what information is needed by Emergency Services and Local Authorities.
Speaker: **D. I. Matthews,**
HM Principal Specialist Inspector (Chemicals), London & Home Counties North Field Consultant Group, Health & Safety Executive

15.30 *Tea*

16.00 **EMERGENCY RESPONSE INFORMATION FOR THE PUBLIC EMERGENCY SERVICES**
Recent changes to legislation regarding the packaging and labelling of transported chemicals has improved the information available to the emergency services when dealing with chemical incidents. However, there are still many cases where the information is not carried with the chemicals. The National Chemical Emergency Centre holds an extensive library of chemical hazard information and can use its computerised information retrieval systems to aid the Services in these situations.
Speaker: **D. S. King,**
CHEMDATA Manager, National Chemical Emergency Centre, UKAEA