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SAFETY AND RELIABILITY DIRECTORATE

A METHOD FOR THE SITE-SPECIFIC ASSESSMENT OF AIRCRAFT CRASH HAZARDS

T. M. Roberts

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UNITED KINGDOM ATOMIC ENERGY AUTHORITY
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WA3 4NE

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A method for the site-specific assessment of aircraft crash hazards

by

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SUMMARY

The report describes the background of, and reasons for, the study of aircraft crash hazards. Two separate methods for the assessment of the hazard at any given site are presented and a discussion of each method's applications and assumptions is also given. These separate methods could be used for independent assessments of the hazard at a given site, or one particular method may be chosen where the availability of data lends itself to that specific approach.

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1. INTRODUCTION

Most aircraft crashes make news headlines. From the crop spraying aircraft which hits telephone lines and crashes into a farmer's field, to the large airliner which ploughs into a mountainside killing a few hundred people, crashes are considered newsworthy events and arouse general interest. Hence, the public is well aware that aircraft crash, but perhaps because of the low level of individual risk associated with air travel, the aircraft crash hazard is generally perceived to be acceptable, or at least as acceptable as the hazard posed by other rare events such as lightning strikes or floods.

To an operator of a nuclear power station (or any other potentially hazardous plant), the hazard posed by crashing aircraft might be termed 'low risk-high consequence'. When choosing a site for a new plant, aircraft crashes are considered, along with other types of extreme load/external hazards in the context of nuclear safety. In Britain a siting policy was produced early in the development of a commercial nuclear power programme which recommended that nuclear power stations should not be sited close to the direct path of runways.(1) Within ten years legislation had been enacted that prohibited or otherwise restricted flying activity near certain nuclear installations.(2)

The position of the non-nuclear industries with respect to concern over aircraft crash was expressed by the Health and Safety Executive (HSE) in the 1985 CIMAH guide, where in Para 113 appears the statement "A safety case may also perhaps say that the risk of an aircraft crashing on the installation is insignificant in comparison with other causes of a major accident, because the site is well separated from the nearest airport and air traffic lanes".(3)

Several countries have adopted the US frequency criterion of designing against aircraft crashes on installations where the frequency is greater than 10^{-7} per year, and then only design against the impacts of light aircraft (the most likely impacts in most places). Several European countries, however, design against aircraft crashes using a pre-defined and smoothed impulse model which is intended to represent the normal impact of a Phantom aircraft travelling at flight speed.

The three principal damage modes expected to dominate aircraft crashes are:-

(1) direct impact leading to penetration or perforation

(2) direct impact or near-misses leading to intense induced vibrations

(3) direct impact or near-misses leading to fuel fires and detonations.

These damage modes and their relative importance clearly depend upon the specific details of the impact, and upon the type of structure and type of aircraft.

2. NATURE OF THE EFFECTS

It is important to decide at the start which events count as an aircraft crash. In the UK the Civil Aviation Authority (CAA) publish annually lists of all notifiable accidents involving British registered aircraft.(4) These include all incidents occurring between the times of boarding an aircraft and disembarking from it, which result in serious injury or death, or substantial damage to the aircraft (that which would seriously affect the ability of the aircraft to fly safely). Military aircraft accidents are divided by the MOD Inspectorate of Flight Safety into five categories. Category 4 accidents necessitate major repairs to an aircraft which normally cannot be carried out locally, and category 5 accidents are so severe that it is not worthwhile repairing the aircraft. Category 1, 2 and 3 accidents are less serious.

Having defined an aircraft accident, it is necessary to decide which sub-set of these events is relevant from the point of view of crashes onto an installation. For military aircraft crashing in the UK, it is reasonable to consider only category 4 and 5 flying accidents, and also to exclude from these accidents those where significant pilot control was indicated just before impact. This exclusion is a reflection of observed "pilot avoidance" as discussed further in Section 3.1.1 (v), and tends to remove about half the total number of category 4 and 5 accidents. For civil aircraft, the selection procedure, for the UK at least, must be performed 'manually' by sorting through all the CAA accidents reports individually. From the point of view of the manager of a nuclear power station, for example, station, for example, it might be reasonable to further exclude accidents incurred by aircraft performing specialised tasks, e.g. crop spraying (which accounts for 20% of notifiable accidents to light aircraft), grid inspections, flying displays, etc., since such activities would be unlikely to take place (and can be forbidden) close to such a station.

3. ASSESSMENT PRINCIPLES AND METHODS

Producing an accurate assessment of the aircraft crash frequency at a given site necessitates using the given data (which may often be sparse) to maximum effect. Only then will the method bring out any specific features of the local or regional environment which may produce a crash rate which is significantly different from a 'background' or 'average' rate. At the same time, the method must be sufficiently straightforward to allow some simplication (for example within the complex pattern of flying activity) without the introduction of significant inaccuracies, and not to require an excessive amount of site-specific data.

The principle employed at the Safety and Reliability Directorate (SRD) is that of using available information to calculate levels of aerial activity, and by using statistical reliability data and empirical correlations, estimate crash frequencies on the ground. This frequency is usually expressed in units of crashes/km^2/year.

SRD has been involved with making assessments of the aircraft crash hazard in the UK for over a decade, and during this period it has acquired data on usages and crash rates of aircraft. In the context of a site-specific assessment, these data can be considered generic in that they are believed to be characteristic of the UK generally. Maximum use is made of UK data, and these are supplemented as appropriate by overseas data. These generic data are shown in Table 1. The given units are activity-specific, i.e. in terms of crashes per movement, for take-off, landing or descent flight phases, and crashes per flight kilometre for the "in-flight" phase. Sections 3.1 and 3.2 discuss grouping and categorisation of aircraft. These groupings were chosen to optimise use of the available data in terms of accident rate and impact characteristics and are defined in Table 2.

Three impact characteristics, namely descent angle, velocity and mass are of importance in an aircraft hazard evaluation. The distribution of descent angles is needed to estimate the effective target area of the plant. The distribution of impact velocities and masses is needed to assess the structural consequences of a crash.

CEGB studies[5] indicated that the descent angle distribution for military aircraft accidents occurring more than five nautical miles from an airfield is bi-modal (Fig. 1). The mean descent angle is 48°. The distribution for light civil aircraft has not been studied, but it has been suggested for large civil aircraft that a broad range of descent angles is to be expected.[6]

Further work performed for the CEGB[7] suggests that for military aircraft the impact velocity is quite strongly correlated with impact angle, with velocities for low descent angle crashes being smaller than those for high angles. Civil aircraft crash velocities follow a broader distribution, with those for light aircraft lying in the range 50-150 ms^{-1}.[8]

Figure 2 shows the distribution of military aircraft crash masses, for those accidents involving aircraft with a mass greater than 2·3 tonnes. This distribution applied to accidents occurring away from airfields but within areas of intense aerial activity (AIAA) (see Section 3.1.1 (iv)), and may be compared with those distributions for light and heavy civil aircraft (Figs 3 and 4).

It is important to note the variation in uncertainties of the data quoted in Table 1, which is either due to the difficulty of obtaining data, or the small number of accidents from which accident rates can be deduced.

3.1 The PRANG code

PRANG is a computer code developed at SRD[9] to assist in the assessment of aircraft crash frequencies using the principles described above. It is based on the idea that the crash rate at any particular site is governed partly by specific features of the local and regional aviation environment, and partly by the national aviation environment which enables estimates of a national background crash rate to be made. A number of levels of assessment are therefore possible, starting at a "level 1", which corresponds to a nationally averaged crash rate, derived simply by assuming a uniform distribution of background crashes in time over the whole country, and proceeding through steps of increasing sophistication to a much more complicated process which can be applied to any site of particular concern. PRANG allows up to five levels of sophistication, as listed below:-

(i) Background crash rate only

(ii) (i) + airfield calculations

(iii) (ii) + airway calculations

(iv) (iii) + special flying zones

(v) (iv) + restricted flying zones.

Any of these levels can be chosen without necessarily involving any of the previous levels. The methods for dealing with each of these features are described later in this section. The categorisation of aircraft type mentioned in Table 1 is defined fully in Table 2. Each of these categories is treated separately and independently when calculations are performed, but a total crash rate in each cell is also produced.

To assess the crash probability at any given site, the site is first placed at the centre of an imaginary mesh which consists of a square of side 40 km (usually), made up of 1600 cells of side 1 km. Experience has shown that any feature of the aviation environment outside a mesh of this size is unlikely to have a significant effect on the calculation for a site located at its centre. Given the scale of the aviation features such as danger areas, airways, etc. generally encountered, the smallest justifiable cell is considered to be a 1 km square. The smallest scale features are the flying restrictions associated with built-up areas. The historical data relating to spatial distribution of crashes, which spans roughly the last quarter-century, could not be used to justify a cell this small, so it is clear that the probabilistic method used in PRANG for relating crash rates to levels and types of flying activity, allows assessment of aircraft rates on a more refined scale than would be possible by direct reference to historical data.

3.1.1 Present methods

(i) Background crash rate

There are few places in the world free from what might be termed a 'background crash rate'. Regardless of separation from airfields, airways or other active regions of air use, there will usually be a residual risk at a chosen site, for several reasons. For example, the 'area of influence' of an upper air route is not restricted to those regions lying directly below the air corridor since a mid-air incident can result in a ground impact some distance from the intended line of flight. The present version of PRANG thus assigns a background rate to all cells as a 'minimum' crash rate within that cell, before any other effects are considered. This background rate has been considered in previous studies[10,11] and the results are summarised in Table 3. The background rate is thus the nationally averaged crash rate due to aircraft crashes occurring away from the vicinity of particular concentrations of flying activity such as airfields, airways, etc. These factors are discussed in more detail later. It should be noted that the distribution of crashes in the UK does not support the view that mountainous regions are necessarily subject to higher than average crash rates per unit area, by virtue of the hostility of the aviation environment, although this may be due to the relatively lower levels of flying activity, especially of private aircraft, in such areas.

(ii) Airfields

According to available directories,[12] there are around 400 airfields in the UK, comprising 160 civil, 40 military and 200 privately owned airfields and helipads. As might be expected, the crash rate around most airfields is much greater than the background crash rate in the surrounding region, for two reasons. Firstly there is a much higher traffic density (in units of movements/volume/year) close to a runway, and secondly there is an increased risk during any flight associated with take-off and landing. Both of these factors would be expected to significantly increase the crash hazard around airfields, and this is borne out when historical data are studied.

Each runway of an airfield is expected to produce a lobal pattern of aircraft crash probability, although this pattern will take different forms depending on the aircraft type using the runway. Analysis of the correlations, developed in the UK and elsewhere[5,11,13-19] leads to the following probability distributions for fixed wing aircraft:

Commercial/military traffic

$$f(R, \theta) = A_1 \exp(-R/5) \exp(-36\,\theta/\pi) \qquad \ldots (1)$$

Light aircraft

$$f(R, \theta) = A_2 \exp(-R/2{\cdot}5) \exp(-3\,\theta/\pi) \qquad \ldots (2)$$

where $A_1 = 0{\cdot}23$, $A_2 = 0{\cdot}08$, R is the radial distance from the centre of the runway, in km, and θ is the angle in radians between the runway centreline and a vector parallel to R. The constants A_1, A_2 are normalising factors whose derivation is given in Appendix 1. Two distributions are calculable from the available data on near-airfield crashes, however, it is not possible to produce more aircraft-specific distributions. These formulae are not expected to apply close (say $\leqslant 0{\cdot}5$ nautical miles) to a runway, and studies are still being undertaken to establish distributions within this range.

Helicoptor take-off and landing accidents generally occur close to the helipad. Information from the CAA[20] supports this trend for civil helicopter accidents, and studies by SRD of historical data regarding category 4 and 5 military helicopter accidents have indicated that the impact position of the crashes associated with take-off or landing lie within 200 m of the helipad. Beyond this distance, normal in-flight accident rates apply. Within the 200 m zone, 93% of impacts were found to occur within 100 m of the helipad with the remaining 7% between 100-200 m. At present PRANG cannot deal with sites located closer than 200 m from a helipad. A separate treatment of the impact rate for helicopters is used for these regions. This method is described in Appendix 2.

(iii) **Airways**

The growth of aviation (there are now around three million aircraft movements (landings or take-offs) annually in the UK) has been accompanied by the growth of regulations intended to ensure a high standard of safety for all air traffic. This control of the airspace directly affects the pattern of flying activity and, hence, the distribution of aircraft crashes. A knowledge of the flight paths of aircraft overflying the areas of interest should, therefore, enable the development of empirical methods of calculation for crash rates on the ground due to these airways. Figure 5 indicates the extent of these airways in UK airspace.

German reactor safety studies assume that for typical airways in German airspace, the crash distribution on the ground on either side of the airway centreline could be described by a normal distribution with a standard deviation about the centreline of 9 km.[21] This figure purports to allow for the deviations in-flight path which do occur, whether intentional or accidental. The standard United States Nuclear Regulatory Commission (USNRC) treatment for less heavily used airways (around 35000 annual movements) is to use the airway width W together with the site's distance away from the airway edge E, to obtain the aircraft crash rate using:[18,19]

$$P = \frac{\alpha N}{W + 2E} \quad (E \geqslant 0) \qquad \ldots (3)$$

$$P = \frac{\alpha N}{W} \quad (E \leqslant 0) \qquad \ldots (4)$$

where α is the Table 1 value of the crash rate per flight kilometre, N the annual airway movement, and P the crash rate per square kilometre. More detailed US studies show that crash trajectories from the flight path are the main reason for a distribution of crash locations.[15,22] These studies found an exponential fall-off rate on either side of an airway, with decay constants ranging from $1{\cdot}5\,km^{-1}$ (military aircraft and certain types of civil aircraft) to $3{\cdot}0\,km^{-1}$ for higher flying aircraft (commercial flights). Figure 6 compares the four airway fall-off rates described above for an airway of width 10 km. (Note that the relative frequency scales are not normalised which accounts for the apparent predominance of the USNRC curve.) It is clear that two types of distribution are present, and that these attach different weights to the near and far field rates.

In the UK, airways are typically 10 nautical miles wide, with traffic tending to be concentrated towards the centreline, and it is unusual for aircraft to fly outside airways. In this case, the normal distribution seems more realistic than the prescription recommended by the USNRC. At the same time, the simple exponential forms may be too narrow and their use could lead to underestimation of crash rates in some cases. One method might be to use the normal distribution with a 9 km standard deviation for wide airways, whilst a narrower distribution might be chosen for non-airway flight paths, which could be at relatively low altitudes.

The method chosen for implementation in PRANG is a blend of these two ideas; the standard deviation of the normal distribution for crashes below, and as a result of airways is set equal to the average flying height.

Branching and bending in the airways can be treated easily with PRANG. As a result of recent modification, any airway which starts and/or finishes within the grid can be represented, as well as ones passing straight through. Airways which have a change of course within the grid can also be modelled; the airway would then be modelled as two separate airways with the first ending and the second starting at the location of the bend. In the case of branching, e.g. where two airways merge into one, work by the CAA[24] suggests that the resultant airway can be successfully modelled as a single route carrying the total traffic of the two 'feeder' airways. The crash rate does not increase as a result of the bunching of aircraft.

(iv) Areas of intensive military flying

Throughout the UK there are many regions which may be termed 'special flying zones', within which it is likely that the crash rate will be significantly greater than the rate which would be calculated if the zone did not exist. In many instances, the increased rate is due to military manoeuvres, such as pilot training, low flying practice, etc. These areas are termed 'areas of intense air activity' (AIAA), and occupy well-defined portions of airspace. The distribution of AIAA's in the UK is given in Fig. 7. Further evidence of their effect is available from studying crash locations of military aircraft in the UK, which show, in most cases, clear concentrations under AIAA's (although it would not be true to say that military training takes place entirely within these areas). In the US, recognition has been given to the potential influence of military training activities on aircraft crash rates, particularly when these involve intensive low level training or practice bombing.[19,24] A relatively simple method has been proposed for the assessment of military aircraft crash rates not in AIAAs within the UK, with particular reference to Sizewell in East Anglia.[5] This method approximates the areas as having the independently calculated background crash rate outside them, and an increased crash rate within them, with no graduation between the two rates. The proposed increase in crash rate is effective only for military combat aircraft although the rates for other aircraft are altered slightly (Table 2). Using PRANG, the procedure is to calculate the crash rate for each cell in the mesh as influenced by airfields, airways, etc. and then if the cell is contained within an AIAA, the calculated rate is increased according to the figures in Table 2.

(v) Restricted flying zones

It is very difficult to quantify the effect on the ground impact rate that the imposition of a restriction or prohibition of flying in the area concerned might have.[5,22] Certainly such prohibitions do result in a dramatic reduction in flying activity and, although the requirements may be difficult to enforce, incursions into such zones are infrequent. However, prohibited or restricted zones are sometimes only sufficiently extensive to influence flying patterns (and hence crash rates) of low-flying aircraft. It has been judged that a prohibition on local low-flying leads to a reduction in crash rates of ten times for military aircraft crashing at low impact angles.[5]

For higher impact angle crashes, this effect is less well understood. In PRANG the chosen method is to calculate the crash rate in a cell of interest due to all the effects mentioned above, and then multiply this rate for any cell corresponding to ground below a restricted or prohibited region, by a factor F_c. In this context, an urban area also corresponds to a restricted area. Flying over such built-up areas is governed by general flight rules which prohibit dangerous flying, low flying, flying closer than 500 ft. of any object on the ground, and flying within 1500 ft. of the highest fixed object in a built-up area.

There are several pieces of evidence which suggests that a value of 0·5 would be a reasonable estimate for F_c, i.e. that an average urban area in the UK is about half as likely to suffer an aircraft impact as an average rural area of equal size. Analysis of category 4 and 5 military air crashes has shown that in roughly 50% of non-airfield related crashes the pilot retains enough control of the aircraft to have some influence over the crash-landing site. These crashes are ones which result in severe damage to the aircraft and stem from failures such as loss of power. It does not seem realistic at this stage to use a value of F_c lower than 0·5 because it appears that about half the military aircraft crashes arise from causes which effectively prevent any pilot control. One would expect a very small percentage of these 'controlled' crashes to result in the impact of a structure. This is consistent with the views expressed by the CEGB in their submission on aircraft crash made in support of the Sizewell 'B' safety case.[5] For civil aircraft the screening process removes 'controlled' crashes, but flying activity for light aircraft which fly generally at low altitudes is reduced over built-up areas (because of the General Flight Rules) to roughly 50% of the average over other regions. In the case of airliners, F_c for en-route crashes should perhaps be closer to unity. However, screening will err on the conservative side for these very rare accidents so putting $F_c = 0 \cdot 5$ in these cases seems reasonable. In the US, a study by NASA[25] indicated that 42% of all severe impacts involving civil transport aircraft (covering a wide range of masses) occurred in an uncontrolled fashion. Investigation of the CAA annual reports regarding crashes of aircraft registered in Britain[4] revealed that in the period 1972-1982 there were 66 non-airfield related crashes, of which 48 occurred in rural areas, 3 in urban areas and the locations of the remaining 15 could not be determined from the reports. However, the fact that no mention of, for example, a building strike was made, implies that no impact was on to a building. Studies of the total percentage of urban land use in the UK[26] indicate that built-up areas occupy around 7·5% of the total for the whole of the UK, rising to around 10% if one includes only England and Wales. The distribution of airfields in the UK implies that the majority of flying (and hence crashing) in the UK takes place over England and Wales, so we would therefore expect to get about 10% of 66 = 6·6 crashes onto urban areas in this period of time. Since only 3 appear to have been recorded, this lends further weight to the case for using $F_c = 0 \cdot 5$. PRANG uses a default value of 0·5 for F_c; alternatively, one can set a different value if circumstances suggest such a modification. For example, there are regions of airspace where flying is prohibited for only part of the time, e.g. when an Army firing range is active, and unrestricted at other times. In such cases, it may be felt after due investigation that a value of $0 \cdot 5 \leqslant F_c \leqslant 1 \cdot 0$ would be more appropriate.

3.2 The PATH code

PATH is a computer code developed at SRD as an alternative method of calculating crash hazards.

In assessments where the considered site is very close to a well-defined flight path or air route (say within 2 km), the method of assessment employed in the code PATH can be used. This program calculates the crash rate of aircraft on to one or more specific target structures due to aircraft travelling along one or more flight paths. Each target structure is modelled as a cylinder with a given height and radius. For structures which are not actually cylinders, the 'target-area' presented to a given crash trajectory will be modelled by several cylinders whose geometry is tailored to give the best approximation for the trajectory being considered. The program therefore allows each structure to be modelled by up to 36 different cylinder combinations, each being applicable to a different range of views of the structure.

Each flight path is represented by a series of (x, y, z) co-ordinates, indicating the end position of up to 50 'steps' in the flight path. These steps need not be of equal length, for instance they may be reduced in size to more accurately model a bend in the path. At each stage along the flight path, it is assumed that the aircraft's velocity vector is directed towards the next co-ordinate point. The code allows up to ten separate flight paths, and up to ten different aircraft types on each flight path. These types can be assigned different reliabilities, glide angles, etc. For each aircraft type, two quantities are required:-

(1) *Minimum glide angle (MGA)* – the smallest angle to the horizontal at which the aircraft can glide, measured in radians. It is assumed that after a failure the aircraft falls downwards at an angle between the minimum glide angle and $\pi/2$, with all descent angles having equal probability.

(2) *Maximum angular deviation (MAD)* – the largest angle measured in radians to the left or right by which the aircraft could deviate from its intended line-of-flight. A triangular probability distribution has been assigned to the angular deviation, i.e. the probability of a certain angular deviation from the line-of-flight decreases linearly with increasing angle of deviation, reaching zero at the maximum angular deviation. For example, if the crash probability is α along the line-of-flight, and the maximum angular deviation is A_{max}, an angular deviation of A will have a probability

$$\frac{\alpha\,(A_{max} - A)}{A_{max}}$$

The stages of calculation for PATH can be summarised as follows:-

(1) The X, Y, Z distances between the target and the current point on the flight path are calculated.

(2) The compass bearing of the target from the current point on the flight path is calculated. From this bearing the appropriate values of target height and radius are taken from the input data.

(3) The compass bearing of the direction of flight of the aircraft is calculated.

(4) If the difference between these two angles is greater than the MAD there is no danger to the target from this point on the flight path, and the following calculations are omitted.

(5) The maximum horizontal glide distance (MGD) of the aircraft is calculated.

(6) If this distance is greater than the horizontal distance from the current point on the flight path to the target, the following calculations are omitted, since this implies that the aircraft could not reach the target.

(7) The area of the sector of ground on to which the aircraft could crash is calculated. This will be equal to

$$(MGD)^2 \times (MAD)$$

where MAD is expressed in radians.

(8) The vertical angle between the aircraft and the target is calculated, and from this the 'shadow' area of the target is deduced. This is the area of ground effectively shielded from the aircraft by the target.

(9) The ratio of the shadow area of the target to the sector area calculated in step (7) is taken. This is used as the 'base' probability of hitting the target, assuming that a failure occurs at this point on the flight path.

(10) The angle between the bearing of the target and the direction of flight is calculated (DT). A factor f can then be calculated using

$$f = \frac{A_{max} - (DT)}{A_{max}}$$

by which the base probability is multiplied, to account for the triangular distribution of angular deviation. This probability is then summed over all points on the flight path, and over all flight paths.

The end result is the probability that the target will be hit, assuming that a failure occurs at some point along the flight path(s). This is converted into an annual probability by multiplying the probability of a failure occurring per flight, and by the annual number of flights (for all aircraft types). One can then assess for a particular site, the probability per annum that one or more of its 'target' buildings will be struck by a crashing aircraft.

4. CONCLUSIONS AND RECOMMENDATIONS

The two methods described in this report and implemented in the SRD codes PRANG and PATH, enable the site specific assessment of the aircraft crash rate to be performed for any given location. Such an assessment involves consideration of the factors such as airfields, airways, danger areas, etc. which can produce a rate significantly different from the national background average. Once this has been done the body of information on aircraft reliability can be used to provide an estimate of the aircraft crash rate at the site. In most assessments, the PRANG and PATH methods could be used to provide independent evaluations of the crash rate; one providing a check on the other. PATH is most useful for sites close to airways or airfields (say $\leqslant$ 5 km) where precise details of air-routes are known, in terms of the bearings, altitudes and position of any turning points close to the site in question. This detailed information is rarely available, so PRANG is probably the more generally useful means of approach.

PRANG will be modified and improved many times in the future, both in its generic data and its approach to problems, to make it more straightforward and more precise. Data on aircraft reliabilities and background crash rates is always open to improvement. Aircraft types are continually being changed; one good example is the trend in military helicopters from single to twin-engineed aircraft, thereby vastly reducing the number of serious incidents caused by engine failure. The background rate throughout the UK must vary from place to place, and more detailed studies of historical data will provide information about this variation, and about the ground impact ratio below AIAA's, restricted areas, etc.

Studies are being performed at present into the pattern of crashes close ($\leqslant$ 1 km) to an air-field, a region which has so far not been studied. Also the consideration for sites very close to a helipad should soon be incorporated in PRANG.

The long-term aim for this program is for fully automatic use, where the user need only input the co-ordinates of the site for which the crash rate must be determined in order to be presented with tabulated results and contour maps of the crash rate around the chosen site.

5. APPENDIX 1

Normalisation of airfield distribution functions

Assume

$$f(r,\theta) = A \exp\left(-\frac{r}{\lambda}\right) \exp\left(\frac{\theta}{c}\right)$$

where

r		is the distance from the centre of the runway
θ		is the angle in radians between the runway centreline and a vector parallel to r
λ, c		are previously determined constants
$f(\theta,r)$	=	probability of the crash occurring between o and θ radians, and θ and r km from runway centreline.

Normalisation condition is

$$A \int_{-\pi}^{\pi} \int_{o}^{\infty} r^{-\frac{r}{\lambda}} e^{-\frac{\theta}{c}} \, d\theta \, dr = 1$$

$$\therefore \; 2A \int_{o}^{\pi} e^{-\frac{\theta}{c}} \, d\theta \int_{o}^{\infty} re^{-\frac{r}{\lambda}} \, dr = 1$$

The value of the normalisation constant A can be evaluated by integrating, hence

$$\int_{o}^{\infty} re^{-\frac{r}{\lambda}} \, dr = \left[-\lambda^2 e^{-\frac{r}{\lambda}}\left(1 + \frac{r}{\lambda}\right)\right]_{o}^{\infty}$$

$$= \lambda^2$$

and

$$\int_{o}^{\pi} e^{-\frac{\theta}{c}} \, d\theta = \left[-c\, e^{-\frac{\theta}{c}}\right]_{o}^{\pi}$$

$$= c\left[1 - e^{-\frac{\pi}{c}}\right]$$

$\therefore$ Normalisation constant A is given by

$$A = \frac{1}{2\lambda^2 c\left[1 - e^{-\frac{\pi}{c}}\right]}$$

6. APPENDIX 2

Method for calculating crash rate at near-helipad locations

Suppose we are concerned with a site which contains a helipad with n flights per year, and we wish to calculate the hazard posed to plant situated closer than 200 m from the helipad. (Locations further than this will be treated as under an airway or part of the background since the effect from landing or take-off accidents is negligible at distances greater than 200 m.)

From Table 1 the take-off and landing crash rate is 4×10^{-5} crashes per movement.

From the figures given in the study mentioned in Section 3.1 (ii), a 'ground impact rate per km² per accident', R, can be calculated by assuming two zones within which the crash rate is spatially uniform. R is the percentage of impacts in the zone divided by the area of the zone.

Hence:

Zone 1 Between 0-100 m

$$R_1 = \frac{0 \cdot 93}{(0 \cdot 1)^2 \pi} = 29 \cdot 6\,\text{km}^{-2}$$

Zone 2 Between 100-200 m

$$R_2 = \frac{0 \cdot 07}{(0 \cdot 2^2 - 0 \cdot 1^2)\pi} = 0 \cdot 74\,\text{km}^{-2}$$

For such a site, therefore, the crash rates would be the ground impact rate multiplied by the number of movements, multiplied by the in-flight reliability.

(1) $R_1 \times 2n \times 4 \times 10^{-5} = 2 \cdot 4 \times 10^{-3}\, n\,\text{km}^{-2}\,\text{yr}^{-1}$

(2) $R_2 \times 2n \times 4 \times 10^{-5} = 6 \cdot 0 \times 10^{-5}\, n\,\text{km}^{-2}\,\text{yr}^{-1}$

At present, this crash rate is not implemented in PRANG. If required, it can be calculated by hand on a site-specific basis. The total crash rate around the helipad is then the sum of these calculated figures, and the crash rate calculated by PRANG in the cell containing the helipad.

7. APPENDIX 3

Definitions of terms used within the report and elsewhere

7.1 Airfield

Any place where landings and take-off of fixed wing aircraft regularly take place. In the case of helicopters, this area is termed a helipad.

7.2 Aerodrome Traffic Zone (ATZ)

The airspace extending from the surface to a height of 2000 ft. above the level of the aerodrome and within a distance of 1½ nautical miles of its boundaries, except any part of that airspace which is within the ATZ of another aerodrome which is notified as being the controlling aerodrome.

7.3 Military Aerodrome Traffic Zone (MATZ)

A region around a military airfield comprising

(a) The airspace within 5 nautical miles radius of the Aerodrome Reference Point, from the surface to 3000 ft. above the aerodrome level.

(b) The airspace within a 'stub' projected from the above airspace having a length of typically 5 nautical miles along its centre/line and width of typically 4 nautical miles, aligned with a selected approach path. The dimensions may vary in some cases.

It is likely that traffic in these zones will be more concentrated, but pilots entering a MATZ are requested to comply with instructions given by the controller at the aerodrome who may supply traffic information and any instructions necessary to achieve safe separation from known or observed traffic in the zone. There are about 50 MATZ's in the UK.

7.4 Special Rules Airspace (SRA)

A zone or area around an aerodrome within which pilots must comply with local flying rules enforceable only in the SRA. These usually include instructions to pilots to call air traffic control (ATC) and obtain permission to use the SRA and also to obey any subsequent instructions which they must listen for.

7.5 Military Training Area (MTA)

Areas established for the operational freedom of military aircraft engaged in exercises or training, the nature of which is incompatible with civil air traffic services procedures. Civil aircraft are now allowed to anticipate any route through MTA's, nor can ATC authorise such flights.

7.6 Danger Area

Air space which has been notified as that within which activities dangerous to the flight of aircraft may take place or exist at such times as may be notified.

7.7 Prohibited Area

An airspace of defined dimensions within which the flight of all aircraft is prohibited.

7.8 Restricted Area

An airspace of defined dimensions within which the flight of aircraft is restricted in accordance with certain specified conditions.

7.9 Bird Sanctuary

An airspace of defined dimensions within which large colonies of birds are known to breed. Pilots are requested to avoid these areas, especially during stated breeding seasons, and are warned of the high risk of bird strikes.

7.10 Areas of Intense Air Activity (AIAA)

An airspace within which military aircraft, singly or in combination with others, regularly participate in unusual maneouvres.

7.11 Airway

A corridor of airspace, commonly of order 10 nautical miles wide and 12 nautical miles altitude, used by civil traffic flying between fixed destinations.

8. NOMENCLATURE

A	normalisation constant for crash rate probability distribution around airfields.
A_{max}	largest angle by which an aircraft under accident conditions could deviate from its intended flight direction
α	crash rate per flight kilometre
DT	angle between the bearing of a point of interest and the direction of flight
E	distance of a site from the edge of an airway
F_c	factor by which the crash rate in a cell is multiplied to account for a restricted/danger area
$f(\theta,r)$	probability distribution function of aircraft crash around an airfield
h	annual number of movements at an airfield
N	annual number of movements along an airway
P	crash rate per square kilometre around an airway
R,r	distance between centre of runway and site under observation (km)
θ	angle between runway centre line and site under observation (radians) $o \rightarrow \pi$
W	width of an airway (km)

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TABLE 1

Estimated ranges of generic UK aircraft crash rates

Aircraft type	Flying activity		
	Take-off/Landing/Descent	In-flight	Special
Airliner/Military Transport	3×10^{-7} [11]	1×10^{-9} [27] 5×10^{-10}	–
All Helicopters	5×10^{-5} [28] 1×10^{-5}	7×10^{-7} [29] 1×10^{-7}	5×10^{-4} [20] 1×10^{-4}
Military Combat	2×10^{-6} [13] 5×10^{-7}	4×10^{-8} [24] 1×10^{-8}	2×10^{-6}+ [30] 5×10^{-7}+
Small Transport	3×10^{-6} [31,32] 1×10^{-6}	4×10^{-8} [14,15,21] 1×10^{-8}	–
Private Light	5×10^{-6} [31,32] 3×10^{-6}	2×10^{-7} [14,15,21] 5×10^{-8}	5×10^{-4} [20] 1×10^{-4}*

KEY

Lower number – lower bound estimate
Upper number – upper bound estimate
* Crop spraying
\+ Intensive training

Units: Take-off/Landing/Descent
– crashes per movement
Otherwise
– crashes per flight km

"Special" means types of activity not normally associated with the aircraft type (e.g. aerobatics) which can result in an increase in the crash rate per flight kilometre.

TABLE 2

Definition of aircraft types

1.	Light Civil Aircraft	fixed wing aircraft generally falling into the CAA classification of less than 2·3 te mass.
2.	Helicopters	all helicopters covering the mass range up to an effective maximum for the range of around 10 te, although heavier helicopters are used on some specific duties.
3.	Small Transport	fixed wing aircraft covering the CAA classification from 2·3 to 5·7 te mass, and also larger civil military transports such as the Skyvan, Heron, Jetstream, etc.
4.	Airliners and Military Transports	any other fixed wing aircraft not covered in types 1, 3 and 5.
5.	Military Combat and Trainers	all military fixed wing aircraft with masses up to some 40-50 te used for, or cable of, aerobatic style flying (i.e. not including type 3 or 4 aircraft).

TABLE 3

The background aircraft crash rate[10,11]

Units: km^{-2} yr^{-1}

Aircraft type	Rate x 10^5
Private light	3·0^{+}
All helicopters	1·0$^{\Delta}$
Small transport	0·1
Airliner/Military transport	0·5
Military combat	1·5*
	6·1

This corresponds to some 15 uncontrolled aircraft impacts annually in the UK in areas which are not especially prone to flying activities.

\+ can increase to 100 inside Low Flying Areas

* can increase to 7 inside Areas of Intense Military Flying

Δ for military helicopters inside Areas of Intense Aerial Activity, the crash rate is assumed to increase from that of the background by the same factor (7/1·5) as is indicated for Military Combat Aircraft

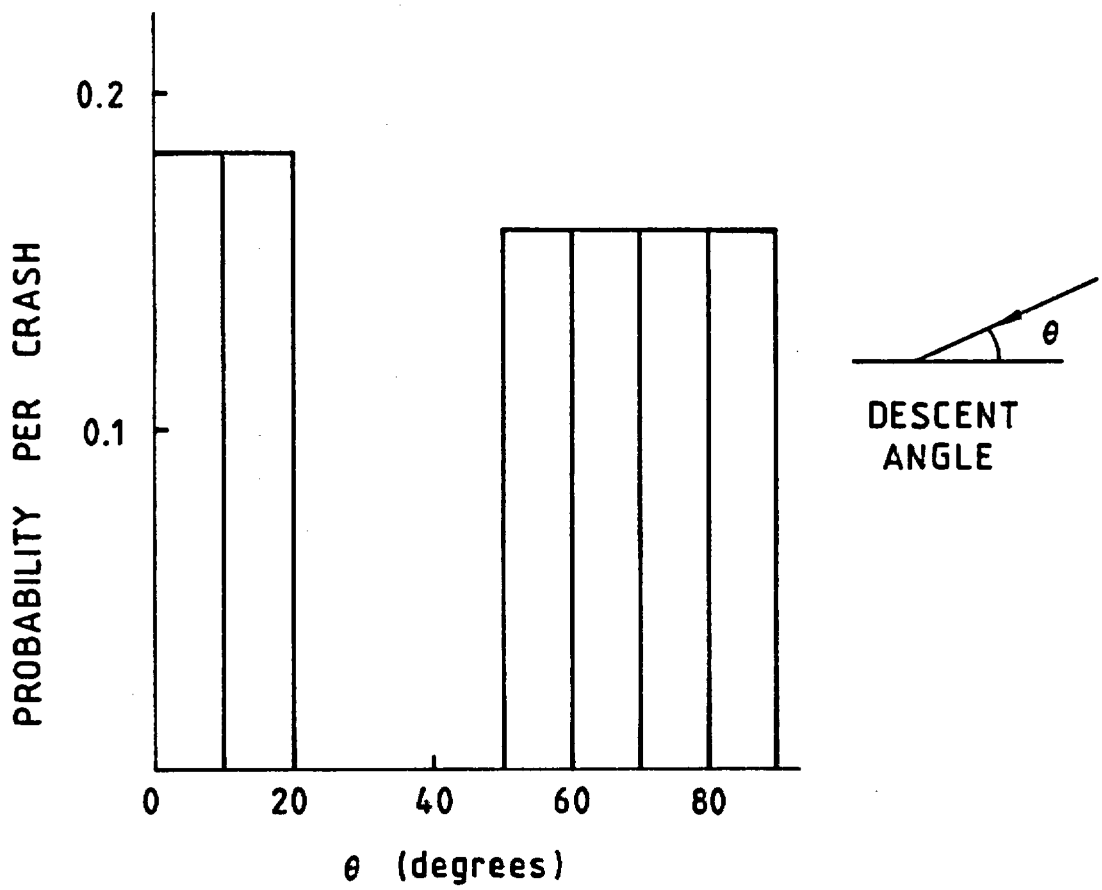

FIG.1 DESCENT ANGLE DISTRIBUTION FOR MILITARY AIRCRAFT CRASHES OCCURING AWAY FROM AIRFIELDS

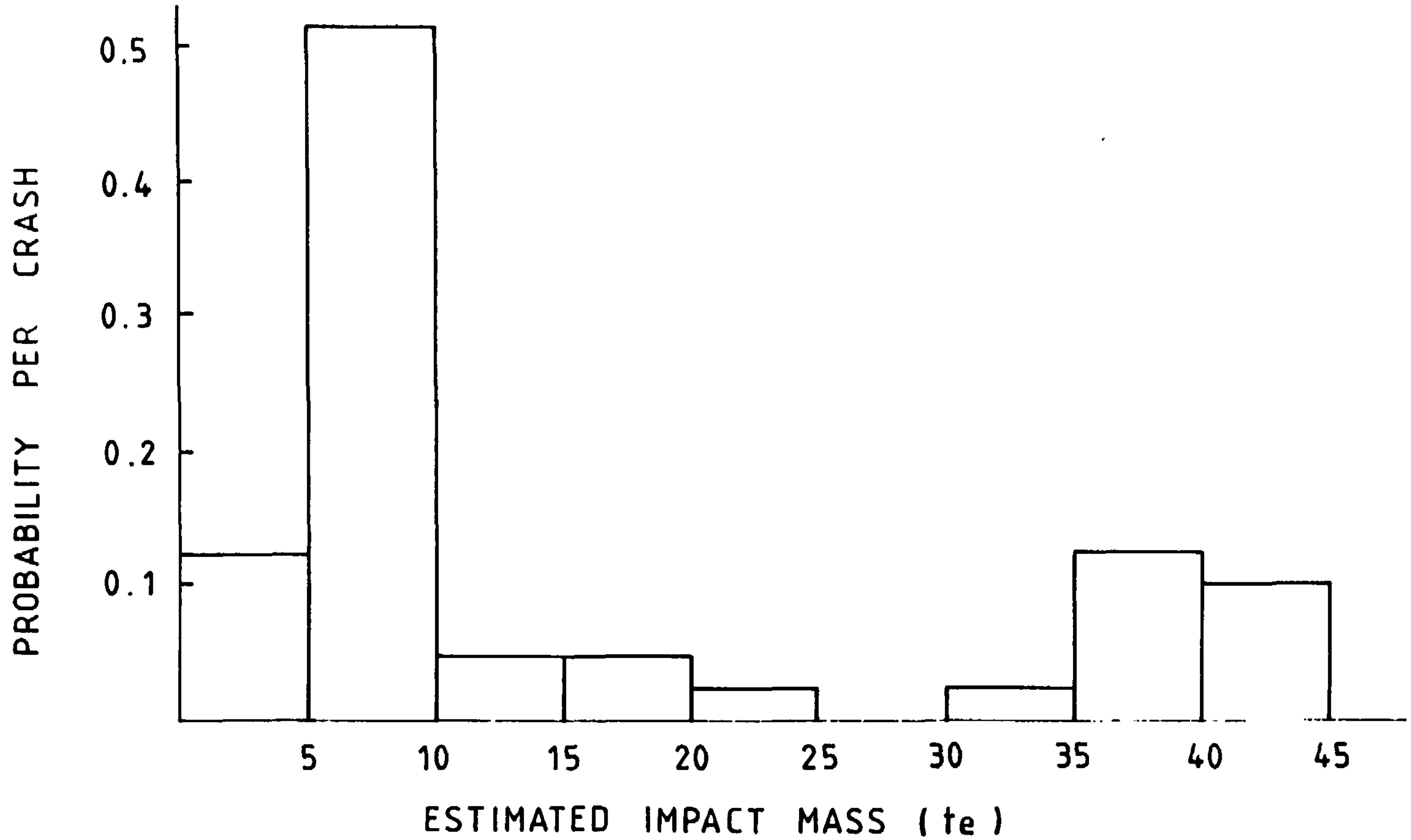

FIG. 2 IMPACT MASS DISTRIBUTION FOR AIAA MILITARY CRASHES NOT NEAR AIRFIELDS. 1978-1983 INCLUSIVE

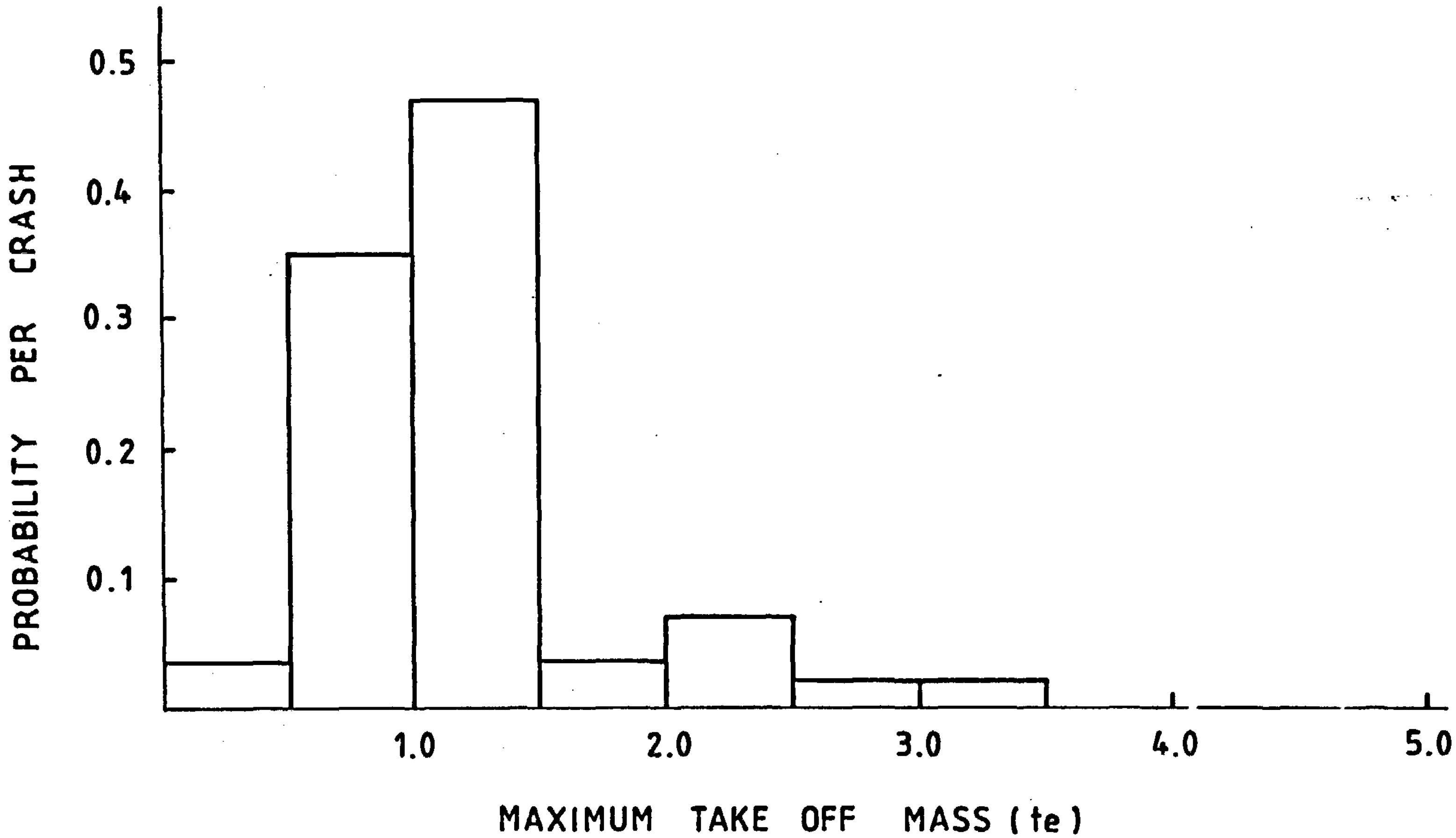

FIG. 3 IMPACT MASS DISTRIBUTION FOR THE 55 FIXED WING LIGHT (0-5.7 te) AIRCRAFT CRASHES INVOLVING EITHER LOSS OF CONTROL OR OCCUPANT FATALITY / SERIOUS INJURY IN THE UK IN 1976

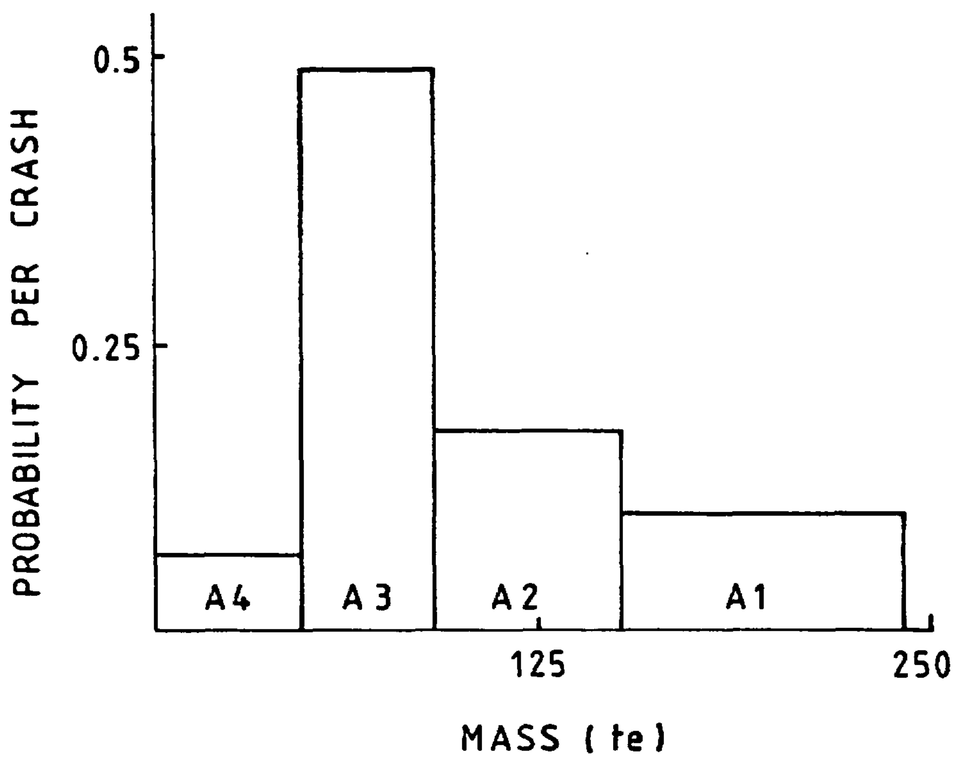

FIG.4 ESTIMATED DISTRIBUTION OF IMPACT MASSES OF LARGE CIVIL AIRCRAFT

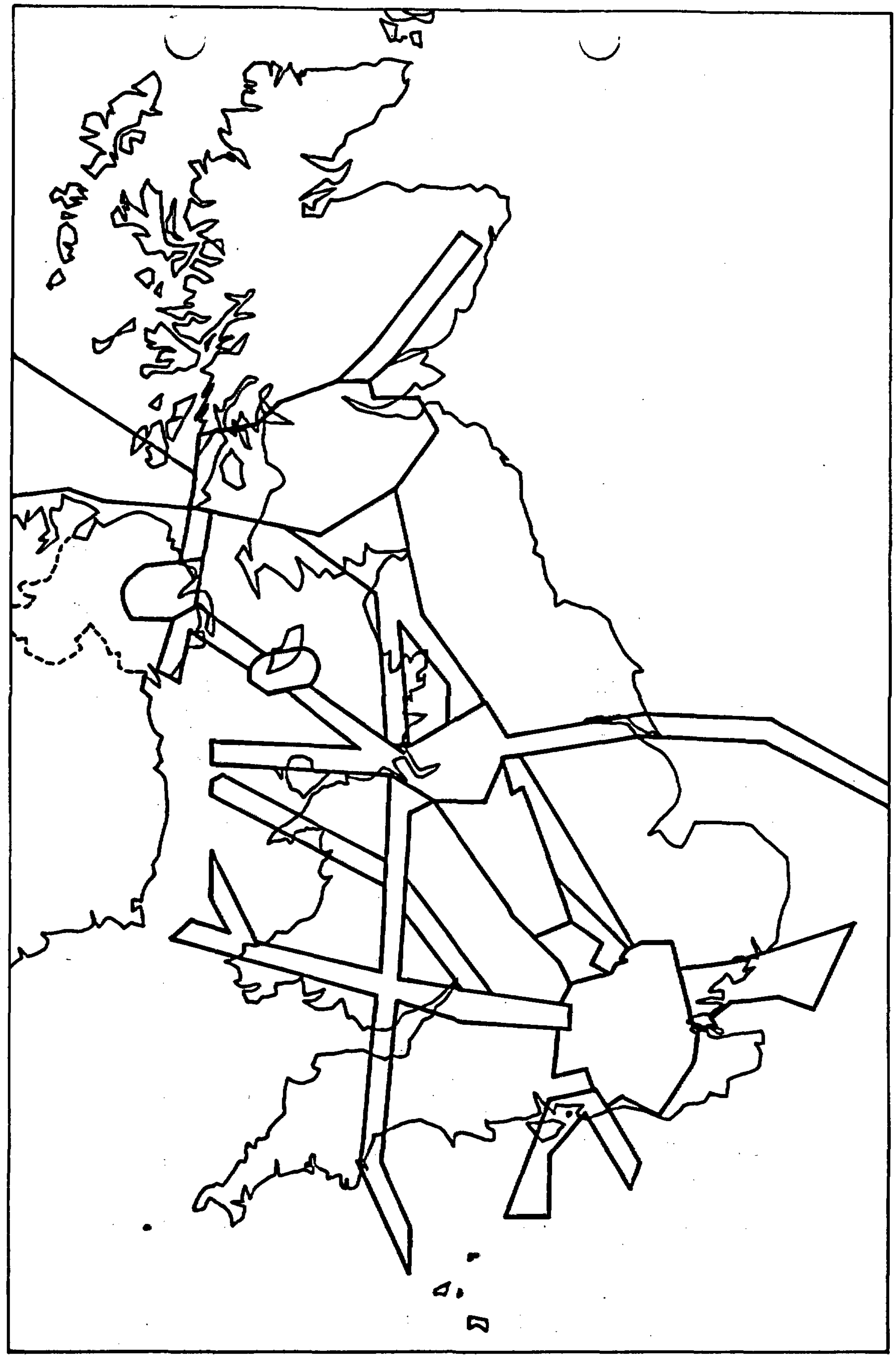

FIG. 5 UK CIVIL AIRWAY SYSTEM
(excluding upper air routes)

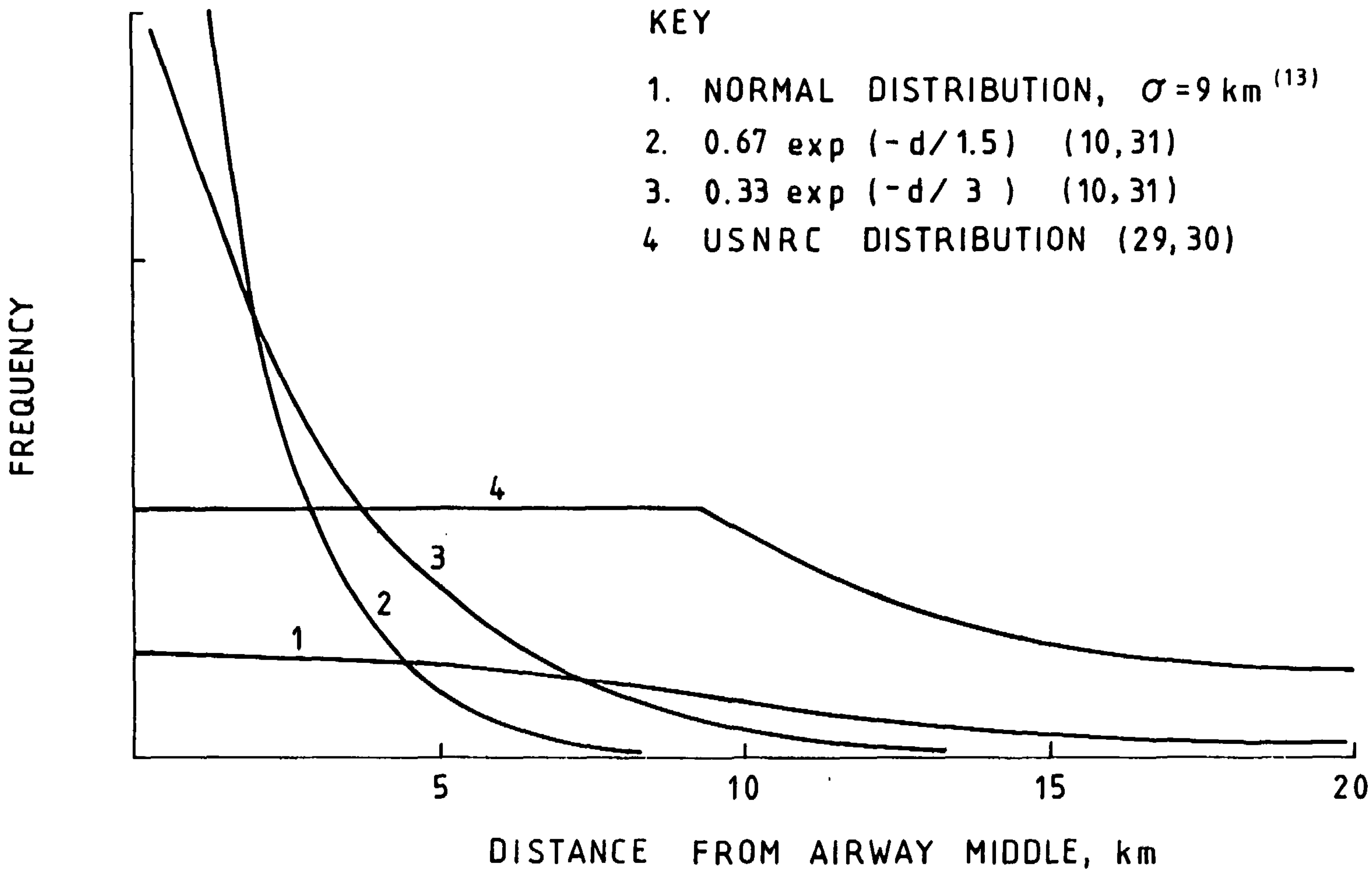

FIG.6 LATERAL DISTRIBUTION OF CRASHES NEAR A 10 km WIDE AIRWAY

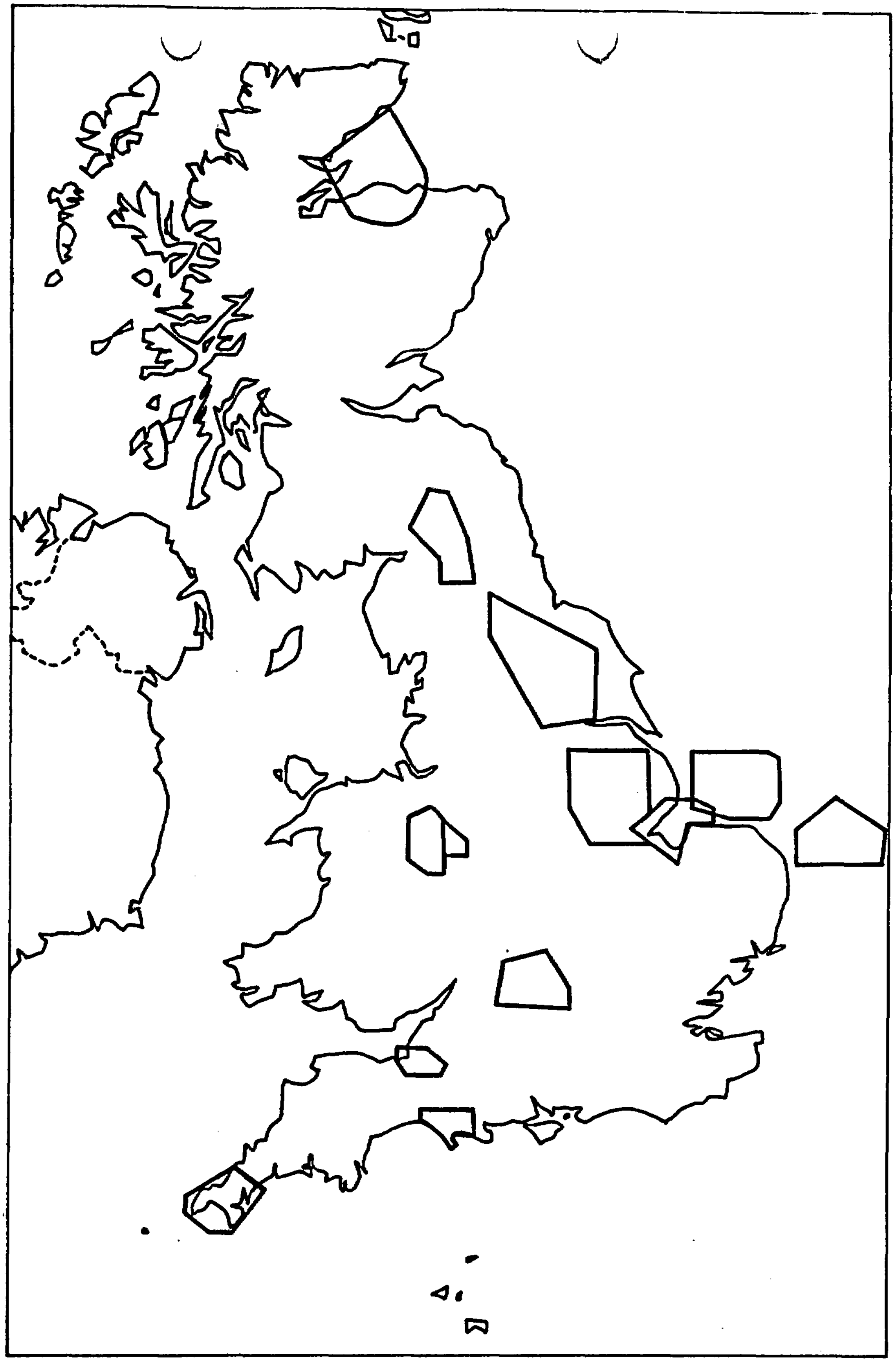

FIG. 7 AIAA'S IN THE UK