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12.09.2014

A Review and Statistical Modelling of Accidental Aircraft Crashes within Great Britain

MSU/2014/07

HSL Report Content

Report Approved for Issue By:	[redacted]
Date of Issue:	12/09/2014
Lead Author:	[redacted]
Contributing Author(s):	[redacted]
Technical Reviewer(s):	[redacted]
Editorial Reviewer:	[redacted]
HSL Project Number:	PH06315
HSL authored sections	7 ,8 ,9 Appendix (a) and Appendix (b)
HSL/Loughborough Joint authorship	1, 2, 11
HSL Quality approved sections	1, 2 ,7 ,8 ,9 ,11 , Appendix (a) and Appendix (b)

Loughborough University Report Content

Report Approved for Issue By:	[redacted]
Date of Issue:	12/09/2014
Lead Author:	[redacted]
Contributing Author(s):	[redacted]
Technical Reviewer(s):	[redacted]
Editorial Reviewer:	[redacted]
Loughborough Project Number:	N/A
Loughborough authored sections	3 ,4 ,5 ,6 ,10 ,12 Appendix (c)
HSL/Loughborough Joint authorship	1, 2, 11
Loughborough quality approved sections	3 ,4 ,5 ,6 ,10 ,12 Appendix (c)

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EXECUTIVE SUMMARY

Background

One of the hazards associated with nuclear facilities in the United Kingdom is accidental impact of aircraft onto the sites. Although it is the responsibility of the licensee to assess this hazard and to demonstrate that the resulting risk is adequately managed, the Office for Nuclear Regulation (ONR) provides oversight and challenge to these assessments and on occasion has the need to make its own independent assessment of the risks. The methods used to assess aircraft crash frequency to nuclear facilities in the UK (the "Byrne model") were originally developed by the UK Atomic Energy Authority during the 1980s. Although it has subsequently been revised by AEA Technology (formed from the commercial arm of the UKAEA) under contract to HSE (HSE Research Report 150/1997, 1997) and ESR Technology (formerly the Engineering, Safety and Risk business of AEA Technology) (ESR Technology, 2008), the method remains substantively unchanged and based upon sparse historical data on accidents that occurred within Great Britain (GB).

Aims

The general aims of this report were to review the methods currently used for assessing accidental aircraft crash frequency to UK nuclear installations and consider whether improvements to the methods are possible and advisable. Specifically the aims were:

- to determine the models that are available to estimate the likelihood of accidental aircraft crash at a particular location, what their key characteristics are and what scope there is for potential further development;
- to compare the Byrne model (Byrne, 1997) with other models, and determine whether it can be enhanced with larger contemporary datasets;
- to develop statistical models for the frequency of accidental aerodrome and off-aerodrome crashes in GB;
- to examine the available data on crash locations and develop a new statistical model for the probability of a crash at a particular location relative to an aerodrome;
- to consider methods for incorporating variation in risks between aerodromes into the assessment methods due to variation in factors such as operational and meteorological conditions; and
- to compare and propose improvements to the existing aircraft crash methods.

Main Findings

Comparison of models

In summary, the Byrne model

- did not account for the hazardous scenario of the licensed nuclear site acting as an obstacle to an otherwise safe flight;
- did address the shadow shielding of part of a site by structures on another part of a licensed nuclear site;

- did address the skidding of an aircraft into a licensed nuclear site;
- did address the projectile bounce of an aircraft making its initial impact outside a licensed nuclear site;
- did address projectiles falling from aircraft;
- did not address issues relating to hazardous materials carried on-board the aircraft and hazardous materials used in the structural composition of the aircraft;
- did not appear to consider gyrocopters, gliders, airships, gas-lifting balloons and hot-air balloons;
- did address unmanned aerial vehicles and concluded that they posed an insignificant risk;
- is considered to be a generalised area model suitable for calculating average crash frequencies over a nation, but not a good model for predicting the crash frequency onto a specific location;
- did not consider curved flight paths; and
- did not consider quantification of uncertainty.

Most other methods of assessing accidental aircraft crash risks do not quantify the overall uncertainty in estimated crash probabilities. As such, their use is considered unsuitable for assessing aircraft crash risk to UK nuclear sites until statistical uncertainty can be quantified.

All of the models suffered from either an inability to consider all types of aircraft, or they may not take local flightpaths into account if the site was within the vicinity of an aerodrome.

Whilst the Wong (Wong, 2007), and ACRP 3 (TRB, 2008) models provide some useful information for assessing inter-aerodrome variation in crash frequencies, some of the risk factors may not be relevant for GB, such as the US Federal Aviation Administration (FAA) hub airport size. The risk factors relating to meteorological conditions, which are based on data rather than an assumed causal mechanism, are considered to be reliable for application to GB.

The model with the greatest ease of application was the DOE standard model (DOE, 2006), allowing non-aviation specialists to take account of site-specific factors more easily than applying the Byrne model and the Philips model if light fixed-wing aircraft had to be accounted for. The model included a tabulated set of data that was relatively easy to apply to a site but it would also be possible to expand the concept to a Geographic Information System (GIS) to highlight the aviation risk exposure over the whole of GB. A GIS would have the benefit of being relatively easy to use for reference purposes and it would be a major advance in public understanding of aviation risk exposure across GB.

Statistical analysis of aircraft crash rates and location distributions

Statistical analysis of aircraft crash data for GB for the period 1985 to 2006 found no evidence of a change in the background annual rate of crashes (expressed per km^2) for any of the aircraft categories considered. However, it should be noted that due to the low number of accidents in the small and large transport aircraft categories (≤20,000 kg and >20,000 kg Maximum Certified Take-off Mass (MCTOM) respectively), the statistical power to detect any trend over time is low.

Statistical analysis of civil aerodrome-related crashes for GB for the period 1979 to 2006 found no evidence for a change in the rate of crashes (expressed per movement) for small and large transport aircraft. However, a statistically significant increase in the accident rate for light aircraft (<2,700 kg MCTOM) of 4.4% and in the accident rate for helicopters of 4.7% per year was found.

Based upon accidents between 1985 and 2006 the estimated background crash rate was greatest for England. For light aircraft, the annual crash rate for England is 2.93 x $10^{-5}km^{-2}$ (95% C.I. [2.34, 3.63 x $10^{-5}km^{-2}$]); for helicopters is 1.39 x 10^{-5}km^{-2} (95% C.I. [1.00, 1.90 x 10^{-5}km^{-2}]); for small transport aircraft is 0.31 x 10^{-5}km^{-2} (95% C.I. [0.14, 0.60 x 10^{-5}km^{-2}]); and for large transport aircraft is 0.04 x 10^{-5}km^{-2} year^{-1} (95% C.I. [0.00, 0.19 x 10^{-5}km^{-2}]).

Based upon accidents between 1979 and 2006 the estimated aerodrome-related crash rates were similar across England, Scotland and Wales, hence the GB rates may be used. The crash rate per million movements for light aircraft is 1.61 (95% C.I. [1.36, 1.90]); for helicopters is 2.12 (95% C.I. [1.43, 3.03]); for small transport aircraft is 3.14 (95% C.I. [2.18, 4.39]); and for large transport aircraft is 0.14 (95% C.I. [0.05, 0.32]). Adjusting the rate for light aircraft by the estimated trend of +4.4% per year gives a crash rate for 2014 of 3.89 per million movements (95% C.I. [2.51, 6.03]). Similarly, adjusting the rate for helicopters by the estimated trend of +4.7% per year gives a crash rate for 2014 of 5.16 per million movements (95% C.I. [2.19, 14.35]).

Analysis of accident data compiled by the US National Transportation Safety Board (NTSB) for the period 1993 to 2012 determined an improvement in reliability of approximately 6.4% per year for flights operating under regulation 14 CFR 121 and 1.6% annum for general aviation. Both these aviation categories relate only to US operated flights and not foreign operated ones. Previous research by Loughborough University has identified that for accidents in the proximity of an aerodrome, the accident rate for flights of foreign origin/destination may be considerably higher than for domestic US flights. Thus even if these improvements in reliability are representative of UK operated flights (excluding light aircraft) they may not be representative of changes in the overall accident rates in the United Kingdom.

An analysis of crash location data for crashes that occurred in the US, supplied by Loughborough University, was undertaken with a number of distributions investigated. Although a gamma distribution was judged the best fitting, other distributions including the Weibull and generalised extreme value distributions provided reasonable approximations to the data. The uncertainty in the probability of a crash at large distances from the runway was considerable; for landing undershoots and assuming a gamma distribution, the 95% C.I. of the probability of a crash occurring at >20 km from the runway threshold ranges from approximately 1% to 6%; for the Weibull distribution, the 95% C.I. ranges from approximately 1% to 8%. The high uncertainty is due to the sparse nature of the data at such distances; although it may be argued that crashes at distances as great as 20 km from a runway should not be classed as aerodrome-related, there have been instances of accidents occurring during the landing or take-off phases of flight where the wreckage ended up at such large distances from the runway. As the crash location distributions are based on accidents involving mainly large aircraft, these distributions may not be representative of light aircraft under 2,700 kg MCTOM.

Correlations between lateral and longitudinal crash distances were determined and the bivariate distribution of these distances modelled using a Gaussian copula. The strength of correlation varies according to the type of crash and is strongest for take-off crashes after the runway stop end, landing overruns, and landing undershoots before the runway threshold. The influence of this correlation on the crash probability therefore varies according the location being considered. For crashes after take-off, ignoring correlation led to an underestimation of the crash probabilities at large distances from the runway threshold and centreline. For landing undershoots, ignoring correlation led to greater estimated crash probabilities along the runway threshold but lower estimates at greater lateral and longitudinal distances from the runway threshold and centreline. These differences were up to two orders of magnitude.

The revised crash rates and location distributions determined in this study were used to estimate the probability of an accidental aircraft crash at a location in the vicinity of Lydd airport. Separate calculations were made per take-off and landing movement for light transport aircraft only. The calculated uncertainty was substantial with approximately a six-fold difference between the lower and upper 95% confidence limits for the hazard posed by take-offs and a three-fold difference for the hazard posed by landings. The existing Byrne and Wong models gave take-off and landing crash probabilities outside of these ranges. However, although the individual landing and take-off probabilities under the Byrne model were lower than and greater than the

HSL landing and take-off probabilities respectively, these differences cancel each other out when landing and take-off crash frequencies were combined to give an annual aerodrome-related crash frequency similar to that calculated using the HSL method.

Recommendations

The operators of licensed nuclear sites should consider conducting local flight surveys to ensure that the number and type of flights operating in the vicinity of the licensed nuclear site is compatible with the assumptions used in the calculation of aircraft accident frequency. They should also ensure that any local operating conditions that may modify the probability of a flight suffering an accident significantly are taken into account.

Data relating to crashes in GB for the period 2007 to 2013 should be collated and added to the data analysed in this report. The UK based organisation Ascend (formerly known as Airclaims) has collated data on accidents involving Western built turbine powered aircraft over 5.7 tonnes MCTOM. These data were supplied to IAEA by the UK Civil Aviation Authority. An attempt should be made to obtain these data to allow further investigation of changes in aircraft accident rates and differences between GB and the rest of the world, in particular, the US and Western Europe.

Any modelling of aircraft accident frequencies at a specific location should include the consideration of the uncertainty both in the crash frequencies and in the crash location distributions. The 95% confidence interval upper bound should be used in safety arguments to demonstrate that a licensed nuclear site does not suffer from excessive risk associated with aviation-related hazards.

Based upon the width of the confidence intervals for the derived aerodrome-related crash rates for GB, data relating to GB are considered adequate for determining average crash rates for the light aircraft, helicopter and small transport categories. However, the confidence intervals for accident frequencies involving large transport aircraft are considerably wider; GB data should be supplemented with data from North America or Europe for this category.

The modelling of accident frequency by averaging over the whole of mainland GB may not be reflective of the local operating conditions above and in the vicinity of a licensed nuclear site. Background crash rates should therefore be recalculated per km flown rather than expressed per km^2 land area and used in conjunction with location specific information on flight density in order to obtain more specific estimates of the background crash probability at an individual licenced site. Alternatively, the light aircraft movements may be multiplied by an estimated average distance flown per light aircraft to provide an approximation to the total km flown. Ideally, the aircraft categories used in the flight movement data should be consistent with the categories used for calculating the background crash rates, otherwise the background crashes may require reclassification before movement data is applied.

For aerodrome-related crashes a three stage assessment is advocated: estimation of an average crash frequency; adjustment of the average crash frequency for local factors, if possible; and application of a crash location distribution.

The first stage may be based on GB aerodrome-related accidents for light aircraft, helicopters, small transport and large transport aircraft, as was carried out in this report. The second stage may be implemented by applying the meteorological factors from the Wong model to a set of geographically diverse GB aerodromes; potential factors include adjustments for precipitation, crosswinds, fog and significant terrain. For the third stage, aerodrome-specific crash location distributions should be obtained by applying the generic crash location distributions around the aerodrome-specific flight paths, rather than around the extended runway centreline.

Crash location data for accidents involving light aircraft in the vicinity of aerodromes in GB should be collated and analysed to determine suitable crash location distributions for this category of aircraft, accounting for local flight operations which may not have been reflected in previous models. Aircraft categories should remain consistent with the available flight movement data, otherwise reclassification may be necessary.

The grouping of aircraft into different mass and kinetic energy groups should be reconsidered with the objective of removing the inconsistencies present within the Byrne model. Operations by ex-military aircraft could be considered for grouping with current military aircraft. Operation of civilian aircraft but on military and state activities could be considered for grouping with current military aircraft.

The Byrne model could be improved through updating the assumptions relating to aircraft impact models, skidding friction factors, projectile bounce factors and projectiles dropping from aircraft.

If any model is to be developed beyond the Byrne model for use in GB then the usability could be improved by changing to look-up tables or through a risk map being published for the whole of Great Britain.

Consideration should be given to hot-air balloons, gyrocopters, gliders, airships and unmanned aerial vehicles to allow extension of the Byrne model.

CONTENTS

1 INTRODUCTION

The Office for Nuclear Regulation (ONR) is responsible for the licensing of nuclear sites within Great Britain (GB). The operator of each licensed nuclear site has to demonstrate that the site is acceptably safe from the perspective of the internal risk of exposure to workers and visitors to the site as well as the external risk to third parties living and working in the vicinity of the site.

One of the external hazards that the operator of a licensed nuclear site has to consider is that of an unintentional aircraft accident with the potential for consequential damage to the site through impact, fuel fire and other effects. The method for undertaking such an assessment has usually had several stages: the identification of the likelihood of an aircraft accident onto the site; the analysis of the consequences to the site equipment and infrastructure of such an impact; the analysis of the consequence to the site equipment and infrastructure of the combustion the aircraft's fuel supply; the release of toxins into the atmosphere; and the subsequent risk exposure to health of workers, visitors and third parties.

This report is concerned with the identification of the likelihood of an aircraft impact onto a licensed nuclear site. Historically, this has been carried out through the application of a model developed by the United Kingdom Atomic Energy Authority and known as "the Byrne model" (AEA Technology/HSE Research Report 150/1997, 1997). This model was updated by ESR Technology (2008). There were no substantive changes made to the model during the revision processes.

In 2012 ONR set up a Technical Advisory Panel (TAP) to review the current methods used for the evaluation of aviation-related external hazards. The TAP identified that the current application of the Byrne model had a number of weaknesses including a reliance on sparse historical data for aircraft accident rates; no consideration of offset, visual and circling approaches and other airport specific risk factors; as well as deficiencies in the modelling of crash locations relative to a runway.

The ONR commissioned a project to examine the current aircraft accident probability, frequency and location models to determine their suitability for use by operators of current, proposed and decommissioning sites in their licensing applications. The project was to be carried out by the Transport Studies Group of Loughborough University working with the Health and Safety Laboratory (HSL). Loughborough University are providing the aviation safety and operations knowledge with HSL leading the statistical analysis. The work presented in this report is not intended to be a like-for-like update or replacement of previous models, but rather to aid the assessment of their suitability for application to licensed nuclear sites in Great Britain.

Scope

Aircraft crash data
A review of datasets from Europe, the United States and other regions where it is considered operations are representative of the UK should be undertaken to extract the following data:

- Frequency of non-military aircraft crash across a range of aircraft types
- Occurrence, frequency and location of non-military aerodrome related crashes

The focus will primarily be on data from the past 10 years, although the data for the 10 years preceding should be examined to identify any obvious trends.

A review of the occurrence of military crashes in the UK over the past 10 years, along with a review of the operational environment should be undertaken to derive an understanding of the application of this data for future predictions.

Model Review
A structured review should be undertaken of worldwide models for the estimation of the likelihood of accidental aircraft crash at a particular location. As a minimum, the following models should be considered: NATS, DNV, IAEA, NLR, GfL, US Models (NUREG-800, Solomon, Sandia, Hornyik, DOE Standard).

Criteria for comparison include, but are not limited to:
- modernity;
- application in a nuclear environment;
- underlying data sets;
- ability to include all phases of flight; and
- regulatory oversight

Data analysis

A statistical model should be developed to estimate:
- the likelihood of non-aerodrome related crashes on a per km/year basis; and
- the likelihood of an aerodrome related crash as a function of aerodrome proximity

A comparison of the computed values should be made with those currently used by the Byrne model.

Joint Authorship
This report has been constructed through a joint working approach between Loughborough University and The Health and Safety Laboratory. The following list identifies who authored and approved each section.

Section	Title	Page	Author	Approved for release by
	EXECUTIVE SUMMARY	i	HSL/Loughborough	HSL
1	INTRODUCTION	1	HSL/Loughborough	HSL
2	REQUIREMENTS TO ASSESS AVIATION-RELATED EXTERNAL HAZARDS	3	Loughborough	Loughborough
3	BACKGROUND TO AVIATION ACTIVITIES OVER GREAT BRITAIN	5	Loughborough	Loughborough
4	SOURCES OF AIRCRAFT ACCIDENT DATA AND DATA ANALYSES	16	Loughborough	Loughborough
5	ANALYSIS OF PUBLISHED ACCIDENT LOCATION LITERATURE	21	Loughborough	Loughborough
6	AIRCRAFT CRASH RATES FOR GREAT BRITAIN	62	HSL	HSL
7	ANALYSIS OF CRASH LOCATIONS	74	HSL	HSL
8	FREQUENCY OF AN AIRCRAFT ACCIDENT IN THE VICINITY OF LYDD AIRPORT	98	HSL	HSL
9	SUITABILITY OF THE BYRNE MODEL FOR CONTINUED APPLICATION	105	Loughborough	Loughborough
10	DISCUSSION	116	HSL/Loughborough	HSL
11	RECOMMENDATIONS	122	Loughborough	Loughborough
	Appendix A - Aircraft Crash Data	126	HSL	HSL
	Appendix B – Crash frequency calculations	134	HSL	HSL
	Appendix C - The licensee's safety case and review criteria for ONR Inspectors	137	Loughborough	Loughborough

2 REQUIREMENTS TO ASSESS AVIATION-RELATED EXTERNAL HAZARDS

This background section details the international requirements that are published by the International Atomic Energy Agency (IAEA) and the national requirements published by the Office of Nuclear Regulation. The IAEA is the international body responsible for global standards of civilian nuclear safety. It is a United Nations agency with its headquarters in Vienna, Austria. The United Kingdom is a Member of the IAEA. Therefore, the minimum standards of the IAEA become the minimum standards required of UK licensed site operators, prior to any increase in safety levels demanded by the ONR.

2.1 INTERNATIONAL REQUIREMENTS

The IAEA has defined requirements for analysis of aviation risk exposure for sites other than nuclear power plants (IAEA, 2003a). This would encompass activities such as fuel processing, fuel reprocessing and weapons manufacturing. A two stage process is applied. Firstly, if the site operator can demonstrate that the probability of impact is sufficiently low (a probability of 10^{-5} per year is suggested) then the operator does not need to carry out a consequence analysis. If the operator cannot demonstrate a probability of impact at or below this level through the application of simple screening models, then the facility must be protected in accordance with the consequence analysis. The site operators are required to collect data relating to at least: the presence of aerodromes close to the site; the probability of an accident based on statistical data for the region around the site; the frequency of flight operations; the mass and impact characteristics of the aircraft as well as the likely speed on impacting the site. The document suggests that aircraft are usually grouped into three categories of general aviation (less than 5,700 kg maximum certificated take-off mass (MCTOM)), commercial aviation (5,700 kg and higher maximum certificated take-off mass) and military aircraft. There does not appear to be any guidance relating to the site's vertical projection acting as an obstacle that could cause an accident. No mention is made of future air traffic scenarios including changes in the types of accident over time, projected changes in traffic levels and changes in aircraft types.

The IAEA requirements for evaluation of a nuclear power plant's location include the consideration of aircraft crashes onto the site (IAEA, 2003b). The nuclear power plant's operator is required to examine the potential for an aircraft crash to affect the safety of the site and assess the hazards resulting from the aircraft crash. If the site cannot be protected adequately against such accidents, then the site will be considered to be unusable.

The requirements for the operators of nuclear power plants to consider aircraft-related hazards (IAEA, 2002) identify three types of general accident types. These are crashes relating to general air traffic in the region (of up to 200 km from the site); crashes relating to take-off and landing operations at nearby airports; and crashes relating to main civil air traffic routes and military flight routes.

The preliminary evaluation is a screening based on distance from airports and flight routes. If a detailed evaluation is required then an analysis should be undertaken to determine the accident rate per year per unit area. The site's effective area (adjusted to include the aircraft's wingspan, trajectory angles and skidding wreckage trails) is then multiplied by the accident rate to give the exposure value.

The safety guide that examines the consequence analysis (IAEA, 2003c) does recognise that long skidding of engines may occur with distances up to 300 metres being recorded. It does not recognise that the engines could be airborne projectiles rather than just skidding along the ground, such as occurred in the crash of Royal Air Force Jaguar GR1A XZ386 (Ministry of Defence, 1988).

2.2 NATIONAL REQUIREMENTS

The Office of Nuclear Regulation publishes the safety assessment principles by which it licenses nuclear facilities in Great Britain (Health and Safety Executive, 2008).

The engineering principles for external and internal hazards relating to aircraft impact[1]requires the total predicted frequency of aircraft crashes (including helicopters) to be derived for locations that may house safety critical functions. This analysis should be based on the most recent crash statistics, flight paths used and flight movement rates for all types of aircraft. Foreseeable future factors should be taken into account.

An acceptable means of compliance with the requirements has been the application of the Byrne model (Byrne, 1997) and its subsequent refinements (Kingscott, 2002 and ESR Technology, 2008). The suitability of the current version of the Byrne model for application to current and potential nuclear licensed sites in Great Britain is examined in this report.

[1] The aircraft impact hazard is given the code EHA 8 in the document and the explanatory material is contained in paragraph 218

3 BACKGROUND TO AVIATION ACTIVITIES OVER GREAT BRITAIN

The operator of a licensed nuclear site has to consider all aircraft operations that could affect their site. The scope of this report is limited to unintentional aircraft accidents crashing onto a site and thus intentional acts are not considered further in this report.

This section of the report examines the different types of aircraft and their operational characteristics; the changing nature of aircraft operations over time and the protection of licensed nuclear sites through the provision of prohibited airspace.

3.1 AIRCRAFT OPERATIONS

The operation of aircraft may be split into two broad categories, those of military flight operations and civilian flight operations. There is an increasing tendency to put some elements of military activity into the civilian sector under long term government plans and these will be considered as civilian special operations within this report. The operation of former military aircraft placed on the civilian register will be considered as civilian aircraft. The operation of remotely piloted vehicles will be considered as a third category, although they are predominantly operated by the military at the current time.

3.1.1 Civilian aircraft operations

Passenger jet aircraft vary in size from the large Airbus A380-800 airliner down to small business aircraft in the very light jet category. It is possible to find some of the smaller business jets making occasional flights from aerodromes with grass runways but usually jets are operated from aerodromes with paved runways. It is usual for these aircraft to operate under the direction of air traffic control and remain within airspace that excludes general aviation traffic.

Passenger carrying turboprop aircraft are usually used for short haul operations and have a commercial advantage over jet aircraft with little increase in overall flight time for the shorter sectors. The most common types in service seat between 50 and 78 passengers although smaller types are found in regional services around GB. Accident rates for turboprop aircraft are usually slightly higher than for passenger jet aircraft. This is usually related to the lack of infrastructure at airports and the relative crew experience levels.

Freight and cargo operations are usually carried out by converted airliners but some purpose built cargo aircraft have been constructed. Freight and cargo operations have had a higher than average accident rate, mainly in the vicinity of aerodromes. The reasons for this rate increase include the shifting of cargo after take-off resulting in significant changes to the centre of gravity leading to a loss of control, as well as an increased probability of a flight at the maximum mass limit of the aircraft. The average age of cargo aircraft tends to be higher than those operated by commercial airlines. For example, the DHL fleet of Boeing 757SF aircraft were converted from airliners after approximately 15 years' service. The use of older aircraft implies that the on-board technologies to prevent accidents may be behind aircraft manufactured recently. The use of older aircraft also implies their reliability may be lower than modern aircraft and thus their reliability-related accident rate may be higher. If a licensed nuclear site is to be located near a freight hub, such as East Midlands Airport, then this may have to be taken into account in the accident probabilities chosen.

The operation of aircraft on the register of some countries appears to be associated with an increased probability of an accident, when measured on a per flight basis. In general, aircraft operated on the register of North American, western European, Australian and New Zealand registers have a lower accident rate than those operated by Latin American, African, Asian and eastern European countries. The significant level of operation of aircraft registered or manufactured in these countries may require modifications to the accident probabilities.

Piston engine aircraft tend to be used for general aviation activities such as basic training and private flying. They tend to be in the 1,000 to 3,000 kg MCTOM range. Some are used for commercial operations with around nine passenger seats. The lighter aircraft may not be equipped with instruments that allow them to fly in cloud, at night and in reduced visibility conditions. Most piston engine aircraft are unpressurised so they are limited to operating ceilings of around 10,000 feet.

There are low level operations that are carried out routinely by civil aircraft. These include coastguard and maritime patrol activities. The largest aircraft involved in low level operations over GB will be a modified Boeing 737 fitted with chemicals for dispersing petrochemical slicks at sea. Aerobatic displays and airshows have a significant element of low level operations associated with them. Some low flying activity is carried out for photographic, filming and surveying purposes. Crop spraying is carried out at very low level. Low level flight operations have a higher accident rate than conventional altitude operations. Whilst protective airspace around a licensed nuclear site may provide protection against this increased accident rate, not every site has this protection and exemptions have been granted to allow aircraft access to these areas (further discussion is given in section 4.4).

There are some special operations carried out by civilian registered aircraft. With the advent of private contractors operating military training contracts and military transport contracts, some aircraft that would be considered as military aircraft are now operated on the civilian register.

There are many vintage aircraft operated over GB. These aircraft may have a slightly higher than average forced landing rate but they are usually of relatively low mass, low structural density, with low fuel loads and fly with low speed. In general they are single piston engine types and do not usually undertake long distance flights or operate in poor weather conditions.

The exceptions to the general vintage aircraft summary are usually ex-military aircraft. These can include transport aircraft and fast jets. These aircraft may have a higher than average accident rate and they have been considered in the Byrne model data collection exercises. For example, the accidents investigated by the Air Accidents Investigation Branch (AAIB) involving a Vickers Varsity T1 on 19 August 1984 (AAIB, 1986) in the Byrne transport category and a Hawker Hunter F4 on 5 June 1998 (AAIB, 1999) that was an ex-military jet but was classified in the Byrne model as small transport.

Civil helicopters vary from single and two seat versions used for private flights and initial training through to commercial passenger types used for transporting offshore workers to rigs. Helicopter operations are regarded as having a higher operating loss rate, per flight/flight hour/unit distance than fixed wing aircraft. The Sikorski S-92 is the largest helicopter found in common civilian use over GB. It has a maximum mass slightly over 12,000 kg and a maximum airspeed of approximately 165 knots.

There are various types of low-level and special operations carried out over Great Britain using fixed-wing aircraft and helicopters. These include Search and Rescue operations, police and ambulance flights, inspection of supply lines and crop-spraying. The operation of helicopters in the Search and Rescue role by civilian organisations is becoming more common and the military fleet will be retired by 2017. The helicopters to be used in this role will be Sikorsky S-92 and Augusta Westland AW-189. HM Maritime and Coastguard Agency use civilian contractors to provide a variety of fixed and rotary wing aircraft to fulfil their requirements. These include Cessna 404 and 406 twin engine aircraft, Sikorsky S-92 and Augusta Westland AW-139 helicopters.

Whilst general civilian operations have to observe the airspace restrictions around licensed nuclear sites (section 4.3), the authors are unaware of any special operating exemptions that may be granted to Coastguard as well as Search and Rescue helicopters now that their operations have been transferred to civilian operators. Police flights are usually carried out by helicopters and there has been one recent accident (AAIB, 2014). Ambulance flights are usually carried out by helicopter but some flights to the Northern and Western Isles are carried out using fixed wing aircraft, typically Britten Norman BN-2 Islanders.

Gas pipelines and electrical power lines can be inspected by helicopter and this necessitates low-level flying. The use of helicopters to access wind turbines, both on-shore and off-shore is becoming more frequent.

Crop spraying using agricultural aircraft necessitates low-level flying during the application of the chemicals. Usually these aircraft are approximately 2000 kg maximum mass. The chemical contents may have to be considered as part of a consequence analysis if one of this class of aircraft were to fall onto a licensed nuclear site. The largest spray aircraft that will be operating over GB shortly will be a Boeing 737 freighter modified for offshore pollution control operations.

Other low-level flying activities, including filming, take place across Great Britain and these require permission from the Civil Aviation Authority for an exemption from the "500 feet rule". Some aircraft carry out aerobatics with a relatively high probability of loss-of-control accidents resulting from these manoeuvres. Similarly, air displays have a relatively high accident rate when compared with average general aviation operations.

Gyrocopters, or autogyros, have a rotor like a helicopter to provide lift above the airframe and an engine mounted horizontally with a propeller to provide thrust. They are usually single or two seat capacity with a maximum mass below 500 kg and maximum speeds below 150 knots. The fuel capacity is usually less than 100 litres of petrol.

There are two general types of gliders in use over GB. These are conventional gliders, usually launched by a winch or towed by a powered aircraft, and self-launching motor gliders. Conventional gliders may be found anywhere over GB, particularly in the summer months. Self-launching motor gliders can be used as very efficient light aircraft or the engine can be switched off after gaining altitude. Engines can be electric, piston or even jet turbine powered. The mass of the self-launching motor glider is usually limited at 750 kilogrammes and a typical fuel tank carries approximately 100 litres of petrol or kerosene. Groundspeeds in excess of 100 knots can be achieved.

Paragliders consist of a parachute type of wing and are generally foot launched. Their lift is derived from thermal air currents, changes in wind over ridges and hills or exchange of potential energy for kinetic energy. These flying machines usually have very little mass above the mass of the pilot(s). Their forward speed is usually low as they are difficult to fly in high wind speeds because of turbulence.

The use of a parachute wing and a small engine to provide thrust gives the potential for longer distance travel and different flight profiles from a foot-launched paraglider alone. The engine is usually small (usually less than one litre swept volume), the fuel load small (although using flammable petrol and oil in engines), the overall mass including the pilot relatively low and the groundspeed relatively low. The licensee should expect to use values of around 200 kg as the maximum mass and around 50 miles per hour as the speed in their analyses.

Airships derive their lift from the gas inside the envelope (with the possibility of aerodynamic lift, depending upon the shape of the envelope) and their thrust from engines. The most well-known airships in use over GB are those associated with television coverage of large outdoor sporting events. The largest size found in common civilian use is the Zeppelin NT with a structural mass of around 1100 kg and a size of similar dimensions to a Boeing 747 jumbo airliner.

There are two different types of balloon in common use over GB. These are those that derive their lift from hot-air and those that derive their lift from a lighter-than-air gas filling the envelope. The maximum mass of hot-air balloons is approximately 5100 kg for a Cameron Z-750 and this type of balloon may carry over one tonne of liquefied propane gas as the fuel for the burners. Whilst the relatively low mass and relatively low impact speed (for example 30 knots if caught in gust conditions) may mean that the kinetic energy is relatively low, the licensee may have to consider the dragging of the balloon over the site colliding with several different parts of exposed equipment and the inertia of the hot-air inside the envelope. The fuel containers should not rupture in a low speed impact but the possibility of explosion exists, particularly if in contact with electrical power lines.

Gas balloons use low density gases such as hydrogen or helium. The gas may be vented out of the top of the balloon and ballast, such as sandbags, may be carried in order to moderate the altitude of the balloon. Whilst helium is an inert gas and the kinetic energy of the overall system is relatively low, hydrogen gas has the potential to explode, particularly if in contact with electrical power lines.

3.1.2 Military aircraft operations

Military aircraft may be classified as fast jet (including fighters, bombers and some reconnaissance aircraft); transport aircraft (including freighters, air-to-air refuelling aircraft and passenger transports); training aircraft (including ab-initio, basic, multi-engine); and helicopters (including heavy-lift capability and battlefield attack). The fast jets may be armed or unarmed and capable of high speed at low-level. As an example, the mass of the Eurofighter Typhoon can be in excess of 23,500 kg with a maximum speed at sea level of approximately 1500 km per hour. The maximum external weapons load is approximately 7500 kg (Eurofighter, 2013).

The maximum speed at sea level may be reduced when carrying a full external weapons load. The consequence analysis may have to consider a combination of maximum speed strike without weapons as well as a maximum speed strike whilst carrying external weapons. Other types of fast jets operate over GB as a matter of course (United States Air Force aircraft based in East Anglia) or whilst on NATO exercises. Military transits and exchange visits as well as diversions may occur at any point.

Transport aircraft types operated by the Royal Air Force have changed considerably over the last few years with the retirement of VC-10, Nimrod, TriStar and original Hercules fleet. The number of Boeing C-17s has increased, the new Lockheed C-130J has been introduced and the Airbus A-330 MRTT tanker has commenced operations. The fuel load of the Airbus A-330 MRTT tanker (at a maximum of 111,000 kg) is less than the fuel load of the Airbus A380-800 in commercial flight operations and the operators of licensed nuclear sites may consider the Airbus A380 as the worst case scenario for post-impact fuel fires. Some of the military operations carried out by these aircraft may be “beyond design case” for the impact and special consideration may have to be given by operators of licensed nuclear sites to these external hazards.

There are bases in GB that can be used by the United States Air Force as forward deployment bases for their bombers. These include Boeing B-52 Stratofortress, Rockwell B-1B Lancer and Northrop Grumman B-2 Spirit stealth bomber. The weapons loads that could be carried include nuclear bombs, the GBU-43/B Massive Ordinance Air Blast and other munitions. The transport aircraft that fly into GB on a regular basis include the Boeing C-17 and the Lockheed C-5 Galaxy. Some of these military operations may be “beyond design case” for the impact and special consideration may have to be given by operators of licensed nuclear sites to these external hazards.

Training aircraft used by the military include single engine turboprop and piston engine trainers as well as twin engine training aircraft. The piston engine aircraft are very similar to civilian training aircraft in terms of operating speeds and mass. However, they undertake formation flying and aerobatics on a more routine basis. The turboprop training aircraft include the Shorts Tucano T1 and this is used to start a pilot's low-level and fast flight experience prior to transition to the BAE Systems Hawk T1 and T2. The King Air B200 is used as the primary trainer for multi-engine aircraft and navigation training with the Super King Air 350ER version known as the Shadow R1 modified for intelligence and surveillance purposes.

Military helicopter operations over GB include the Boeing CH-47 Chinook with a maximum mass in excess of 22,000 kg and visits by the Sikorsky CH-53E Super Sea Stallion with a maximum mass in excess of 33,000 kg. Both of these helicopters can lift external military equipment with a mass in excess of 10,000 kg. Whilst the speed of the helicopters may be relatively slow, when compared with the fixed-wing aircraft that have to be considered, the possibility of a helicopter jettisoning a military external load and it dropping onto a licensed nuclear site has to be considered. The density of the equipment and its impact frangibility will have to be considered in the consequence analysis.

There are two main types of attack helicopter, as opposed to transport helicopter, and these are the Augusta Westland Apache AH1 and Lynx types. Attack helicopters operate at low-level with a maximum speed of less than 250 knots and a maximum mass of less than 10,000 kg.

3.1.3 Remotely Pilot Vehicle Operations

The military are also the primary operator of remotely piloted vehicles over Great Britain, along with test and development work carried out by BAe Systems. The military have five different types in use (declared to the public, although other types may be in use but given a security classification that means they are not declared to the public). The current aircraft vary from palm sized helicopters similar to those found in toy shops through to aircraft transiting UK airspace operated by the United States that have wingspans approximately the same dimension as 150 seat airliners and a maximum mass of approximately 15,000 kg. Other types are being developed by the UK aerospace industry, such as the BAE Systems Taranis (Flightglobal, 2013).

3.2 THE CHANGING BASIS OF AIRCRAFT OPERATIONS OVER TIME

The original airliners in use at the time of the start of widespread nuclear power generation were types such as the Boeing 707 with an original maximum certificated take-off mass of around 112 tonnes. Current operations see the physically much larger Airbus A380-800 in use in some countries and transiting over many others, with a maximum certificated take-off mass of around 575 tonnes. The approximately five-fold increase in mass of a potential accident onto site will have to be accounted for in the structural analyses of the sites.

The aircraft's engines are usually considered to be the densest element of an aircraft and thus form a significant element of the post-impact structural analyses that have to be carried out. The mass of an individual engine, such as the Pratt and Witney JT3 series fitted to Boeing 707s was under two tonnes mass (dry) whereas current operations see the General Electric GE90-115B fitted to the Boeing 777-300ER with a mass over eight and a half tonnes (dry). The mass of the core of the current engines has increased but also the energy stored as rotational inertia within the turbine and compressor sections has increased. Both the increase in mass and the increase in rotational energy will have to be accounted for in the structural analyses of the sites.

The maximum fuel load of an aircraft has increased over time with the Boeing 707 carrying a maximum fuel load of approximately 65,000 litres whereas the Airbus A380-800 has a maximum fuel load of approximately 323,000 litres. The increase in fuel carried by the aircraft will have to be accounted for in the post-impact consequence analyses.

There has been a change in some of the structural materials used in the construction of airliners over time. Whilst the Boeing 707 is mainly aluminium, more modern aircraft have significantly different metal compositions and considerable amounts of carbon fibre. The carbon fibre may act as an additional combustible item in a post-accident fire scenario at the licensed nuclear site (Federal Aviation Administration, 2007). The post-accident blowing of carbon fibres around the site and off-site may need to be considered as part of the consequence analysis. In addition, some aircraft contain other toxins as part of their structure, such as depleted uranium, that may need to be considered in the consequence analysis. Likewise, the carriage of hazardous goods as part of an aircraft's freight load may need to be considered.

The flight routes taken by airliners have changed over time. The flight routes that were flown on airways were from navigation beacon to beacon. Some aircraft began to carry Inertial Navigation Systems and other wide area navigation systems that allowed air traffic controllers to authorise the pilots to skip some beacons and make more direct flights. After the introduction of Basic Area Navigation in April 1998 (CAA, 2011b), all aircraft equipped to fly instrument flight rules above flight level 100 (approximately 10,000 feet above mean sea level) can now navigate between way points that are defined by geographic coordinates, but not necessarily with a navigation aid below them. This means that the frequency distribution of overflights of any particular location in GB has changed. In some areas away from the traditional airways, airliners now fly more routinely. In other areas, the distribution of flights associated with navigation accuracy issues has become much tighter around the nominal route as higher quality autopilot systems have been introduced and improvements in position determination, such as the Global Positioning System, have been adopted.

The use of remotely piloted aircraft will continue to increase from current levels. Very few operations took place during the accident survey periods associated with the Byrne report and its updates. The mass of the aircraft is expected to increase beyond 15,000 kg with greater fuel loads in the near future.

Military flight operations have changed over time with a reduced frequency of flights over the UK owing to the reduced number of United States Air Force aircraft based in the UK and mainland Europe, the reduced number of British military aircraft in service and the greater use of simulators for training purposes.

Airline operations at some regional airports have increased significantly with the introduction of low-cost services by airlines such as EasyJet and Ryanair. Some of these airports, such as Liverpool, have approach flightpaths that cut through the protective airspace around some licensed nuclear sites under exemptions from the Civil Aviation Authority (as discussed in section 4.4).

General aviation activity has changed over time with the introduction of small business jets into the market and the tendency of small general aviation activity to reflect the available disposable income of private pilots. There can be campaigns by the aviation industry to increase awareness of better flight operational techniques and new procedures to address some hazards, whilst other safety systems such as Extended Ground Proximity Warning System are helping to reduce other hazards. These changes may alter the relative proportion of the different types of accident over time.

The balance also has to be made between world average statistics and the types of accident that European and North American operations tend to consist of.

Overall, the recent changes that have taken place and will continue to take place require re-evaluation of the operational data and accident data in order to ensure that the calculated risk is still valid. This is a requirement set by ONR (section 3.2) and is included as a requirement in the suggested guidance to ONR Inspectors (Appendix C).

3.3 THE PHASES OF FLIGHT AND ACCIDENT PROBABILITY

Many of the accident models consider commercial aircraft accidents onto and into the site. This section has been provided as a background to the different phases of a flight because they usually have different accident probabilities associated with them.

The phases of flight have been defined by the International Civil Aviation Organization and the Commercial Aviation Safety Team (CAST) (CAST, 2013) with the aim of standardising the classification amongst aviation safety analysts. This background section covers the definitions for a flight conducted under Instrument Flight Rules, which covers commercial operations, rather than Visual Flight Rules which would represent most of the private flights carried out as a pastime.

The ground activities that do not involve use of the runway include the taxiing of the aircraft around the aprons and taxiway system; loading and unloading of the aircraft performed at a stand; the aircraft being left parked and unattended as well as the aircraft being towed between parking positions, which may include away from the main area to remote or maintenance areas.

The take-off phase of flight starts from the application of take-off power, through the rotation of the aircraft and up to an altitude of 35 feet above the runway elevation. This phase of flight also includes any rejected take-off manoeuvre.

The initial climb phase of flight starts at the end of the take-off phase of flight and lasts until the aircraft reaches 1,000 feet above the runway elevation or the first prescribed power reduction, whichever comes first.
The climb phase of flight starts from the completion of the initial climb until arrival at the initial assigned cruising altitude.

The cruise phase of flight starts at the end of the climb phase until the start of descent to the destination.
The descent phase of flight starts when the descent from the cruise commences until arrival over the Initial Approach Fix.

The holding phase of flight is when the aircraft executes a predetermined manoeuvre (usually an oval racetrack pattern) within a specified portion of airspace whilst awaiting further clearance to proceed. This is usually over the Initial Approach Fix.

The initial approach phase of flight starts when the aircraft leaves the Initial Approach Fix (after any holding pattern, if required) and lasts until the aircraft arrives at the Final Approach Fix.

The final approach phase of flight starts at the Final Approach Fix to the beginning of the flare manoeuvre (lifting of the nose attitude relative to the horizon) prior to touchdown. If the final approach is abandoned and the crew adds power then this is the start of the go-around phase of flight and the aircraft follows the missed approach procedure until reaching the Initial Approach Fix for another approach.

The landing phase of flight starts from the beginning of the landing flare until the aircraft exits the landing runway; or comes to a stop on the runway; or when power is applied for another take-off in the case of a touch-and-go landing.

The statistics for accidents when split into the different phases of flight may help to build an accurate insight into the likelihood of an individual aircraft accident occurring onto a licensed nuclear site. For example, Lydd airport near the Dungeness licensed nuclear sites, has en-route cruise overflight traffic using a local navigation beacon, holding pattern aircraft awaiting onward clearance into London Gatwick circling slightly lower using the local navigation beacon as well as aircraft arriving and departing from the airport. Not each of these aircraft flights pose the same probability of an accident onto the site. The most recent statistics for western-built commercial jets (Boeing, 2013) give a breakdown for the decade 2003 to 2012 as shown in Figure 1 below.

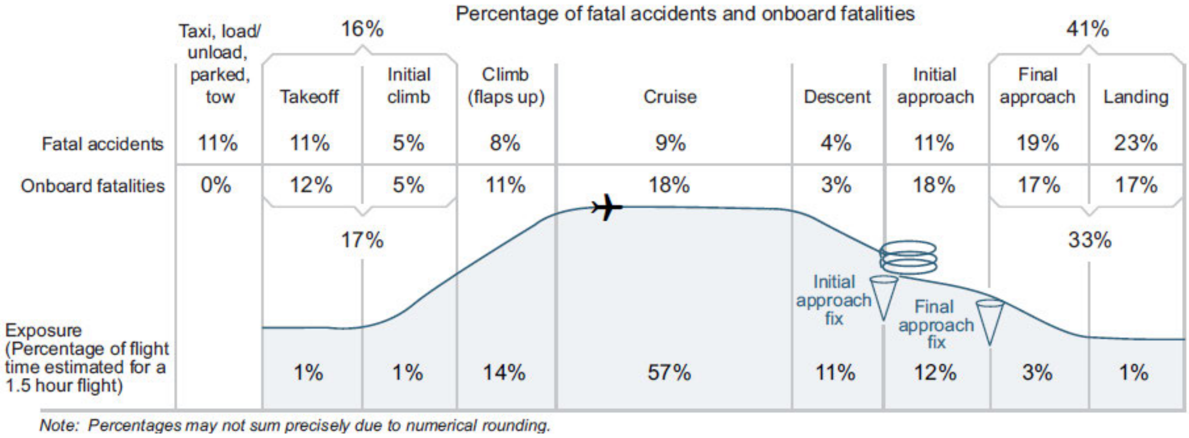

Figure 1: Fatal accidents by phase of flight 2003-2012

Figure reproduced courtesy of Boeing "2012 Statistical Summary report"

It may be reasonable to use this type of phase of flight breakdown as the basis of a model, rather than just a blanket background and vicinity of an airport rate.

3.4 AIRSPACE RESTRICTIONS AROUND LICENSED NUCLEAR SITES

There are 37 sites licensed by ONR and these include research sites, nuclear power plants, nuclear fuel manufacturing, nuclear source manufacturing for medical purposes, fuel recycling, weapons manufacturing and sites undergoing decommissioning. Some of the sites have civil flight activity restrictions placed around them "in the public interest" by the Air Navigation (Restriction of Flying) (Nuclear Installations) Regulations 2007 (Statutory Instrument, 2007) whereas other licensed sites have no protective airspace at all. Any potential site licensee seeking a licence to operate a new location would not be covered by this regulation.

Most nuclear power generation sites have protected airspace that extends approximately 2000 feet above the ground level of the power station and has a radius of two nautical miles (see Table 1 for exact details). Not all flight activity is prohibited within these volumes of airspace. Some have exemptions that allow civilian helicopters to operate to and from the sites. Others have exemptions that allow flights by helicopters to ships and helipads within the protected volumes. The exemptions are not uniform across similar types of sites. The active Advanced Gas-cooled Reactor located near Hartlepool is located approximately 11 nautical miles from Durham Tees Valley Airport and they are on the extended centreline for the approach to Runway 23. Aircraft are allowed to penetrate the protected airspace and fly directly over the site on an instrument approach to the airport (NATS Limited, 2014). This may be compared with the Chapelcross MAGNOX reactors which are being decommissioned by the Nuclear Decommissioning Authority (NDA) where no fuel is on-site (NDA, 2013) and no fixed-wing aircraft are allowed to penetrate the protective volume of airspace.

The Statutory Instrument does not mention the special exemption for aircraft to operate at Brimpton Airfield given by the Civil Aviation Authority (reference is not in the public domain) which is inside the Aldermaston protection airspace. A comprehensive survey of exemptions has not been carried out but it is illustrative that exemptions exist.

The ability of the protected airspace volume to safeguard the licensed sites from a civil aviation accident could be challenged. Firstly, the flights following instrument flight rules in the en-route phase of flight are able to fly directly overhead the plant well above the protected airspace. There are no en-route air traffic control restrictions to prohibit overflight and therefore any mid-air collision; loss of control or in-flight structural failure could lead to wreckage descending directly onto the site.

The elevation of the protective airspace may be adequate to give some element of protection by enabling an aircraft to glide clear of the site in the event of an engine failure. However, gyrocopters and helicopters may not be able to undertake an autorotation manoeuvre at a glide angle sufficient to clear a site. There are additional aviation-related hazardous scenarios that the airspace protection will not eliminate completely. Therefore, the licensed nuclear site operator will still have to carry out an analysis of the probability, frequency and consequence of civil aviation crashes onto and into the site, despite the provision of protective airspace.

Military restrictions are placed by the Royal Air Force's Provost Marshal (Royal Air Force, 2014). In general, licensed nuclear sites have some protected airspace round them. Exemptions to allow military flights into these zones may exist but are not published at the unclassified level for security reasons. However, each individual licensed nuclear site operator should be aware of any such exemptions that may apply, for example, in the event of a terrorist attack or training for a military response to such an event.

Military overflights at altitudes above the restrictions are permitted. Occasional navigation errors have occurred and military aircraft have penetrated the restricted airspace unintentionally. Analysis of the probability of a military flight colliding with the site, either as the result of an aviation-related cause or because the site's vertical structures lead to a collision with a serviceable aircraft are still required for all sites.

Table 1 Protected Airspace Above Licensed Nuclear Sites

Licensed Site	Protected Airspace Radius (nautical miles)	Protected Airspace Altitude above mean sea level (feet)	Exemption to allow helicopters to land on-site?	Other allowable transitions of the protected airspace by civil aircraft
Aldermaston and Burghfield	1.5 1.0	2400 2400	YES	NO[2]
Amersham	No protected airspace for this site			
Barrow	0.5	2000	YES	NO
Bradwell	2.0	2000	YES	Aircraft following an instrument approach procedure at London Southend Airport can penetrate but must not operate lower than an altitude of 1500 feet above mean sea level
Capenhurst	2.0	2200	NO	NO
Cardiff	No protected airspace for this site			
Chapelcross	2.0	2400	YES	NO
Clyde Naval Base	2.0	2200	YES	Helicopters operating to and from ships within HM Naval Base Clyde
Derby	No protected airspace for this site			
Devonport	1.0	2000	YES	Helicopters operating to Plymouth Western Mill Lake Helicopter Site. Helicopters operating to ships within the dockyard.
Dounreay	2.0	2100	NO	NO
Drigg	Partially or wholly enclosed within the Sellafield protected volume		UNKNOWN	NO

[2] It should be noted that Brimpton airfield is contained within the restricted airspace and is not mentioned in the Statutory Instrument. This exemption is granted by the Civil Aviation Authority

Licensed Site	Protected Airspace Radius (nautical miles)	Protected Airspace Altitude above mean sea level (feet)	Exemption to allow helicopters to land on-site?	Other allowable transitions of the protected airspace by civil aircraft
Dungeness A Dungeness B	2.0	2000	YES	Aircraft departing or arriving London Ashford (Lydd) Airport are permitted within 1.5 nautical miles of the centre of the protected airspace volume
Hartlepool	2.0	2000	YES	Aircraft following an instrument approach procedure at Durham Tees Valley Airport can penetrate but must not operate lower than an altitude of 1800 feet above mean sea level
Harwell	2.0	2500	YES	NO
Heysham 1 Heysham 2	2.0	2000	YES	NO
Hinkley Point A Hinkley Point B Hinkley Point C	2.0	2000	YES	Helicopters flying within the Bridgewater Bay Danger Area (a) must remain outside one nautical mile of the centre of the protected airspace volume.
Hunterston A Hunterston B	2.0	2000	YES	NO
Imperial College	No protected airspace for this site			
Lillyhall	No protected airspace for this site			
Oldbury	2.0	2000	YES	NO
Rosyth Royal Dockyard	0.5	2000	NO	Aircraft operating along the Kelty Lane visual flight rules route to/from Edinburgh Airport can penetrate the protection airspace volume
Sellafield	2.0	2000	YES	NO
Sizewell A Sizewell B	2.0	2000	YES	NO

4 SOURCES OF AIRCRAFT ACCIDENT DATA AND DATA ANALYSES

The construction of an accurate model to determine the frequency of an aircraft accident onto or into a licensed nuclear site requires knowledge of the local flightpaths, the number of flights along each flightpath, the probability of any flight having an accident and the distribution of the accident's location around the nominal flightpath. The model requires some knowledge of historic accidents. This section of the report examines sources identifying individual accidents and also some accident data analyses that may be of use in the predictive hazard analysis for a licensed nuclear site.

Most of the aircraft accident databases are focused on fixed-wing aircraft and at the heavier end of the maximum certificated take-off mass aircraft. This usually implies commercial aviation and business aviation accidents. Military and private general aviation flights are not usually listed. Some databases only list events with significant damage to the aircraft (such as 10% of hull value) and may not list an event such as a runway excursion where no significant damage or injuries were sustained. Events such as runway excursions with minimal damage are not likely to be relevant to this review as the aircraft's ground run does not usually exceed the aerodrome's boundary.

Some databases exclude aircraft built in the former USSR. Whilst most commercial flights by former Warsaw Pact airlines that fly to, from and over the UK use western built aircraft these days, there are some jet aircraft cargo flights that involve aircraft such as Antonov AN-74, AN-124 and AN-225, as well as the Ilyushin IL-76TD-90VD. There are also some turboprop cargo flights by AN-26 and IL-18 aircraft. Modifications to accident rates may be necessary if these aircraft operate into an airport close to a licensed nuclear site.

Other non-European countries that have produced commercial aircraft include China, Japan, Indonesia and Brazil. The project team did not know of any commercial aircraft that were built in China, Japan or Indonesia that operate into or over GB but it may be possible that these aircraft are infrequent visitors, such as to the Farnborough Air Show. Brazil is now a major manufacturing force in the regional aircraft business. Most of the databases include Embraer aircraft in their accident listings. The Brazilian built turboprops are operated infrequently into or over GB but the commercial jet and business jets are operated routinely by British airlines and businesses, as well as foreign concerns.

Data references have been provided for flight operations beyond GB as the British statistics contain so few accidents. These sources include flight operations over mainland Europe, North America, New Zealand and Australia. These areas were included as the authors considered that these flight operations may be representative of the aircraft types, types of flight operations, meteorological and topographical conditions, flight crew culture, maintenance regimes, security and regulatory regimes that were sufficiently similar to operations within GB. Data that includes worldwide statistics may have to be modified to reflect the national conditions experienced within GB airspace.

4.1 STATISTICS PUBLISHED BY CIVIL AVIATION ADMINISTRATIONS AND ACCIDENT INVESTIGATION AGENCIES

The International Civil Aviation Organization (ICAO) (the aviation equivalent of the International Atomic Energy Agency) carries out statistical analyses of global aviation safety but focused on commercial airline activity. Traffic figures are given for each ICAO region, including Europe in terms of the number of scheduled flight departures annually between 2005 and 2010 inclusive. Accident trends are plotted for the same time period as well as a breakdown into four categories of accident (the "high risk" category of runway safety related, loss of control in-flight and controlled flight into terrain, and then others) which may be a useful guide if detailed analyses of hazardous scenarios are required. For example, the operator of a licensed nuclear site may wish to screen out "controlled flight into terrain" if it can be shown that their physical site's location is not prone to this type of aviation accident. However, focus may be given to a loss of control in-flight type of accident as these flights could fall into a wide corridor around the intended flightpath. Similarly, screening of runway safety related accidents may be possible if a licensed nuclear site is located a significant distance from aerodromes.

The European Aviation Safety Agency (EASA) provides an annual flight safety report (EASA, 2013) and this includes statistical analyses for all types of general aviation and commercial aviation within their geographic boundary, which includes the United Kingdom. The only significant category that is omitted from this analysis is remotely piloted aircraft. The maximum certificated take-off mass categories used have boundaries at 2,250 kg, 5,700 kg, 27,000 kg and 272,000 kg. These boundaries differ from those used in other statistical breakdowns with the exception of the 5,700 kg category which is used relatively often in aviation statistics. Fatal accidents from around the world are listed for all aircraft types above 2,250 kg in commercial operation.

Aviation accidents within the UK as well as aviation accidents involving aircraft appearing on the UK register but operating overseas were analysed by the Civil Aviation Authority for the decade 1992 to 2001 (CAA, 2002) with an update included in the 2011 safety performance review (CAA, 2011c). The data analyses contained within these two reports may be very useful as a source of accident rates as it includes specific breakdowns for some of the special operations (such as police helicopters in the first report and gliders in the second) that other sources do not provide.

The Air Accidents Investigation Branch of the Department for Transport (formerly known as Department of Transport and later the Department for Environment, Transport and the Regions) has individual accident reports available via its website (www.aaib.gov.uk) and earlier reports are available either from their library, the Civil Aviation Authority library or the National Archive. This will cover all civilian aircraft accidents occurring within GB and coastal waters.

The Department for Transport (DfT) carries out an annual evaluation of casualties resulting from aviation activities in the United Kingdom (DfT, 2014) but most of the other published data are too high level to be of interest to this project. A search for operational data is best carried out using statistics from the Civil Aviation Authority. Reference to third party risk in a nuclear site's safety case may make reference to the DfT publication but it should not be the sole source for crash risk frequency calculations.

The Transportation Safety Board of Canada (TSB), the national aircraft accident investigation agency for Canada publishes an annual analysis of aviation safety occurrence statistics (TSB, 2014). This publication includes several accident rates that may be of interest. Ultralight aircraft, balloons, gyroplanes, gliders and airship data are not included in the analyses.

The Australian Transportation Safety Bureau (ATSB), the national aircraft accident investigation agency for Australia carries out safety analyses as well as accident investigation. Their most recent report (ATSB, 2012) examined occurrences from 2002 to 2011. This report provides useful accident rate data that can be used as a sensibility check on calculated rates for GB but the accident rates may not be directly transferrable. The main reason for some accident rates not being suitable for application in GB is the different climate. Suitable screening of the data may allow the accident data to be used.

The National Transportation Safety Board (NTSB), the national accident investigation agency for the United States of America, publishes an extensive set of accident reports and statistical analyses. The publications include a review of civil aviation accident rates from 2011 (NTSB, 2014) which includes potentially useful accident rate data. Some data relating to flight activity and accidents are provided in downloadable CSV files (http://www.ntsb.gov/data/aviation_stats_2012.html
Data from this source were used in the analyses carried out in this report.

The Federal Aviation Administration (FAA), the national aviation safety regulator for the United States of America, publishes flight activity statistics on its website
(http://www.faa.gov/data_research/aviation_data_statistics/general_aviation/)
as well as fatal accident statistics derived from quarterly reports (http://www.faa.gov/about/plans_reports/Performance/quarter_scorecard/). Data from these sources were used in the analyses carried out in this report. A more in-depth analysis could be carried out using the FAA Aviation Safety Information and Analysis Sharing system http://www.asias.faa.gov/pls/apex/f?p=100:1.

The Civil Aviation Authority of New Zealand published a report relating to their fixed-wing accidents between 1995 and 2004 (Wackrow, 2005) and more recent individual accident reports can be found via the national aircraft accident investigation agency (www.taic.org.nz). Wackrow's analysis includes accident rates per flight hour for different operational groups. These rates may be used as a sensibility check on other rate calculations for GB but may not be suitable for direct use without screening the data for climate and topographical factors.

4.2 STATISTICS PUBLISHED BY TRADE BODIES, MANUFACTURERS AND PROFESSIONAL CONSULTANCIES

The main airline trade body is the International Air Transport Association (IATA). Their statistics may be useful in determining the general amount of aviation traffic if worldwide accident statistics are to be used. They publish safety data analyses (via their website: www.iata.org) at various times and this may include statistics showing a balance between airlines that they represent and others, as well as general regional variations in accident rates. There may be a commercial fee for accessing further data from this source. The main airlines that are not represented by IATA that operate around Europe are the low-cost carriers. A search of the European Low Fares Airline Association did not reveal any relevant statistics.

Boeing Commercial Aircraft, a manufacturer of a significant proportion of the world's jet airliners produces an annual statistical summary of jet airliner accidents (Boeing, 2013) which includes very useful breakdowns of loss rates. The data includes accident rates per aircraft type and an analysis of the phases of flight when the losses have occurred. It may be reasonable to use the Boeing data, and extrapolation to turboprop aircraft for the phase of flight analysis, in any model of accidents onto or into a licensed nuclear site.

The main source of aircraft accident data used within the Byrne and NATS models comes from a database operated by Ascend (www.ascendworldwide.com), formerly known as Airclaims, and was the origin of the Worldwide Aircraft Accident Summary published by the Civil Aviation Authority (publication since discontinued). Ascend is now part of the Flightglobal group that includes Flight International magazine. This database is used extensively by the aircraft insurance industry and has worldwide coverage. Access is via a subscription basis and data can be purchased under a licensing agreement. It is possible to build up aircraft loss data from the archive material published within Flight International magazine (www.flightglobal.com) using the search term "commercial aviation safety" and "general aviation safety" for data up to the end of 2004. A search of the paper copies of the magazine would be necessary to complete the data if a subscription were not purchased. The data published by Ascend may be considered to be authoritative and suitable for reference.

The International Association of Oil and Gas Producers (OGP) has published a guide to enable its members to evaluate risk to workers related to aviation flight activities (OGP, 2010). Various datasets are used and cover flight activities from the late 1990s to around 2006. The analysis includes helicopter activities in greater detail than found in most other locations, on the basis that many commercial helicopter flights are carried out in support of oil and gas related industries. The publication was considered to be a suitable source for reference.

The Aviation Safety Network database http://aviation-safety.net/database is maintained in cooperation with the Flight Safety Foundation. The Flight Safety Foundation is an international, independent organization that is well respected and draws on expertise from around the world to produce its reports. This database was considered to be a suitable source for referencing accident data. The statistics section had some data breaking down accidents by phase of flight which may be useful when combined with the Boeing data.

4.3 OTHER CIVIL DATABASES

The Jet Aircraft Crash Data Evaluation Centre, based in Hamburg, has an extensive database of aircraft accidents. Their website (www.jacdec.de) was being overhauled as this report was published. This database is accessible via subscription. The project team could not carry out an evaluation of the scope, contents, usability and usefulness of this source of accident data.

A comprehensive listing of over 5,000 accidents is available from the website
http://www.planecrashinfo.com/database.htm
The database includes all civil commercial aviation accidents for scheduled and charter airlines involving a fatality; cargo, positioning, ferry and test flight fatal accidents; military transport accidents with 10 or more fatalities; all commercial and military helicopter accidents with greater than 10 fatalities and fatal airship accidents. The database is a listing of accidents on an annual basis. There is no search engine for the database. The database may serve as a useful check that recent accidents that may be relevant to the scope of this project have been included. The website also includes some accident data analyses but these are not of sufficient quality or depth of analysis to be useful to the intended audience of this report.

Airline analysis, aircraft type analysis and other statistical data are available from www.airsafe.com. The website includes an analysis of accidents occurring to European airlines. This website did not add significantly to the volume of data that were available from other sites and was not available for searching a significant period of time. The project team considered that other data sources were available that could be accessed more easily than this website.

The Cabin Safety Research Technical Group have a database operated by R.G.W. Cherry and Associates Limited https://www.fire.tc.faa.gov/adb/adb/ADBlist.asp The latest data included appears to be up to the end of 2011. The database can be exported. The database was not the most comprehensive scope. The contents relating to an individual accident suited the aims of the database but were not necessarily aligned with use for evaluation of a licensed nuclear site. The database was not particularly user friendly in its search functions. Overall, the project team did not consider that this website was superior to others and discounted it from further consideration.

A frequently quoted database is http://www.airdisaster.com/ but updates to this site appear to have stopped in a systematic basis around 2010 although some news items have been posted since then. The database's scope is related to commercial aviation flights and is reasonably comprehensive until around 2010. The data includes aircraft built anywhere in the world. The database was considered to be a useful backup resource to other sources of data and may be used to help identify accidents of interest as the accident description section was relatively comprehensive. This may allow screening out of irrelevant accidents from any dataset. The project team considered that the statistical data analyses were out-of-date.

The Bureau of Aircraft Accident Archives' database has approximately 20,000 accident and incident records available. A search engine allows the accident within 10 km of an airport to be identified, or screened out of the results. This may be a useful feature when building models for accidents within the vicinity of aerodromes and background crash location data. The search engine was relatively easy to use. The scope of the accidents covered includes some of the relatively low maximum certificated take-off mass aircraft if they are engaged in commercial operations. The project team considered that the statistical data analyses published on the website were not particularly useful. The website can be accessed via: http://www.baaa-acro.com/

The University of Warwick held a database of commercial aircraft accidents. Their website (www.air-accidents.warwick.ac.uk) was not functioning when access was attempted during the timescales of this project. It was not established if the database has been withdrawn or if it is a technical fault. The project team could not carry out an evaluation of the scope, contents, usability and usefulness of this source of accident data.

Loughborough University has its own comprehensive database of aircraft accidents at, and in the vicinity of, aerodromes based on data from the United States of America. This database was used within this project.

4.4 MILITARY AVIATION

The aircraft losses associated with military activities are published into the public domain after presentation to Parliament. The National Archive has records available for searching, assuming that they have been declassified to an appropriate level. These can be found using the search term "military aircraft accident summary" or "service inquiry" on the www.gov.uk site.

Three alternative sources of military loss data were identified during the project. The website www.ukserials.com has more than 50 years of data listed on an annual loss basis and is a searchable database. The Dutch military aviation enthusiasts' site www.scramblemagazine.nl has a database but this is subscription based. An authoritative database of worldwide military losses is published by Ascend in the magazine Flight International. This may be accessed via the corporate website www.flightglobal.com for back copies up to around 2005 using the search term "military safety". Paper copies of the magazine may be necessary to complete this list. Alternatively, the data can be purchased from Ascend.

5 ANALYSIS OF PUBLISHED ACCIDENT LOCATION LITERATURE

A variety of models were identified during the literature search. Their geographic scope included general background crash locations away from airports (off-airport); within the vicinity of an airport, usually examining third party risk around airports up to a distance of approximately 10 statute miles; and on-airport models concentrating around the runway and its safety areas. For the purposes of this report, it was assumed that no licensed nuclear facilities would be built either within the boundary of an active aerodrome (whether or not it had been licensed by the Civil Aviation Authority or approved by the Military Aviation Authority); or in an area corresponding to 300 metres beyond the start/end of any runway and a width of 150 metres either side of the centreline of any runway if this rectangular area extended beyond an aerodrome's boundary. Whilst some models covered the vicinity of the aerodrome and inside the aerodrome's boundary, the mathematical modelling errors very close to the runway could be ignored.

The review criteria for the models considered how the frequency of flights were taken into account; the probability of an individual flight having an accident; how the individual flight's probability varied along the nominal flightpath and phase of flight; how the model accounted for the distribution of the point of first impact around the nominal flightpath; as well as how the angle of impact and length of wreckage trail were accounted for.

It was recognised that the probability of an accident per flight depended upon the type of flight being performed and the type of aircraft involved. Therefore, flights were separated between civilian and military and each category was then further sub-divided according to aircraft operating characteristics.
The characteristics of fixed-wing aircraft were split into commercial jet operations, commercial turboprop operations, commercial piston engine operations and business aviation. General aviation was split between single engine and multi-engine operations. A specific category of low-level flight operations was included to encompass operations such as coastguard patrols; air displays and agricultural crop spraying activities. It was recognised that vintage aircraft may have higher accident rates than more modern aircraft. This may arise because of difficult maintenance, fatigue, poorer flight performance and more difficult pilot handling skill requirements. It has also been recognised that "foreign operators" (for example, those outside western Europe, North America, Australia and New Zealand) may have a higher accident rate per flight and also that freight/cargo operations may have higher accident rates per flight. How the frequency of crashes onto any particular location took these historic data analyses into account was also considered when examining each model.

The operation of civilian helicopters was split into commercial multi-engine operations, commercial single-engine operations and private flights. A specific classification of low-level flight operations was included to encompass operations such as search and rescue, ambulance evacuation, police and infrastructure inspection activities.

The operations of other types of manned flying machine were split into the individual groupings of: gyrocopters, gliders, airships, gas balloons and hot-air balloons. Civilian and military operations were combined for these types.

Unmanned aerial vehicles were considered as a single group for all operations.

Military aircraft were split into four basic categories of light trainer, fast-jet, transport and helicopters. The light trainer aircraft included the ab-initio training aircraft which were single-engine. The fast-jet category included what may be thought of as fighters and bombers, usually jet powered and usually either single or twin engine. The transport category included passenger and freight transporters, refuelling aircraft and surveillance aircraft. The helicopter category included all rotary-wing aircraft.

The models were examined to see if they catered for all aspects of flight operations overhead any specific location and the different probability of an accident for each phase of flight. The operations that were identified as of relevance were conventional take-off and landings at airports (and any associated go-around manoeuvres), circuit flying for pilot training at airports, climb and descent phases of flight, en-route cruising at fixed levels and climbs associated with fuel-burn, and holding patterns awaiting further clearance to proceed along the intended track. Holding patterns can be particularly problematic for crash calculations because although the probability of an accident is relatively low, the aircraft can make many passes overhead a beacon (and thus within the vicinity of a licensed nuclear site) prior to onward clearance. For example, inbound delays of 40 minutes may mean 10 passes around the four minute race track pattern before making an approach, thus increasing the number of passes but without increasing the actual number of individual flights passing a specific location. The mid-air collision probability in a holding pattern used to be relatively high although this has reduced with technology advances implemented since the original Byrne report.

The scatter of the point of first impact laterally around the nominal flight route is a significant element of the review criteria. The accuracy of prediction for points of first impact depends upon knowing where the aircraft should have been rather than trying to make a mathematical model from a scatter plot. This is particularly important for models that consider aspects of flight other than straight-in approaches to runways. Background distribution of accidents across a whole country may be conservative in areas with relatively few flight operations but may significantly underestimate the hazard frequency if there are many flight operations overhead the site being considered. Models of crashes in the vicinity of airports that do not consider circuit patterns and turns made by departing aircraft may underestimate the hazard frequency if there are flight routes close by but be conservative if the normal routes flown by local traffic are concentrated elsewhere.

Aircraft accidents have different ranges of angles of impact depending upon the type of accident being considered. A loss of control accident associated with a stall may have a relatively steep angle of descent to the ground. A controlled flight into terrain or a man-made obstacle may have a very shallow impact angle. How these factors are accounted for in each model was considered in the review either as a direct consideration of the impact angle or as a modification of the shadow area of the site.

The angle of impact affects the wreckage trail length and lateral scatter, as do various other aspects of the aircraft's structural design, ground features, obstacles and their frangibility, as well as initial impact groundspeed. How each model accounted for these variables was considered within the review criteria. The review criteria included consideration as to whether the models considered three separate hazardous scenarios. These were the calculation of "beyond design case" accidents (which were aircraft operations that exceeded the structural impact design criteria); the wreckage associated with an aircraft accident striking the plant (direct impact, sliding into the plant or post-crash missile projection); and the loss of external services to/from the plant relating to a crash in the vicinity of a licensed nuclear site but not necessarily directly onto the site.

The usability and usefulness of each model was evaluated in qualitative terms.

The review is presented in terms of the estimated time that each model was first published. The models are described in terms of what they do account for and general comments may be given for what is not taken into consideration when compared with the review criteria. A results table is presented at the end of each model's review to provide an overview of the model. The generic format is given below.

Review Criterion	Review Comment
Location	Background and/or vicinity of an aerodrome
Flight frequency	How this was considered
Fixed wing	Civil and/or military; classes of aircraft
Helicopters	Civil and/or military; classes of aircraft
Gyrocopters	Considered or not
Gliders	Considered or not
Airships	Considered or not
Balloons	Considered or not
UAVs	Considered or not
Phases of flight	Which phases are considered
Impact scatter	How the lateral distribution of point of first impact was considered
Impact angle	How the range of impact angles were considered
Wreckage trail	How the trail length and lateral distribution were considered
Hazard scenarios	Which of the four hazardous scenarios were considered
Usability/useful	General comments

Not all aspects of the review criteria were applied to each model if the reviewers considered that the model was unsuitable for application within a licensed nuclear site's safety case.

5.1 THE CHELAPATI MODEL (1972)

This extensive paper (Chelapati et al., 1972) considers the probability, location and subsequent structural consequences of an aircraft striking a nuclear power plant. The model caters for sites located within a five mile radius of an aerodrome (vicinity of an aerodrome) and areas outside that circle (background).

The model uses a simple ratio between background risk and vicinity of an aerodrome accident frequency as a factor of approximately 2.3 increase over the background rate if the site is within the vicinity of an aerodrome. The reviewers considered that the simple risk ratio was unrepresentative of the ratio that could be applied generically across GB. The model used data from the 1960s that the reviewers considered were unrepresentative of modern accident data.

The model was rejected as unsuitable as it was considered to be too inaccurate for application in Great Britain.

Review Criterion	Review Comment
Location	Background and vicinity of an aerodrome
Flight frequency	Simple risk ratio and 1960s data
Usefulness	REJECTED

5.2 THE HORNYIK MODEL (1974)

The initial model (Hornyik and Grund, 1974) and minor update (Hornyik, 1997) examined the likelihood of a military aircraft in a racetrack bombing pattern striking a nuclear plant in the vicinity of the bombing range. The model was extended to include a military racetrack circuit pattern at an aerodrome for pilot training in take-off and landings. The model accounted for both the standard aircraft accident and also the plant acting as an obstacle to an otherwise safe flightpath. Civilian aircraft operations were not considered in detail within this model. It was noted that the probability of an accident, when measured on a per flight basis varied between civilian and military operations and also the variation in accident rate depending on weather conditions was noted.

The paper attempted to reduce the uncertainty by balancing best estimate techniques with conservative simplifications or an increase in analytical effort to produce lower uncertainty for parameters within the model.

An assumption was made that any nuclear site would not be located very close to the bombing target so the mathematical discrepancies around the target point could be ignored. This would appear to be a reasonable assumption if the model were to be applied in GB but this would have to be highlighted in the relevant safety analysis documentation.

Deviations from the nominal flightpath were modelled using Gaussian distribution with a greater standard deviation and weighting factors to account for various unknown and random combinations of flightpath deviation. A model using polar coordinates was developed for the flightpath. It was noted that the nominal lateral deviations around the flightpath had considerably less spread than the impact site deviations so the flightpath lateral deviations could be ignored. A fraction of the accident rate was discounted to account for a pilot's ability to manoeuvre an aircraft away from the nuclear site.

The theoretical model may be enhanced through the use of more recent data as the data available at the time of initial publication was sparse. The statistical significance of applying the model in its current form will be low. Many of the assumptions need to be validated through further analysis prior to its application within GB. However, it remains the only published literature as to how to calculate crash rates in the vicinity of military bombing ranges based on the nominal flightpath rather than analysis of historic crash locations around bombing ranges.

Review Criterion	**Review Comment**
Location	Vicinity of a bombing range and military circuit patterns
Flight frequency	How this was considered
Fixed wing	Military bombers only
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Racetrack pattern for target practice
Impact scatter	Assumptions made based on unpublished historic data review
Impact angle	Assumptions made based on unpublished historic data review
Wreckage trail	Assumptions made of 500 mph fighter/bomber and unpublished historic data review
Hazard scenarios	Standard accidents and collisions with obstacles
Usability	Polar coordinates make it difficult to integrate with other models.
Usefulness	This model can be used after validation of assumptions but integration with other models may be difficult because of different coordinate selection.

5.3 THE AMERICAN STANDARD NUREG-0800 (1975 ONWARDS)

The nuclear licensing standards for use within the United States are published by the United States Nuclear Regulatory Commission (US NRC) as a series of nuclear regulations, known as NUREGs. The regulation published for the evaluation of aircraft related hazards (US NRC, 2010) requires the operator to consider airports, federal airways, holding and approach patterns as well as military airports, training routes and training areas.

The regulation allows for a screening review and the risk is considered to be acceptable if three conditions are met in their entirety:

A. The plant-to-airport distance D is between 5 and 10 statute miles, and the projected annual number of operations is fewer than 500 D^2, or the plant-to-airport distanced D is greater than 10 statute miles, and the projected annual number of operations is fewer than 1000 D^2.
B. The plant is at least 5 statute miles from the nearest edge of military training routes, including low-level training routes, except for those associated with usage greater than 1000 flights per year, or where activities (such as practice bombing) may create an unusual stress situation.
C. The plant is at least 2 statute miles beyond the nearest edge of a Federal airway, holding pattern, or approach pattern.

The assumption was made that if all three conditions are met then the probability of an aircraft accident onto and into the plant has a probability of less than $1x10^{-7}$ per year. This assumption has not been justified with references to current calculations. Whilst it is beyond the scope of this report to comment on the chosen target level of safety, the validity of the screening criteria listed above must be questioned for application in GB given the lack of referenced data and calculations.

A detailed review must be carried out if these screening conditions are not met. The detailed review can use the formulae and data suggested within the regulatory document to build up the overall accident rate. The airway contribution is built up of a crash rate per mile for aircraft multiplied by the number of flights per year along the airway and multiplied by the area of the facility. This calculated value is then divided by a factor that is meant to represent the horizontal distribution of accidents from the airway's centre line. This is given as either the width of the airway (if the facility is directly below the airway) or the width of the airway plus twice the distance from the plant to the edge of the airway if the facility is adjacent to the airway and not below it. No justification is referenced for this horizontal distribution.

A formula is given for civilian and military airports and for heliports. The probability for an accident per square mile variation with distance from an airport is given by a table which then has to be multiplied by the relevant movement rates. This table comprises data from the early 1970s (Eisenhut, 1973) and is not a smooth degradation of probability with distance from the airport. For example, the distance from the end of the runway values for US air carriers (airlines) in the four to five statute mile distance is given as a probability of $0.27x\ 10^{-8}$ with the five to six statute mile band decreasing to zero before increasing to $0.14x10^{-8}$ in the eight to nine statute mile band. The table does provide for both military and civilian operations in a total of four separate classes of aircraft operations.

A category of designated airspace is given to account for special operations in the vicinity of the plant. The airspace designation may be for military training or other uses. No data are provided for this background crash rate. A site specific calculation of the background crash rate per unit area in the designated airspace and the site area are required.

The final item that has to be considered under these regulations are holding patterns. The calculation considers that the number of holding operations should be converted into an equivalent number of en-route passages. No mention is made of adjusting the accident rate per passage for this phase of flight. Given the lack of clarity in the screening criteria and the issues associated with the airport crash data rates, the project team considered that this model was not suitable for application in the licensing of nuclear sites in GB.

Review Criterion	**Review Comment**
Location	Generic including vicinity of aerodromes and background.
Flight frequency	User required to collect data for screening and if further analysis was required then additional data collection may be required.
Fixed wing	Civil split into commercial and general aviation, military split into US Air Force and US Navy/Marine Corps. US Army not included. Average rates for crashes given with no confidence limits or identification of specific aircraft with above average accident rates.
Helicopters	Helicopters were included in the crash rates
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Racetrack pattern for target practice
Impact scatter	Assumptions made based on unpublished historic data review
Impact angle	Assumptions made based on unpublished historic data review
Wreckage trail	Assumptions made of 500 mph fighter/bomber and unpublished historic data review
Hazard scenarios	Standard accidents and collisions with obstacles
Usability	Polar coordinates make it difficult to integrate with other models.
Usefulness	This model can be used after validation of assumptions but integration with other models may be difficult because of different coordinate selection.

5.4 THE SOLOMON MODEL (1988)

One paper relating to the Solomon model (Solomon, 1988) was obtained whereas other works by the author from his time at the University of California in the 1970s could not be obtained. The paper gives generic guidance as to how to model accident frequencies and builds on the models referenced earlier in this review.

Data are provided for accident rate per million miles flown in different phases of flight based on an average value derived from a review of accidents in the United States between 1967 and 1984-5 timeframe. The military accident rate was estimated and a value of five times the US commercial air carrier rate was chosen. The en-route cruise phase of flight was defined as being from five statute miles beyond the departure aerodrome to five miles before the arrival aerodrome. This allocation of phases of flight into take-off, in flight and landing may be a simplification but may provide an underestimate of the crash frequency in the area slightly beyond five miles from the aerodrome.

Equations are provided to calculate the effective area of the plant and the skid area to provide a total target area. Values are given for the skid distance of 0.3 statute mile for US commercial air carrier, 0.6 statue mile for military aircraft and 0.06 statue mile for general aviation. These values were referenced from earlier work carried out by Solomon (1974) but the analysis could not be reviewed as the report could not be accessed.

A sample calculation is provided for a plant affected by several aerodromes and an airway. Guidance is given for best estimate and pessimistic analysis techniques.

Comments were given that flight category and flight mode were the most important influences on accident rate. The paper indicated that weather conditions were related but not strongly whereas pilot experience and different aircraft types were not related significantly. The statement relating to aircraft type included a comparison of the Boeing 707 and the DC-10 and concluded that their different accident rates were associated with statistical variation and not one aircraft being inherently safer than the other. The difference in fatal accident rate is at least a factor of three (Boeing, 2013, p.19) and it would be more exaggerated when comparing the Boeing 707 with modern airliners.

The model had a unique feature in its consideration of surface to air missiles and it should be noted that missile always referred to this type of projectile, rather than parts of an aircraft following an in-flight break-up.

The model was simple to apply but suffered from the use of historic data and potential oversimplification of flight routes.

Review Criterion	**Review Comment**
Location	Generic including vicinity of aerodromes and background.
Flight frequency	User to collect data on all flight operations in the vicinity of the site.
Fixed wing	Civil split into commercial and general aviation as well as military. Surface-to-air missiles were also included.
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	All, simplified to three groups
Impact scatter	Not mentioned specifically
Impact angle	Stated that skid distance more significant than impact angle assumptions
Wreckage trail	Analysed data, not reviewed within this project
Hazard scenarios	Standard accidents
Usability	Relatively easy to use
Usefulness	Worth considering as the basis of a new model

5.5 THE KOBAYASHI MODEL (1988)

The paper (Kobayashi, 1988) suggested a combination of existing and a new model in order to determine the aircraft accident probability at a specified location. A total of five models were combined to generate the generic model.

The first model was to be used to evaluate the accident frequency close to an airport. The model (Vallance, 1972) was based on the contribution of a specific aerodrome to a specific nuclear site. The flightpaths at this particular airport may not represent the flightpaths at other airports. No significant description of the flightpaths was provided. This model was to be used for the contribution to the aircraft crash frequency associated with operations with five miles of an aerodrome. The point at which the five mile radius started was not described in the paper. This could be at the start/end of the runway, in the centre of the runway or at the aerodrome reference point (the nominal published location of the aerodrome). The model was considered to be inaccurate from the description given by Kobayashi and no attempt was made to source the original model.

The second model for use beyond the five mile radius of the aerodrome (Niyogi et al., 1977) assumed that the flightpaths were axisymmetric. This assumption was considered to be flawed by the project team.

The third model was for use when an aircraft was in a straight flight direction and at cruise altitude. This model was published by Solomon but an earlier paper (1976) than reviewed in the previous section (1988). The differences in the model's development over time were not known. Solomon proposed a lateral distribution (x) of crashes around the nominal flightpath based on a decay constant (g) and using the formula:

$$\text{Crash site distribution function} = (g/2).e^{-gx}$$

The origin of the formula was not stated in the Kobayashi paper and a copy of the Solomon paper was not found. The decay constant was given values of 1.0 per mile for military aircraft and agricultural aircraft; 1.6 per mile for commercial operations and 2.0 for general aviation flights. The project team could not verify these values.

The racetrack holding pattern was taken from the Hornyik model but it appeared to be the bombing range pattern that had been referenced rather than a general holding pattern or circuit practice pattern. The final model is for free flight and assumes a uniform distribution of flights, flight directions and accident locations. This model was proposed by the author and reference made to a model by Sutterlin (1975) used in the calculation of military crash rates in the former West Germany. This model does not represent the actual flightpaths and therefore may be optimistic or pessimistic in the calculated results. Overall, the project team considered that whilst an attempt to combine various models was a good idea to address the various different phases of flight, this combined model did not produce accurate results. This combined model was rejected from further consideration because many of the aspects were unjustified and the crash distributions could not be verified.

Review Criterion	Review Comment
Location	Generic including vicinity of aerodromes and background.
Flight frequency	One main value chosen for some of the calculations
Fixed wing	The split and values for crash rates were not mentioned specifically but values were calculated but not necessarily reproducible.
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Split into two vicinity of airport models, en-route cruise, racetrack and free flight.
Impact scatter	Distribution function suggested but not justified

Impact angle	Not mentioned specifically
Wreckage trail	Not mentioned specifically
Hazard scenarios	Standard accidents
Usability	Combination of previous models
Usefulness	REJECTED

5.6 THE DAVID ANALYSIS (1990)

The Federal Aviation Administration carried out an examination of over 500 accident and incident records from events occurring between 1978 and 1987 (David, 1990). The appendices contain data extracted from the accident and incident records relating to the location of the accident relative to the runway used, or intended to be used, by the flights involved in the events.

The data filtering reduced the number of events examined down to 246. The convention of distance x, measured from the threshold of the runway along the centreline of the runway for approaches, was established in this report. The distance x for overruns and take-offs being measured from the "departure" end of the runway was also established as the convention, with perpendicular distance being given as y.

The concept of "departure" end of a runway is not well defined in airport terminology. It is not clear if David understood the difference between the take-off threshold in the reciprocal direction, the end of a stopway available for rejected take-offs, the end of the runway's take-off run available for departures to have wheels on the ground or the end of the stopway by which departures must have reached the relevant safety height above the end of the runway and be established in a climb. This confusion is common and may have affected the accident investigators in their initial on-site work.

The report provides a series of histograms showing the number of events against distance along the centre line as well as x, y plots of locations. No statistical curve fitting was attempted or formulae suggested in the report. The report should be treated as a valid data source for models at and in the vicinity of an aerodrome but does not provide any model that can be applied.

Review Criterion	Review Comment
Location	Vicinity of a runway
Flight frequency	Not examined – historic crash report analysis only
Fixed wing	Civil aircraft operating on commercial flights
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Take-off, initial departure, landing
Impact scatter	Single location given for wreckage location
Impact angle	Not mentioned specifically
Wreckage trail	Not mentioned specifically but can be inferred as the reports are referenced
Hazard scenarios	Standard accidents
Usability	Combination of previous models
Usefulness	Source of data for on aerodrome and vicinity of aerodrome models

5.7 THE DNV MODEL (1990 ONWARDS)

Det Norske Veritas (DNV) were commissioned by the Dutch government to examine the third party risk exposure around Amsterdam Airport Schiphol (DNV, 1990). The London office (originally called Technica and then DNV Technica) developed the model. DNV merged with GL in 2013 to form DNV GL. The model is usually referred to as the DNV model and this convention will be retained in this report. The model was applied at the Manchester Airport public inquiry for the planned developments of new runways (Department of Transport, 1995).

The model was developed into a computer program AIRCRASH. This computer program was updated to include the 1997 NATS model for comparison (Smith, 1998). The search of published literature indicated that the model does not appear to have been updated since that time. Given that Smith reported a good degree of agreement in the calculated results between the DNV model and other methods, and with AIRCRASH including the NATS 1997 model, the DNV model appeared to offer no unique features or benefits of application that other models would not provide. The lack of reported updating to the model and recent application of the model indicated that no significant benefit in changing to this model, when compared to the updated Byrne models or changing to the NATS model, would arise from its use by the operators of licensed nuclear sites.

Review Criterion	Review Comment
Location	Vicinity of a runway
Flight frequency	Considered
Fixed wing	Civil aircraft operating on commercial flights
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Take-off, initial departure, landing
Impact scatter	Considered but no model specified
Impact angle	Not mentioned specifically
Wreckage trail	Considered but no model specified
Hazard scenarios	Standard accidents
Usability	AIRCRASH computer model was not evaluated.
Usefulness	REJECTED

5.8 THE NLR MODEL (1993 ONWARDS)

The Dutch National Aerospace Laboratory (Nationaal Lucht en Ruimtevaartlaboratorium) (NLR) has been involved in the modelling of third party risk exposure in the vicinity of aerodromes since the El Al Boeing 747 freighter crash into a suburb of Amsterdam in 1992. Their original model was published in 1993 (Piers et al) and improvements were made to the curved departure track accident location model (Couwenberg, 1994) with an update to the model being published in 2000 (Pikaar, Piers and Ale). The possibility of changing the model towards a causal probabilistic model working dynamically was explored (Roelen et al., 2000). Recent model updates and further commercial applications of the model are not reported in the public domain although they are likely to have occurred (e.g Frankfurt Airport application in 2003).

The model consists of three main elements: a calculation of accident probability based on the movement rate at the aerodrome and the accident rate per flight; the local flight route structure and an accident location model; the local probability model is determined from combining the previous two models and then a consequence model is added to calculate the risk exposure.

The calculation of accident probability was carried out using standard methods of historic data searches of accident reports and subjective screening for relevance. The screening for Amsterdam Airport Schiphol included use of data from first world countries and the use of accidents occurring at large aerodromes only. The aerodrome factors have included criteria such as: approach radar being available; weather data broadcast over the radio on a routine basis; no terrain, obstacles and vegetation higher than 2000 feet above aerodrome elevation within six nautical miles of the aerodrome; weather and operational circumstances not significantly different from the study aerodrome; at least 90% of traffic originating from North America and countries that were members of Joint Aviation Authorities group (predominantly western European); more than 70% of all approaches are precision approaches; and airports with more than 150,000 movements per year. These selection criteria limited the number of airport datasets to 40. The aircraft accident data used were from the period 1976 to 1990.

The accident location probability model was based on a two-dimensional probability distribution function. The model was based on a curvilinear coordinate system with the variable s being used for the distance along the track to/from the runway and the variable t being used for the cross-track distance from the intended flightpath. Only 20% of the accident reports contained adequate data to carry out the curvilinear analysis. These data points were then transformed into Cartesian x,y coordinates. Several different probability density functions were used including the Dirac delta function, Weibull and generalised Laplace and tested against the Kolmogorov-Smirnov “goodness-of-fit” test. Confidence intervals were calculated to give 95% confidence areas. At the time of the model’s publication, this was the model with the greatest number of data points considered and the only model that considered different categories of traffic, coordinate dependence and a goodness of fit test.

The update to the model (Pikaar, Piers and Ale, 2000) changed the accident data included to the period 1980 to 1997; excluded helicopters, military aircraft, test flights and air show accidents; excluded aircraft with a maximum certificated take-off mass below 5,700 kg; excluded the later portions of the climb; en-route cruise, initial descent and holding phases of flight; and excluded intentional and military causes of accidents. Different accident rates were then calculated for three different generations of aircraft for various hazardous scenarios. A consequential crash area of 0.083 metres^2 per kg of MCTOM was derived. The accident ratio calculated using the new model was 30% of the value calculated in the earlier model. Most of this influence was related to the change in generation of the jets to the modern variety.

The feasibility study to examine a change in the model towards a causal basis concluded that it would be possible but that an increase of the level of detail and the inclusion of modelling management behaviour would be necessary. These changes may not be necessary for the modelling of general accident rates in the vicinity of aerodromes in GB if adequate margins or safeguards are built into the values of the target levels of safety. For example, if the central value for the aircraft crash probability onto a licensed nuclear site is calculated assuming an uncertainty in the data of an order of magnitude and an additional factor of two is still available for not moving to a more causal modelling basis, then this could be acceptable.

The NLR model represents a reasonable model for use within the vicinity of an aerodrome and an improvement over the basic Byrne model for those licensed nuclear sites in the vicinity of a large aerodrome having a significant proportion of traffic above 5,700 kg MCTOM. The NLR model does not address several other important aspects contributing to the aircraft crash hazard rate.

Review Criterion	Review Comment
Location	Vicinity of a runway
Flight frequency	Considered
Fixed wing	Civil aircraft operating on commercial flights (over 5,700 kilogrammes)
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Take-off, initial departure, landing
Impact scatter	Considered but no model specified
Impact angle	Not mentioned specifically
Wreckage trail	Considered but no model specified
Hazard scenarios	Standard accidents
Usability	The NLR computer model was not evaluated.
Usefulness	Potential to improve the accuracy of calculated results when compared to Byrne in the vicinity of aerodromes

5.9 THE LAWRENCE LIVERMORE NATIONAL LABORATORY MODELS (1993 ONWARDS)

An initial method for examining the risk exposure from aircraft was proposed by the Lawrence Livermore National Laboratory (LLNL) (Kimura and Bennett, 1993). This paper identifies that a good understanding of the local traffic routes was required to be able to predict the risk exposure. This was in contrast to earlier studies (including Goldstein et al., 1992) and used probability density functions on a stochastic process basis for distribution of aircraft accident locations. The paper then explains some methods by which analysts may be able to build up a map of flight routes, flight frequencies and aircraft types. They went on to look at how to analyse risks at and around an airport with Amarillo Airport being chosen as an example. Crash probabilities for air carrier and air taxi operations were calculated but not for general aviation. Normalisation of the data by grouping similar airports to Amarillo was suggested. The paper concluded that it was an outline study looking at preliminary data gathering and analysis as well as preliminary models for crash location.

The United States Department of Energy (DOE) “Standard Model” was based on the Aircraft Crash Risk Analysis Methodology (ACRAM) (Kimura et al, 1996). This document contains extensive analyses relating to accident probabilities and rates for background and vicinity of an aerodrome flight routes.
The modelling of departure accident locations along the flightpath is useful as this model has the coordinate system based at the start of the departure runway’s threshold. The total distance travelled between the start of the take-off roll (assuming that a runway entry point at an intermediate point in the runway was not used and also assuming that there was no starter extension to the runway provided) and the point of first impact was used.

The cross-track deviation from the intended flightpath was not analysed in the same way, a distribution of actual locations was plotted. The analysis carried out examined the off-runway heading distributions but this analysis appeared to be entirely statistical rather than related to the actual distributions of headings when compared with intended headings for aircraft flightpaths. Whilst understanding that the crash dynamics may be required in an application of the models, there can be a spurious relationship between aircraft heading and the aircraft's inertia in turns. The heading values and the inertia in a straight-line situation also depend upon the crosswind component as well as any out-of-balance yaw forces that may be present. The reviewer concluded that the heading distribution model could not be relied upon to give accurate predictions. The plot of average accident locations would not lead to an accurate estimation of risk at a particular location because the intended flightpath was not represented adequately. The estimation may be optimistic or pessimistic.

There are differences in the coordinate systems used between the actual standard and some of the LLNL supporting work. The standard uses the centre of the runway as the origin whereas the LLNL supporting work uses the runway threshold.

The post-impact deceleration of aircraft was modelled with an assumption that the decelerations were constant. This is not usually the case because of two separate factors. Firstly the deceleration drag may depend upon the ground friction which is, in turn, a function of the weight of the aircraft that may be benefitting from aerodynamic lift. Secondly, the aircraft may be subjected to large decelerations upon collision with relatively massive objects, such as a building. No account of engine detachment and ballistic projection is taken into account by this model.

The modelling of general aviation accidents was split into two models, one for approach accidents and one for departure accidents. A cut-off radius was set at one mile from the airport and accidents closer than this were not modelled. A nonparametric bivariate estimation technique was used. The modelling of skid distance suggested that a value of 135 feet covered 90% of the range but it was not stated if the distances recorded were truncated by impact with solid structures or terrain.

Military accidents were modelled by splitting the aircraft into two categories, large and small, and into two phases of flight, take-off and landing. A non-parametric kernel estimation technique was used to derive the results which were then tabulated. No formulae were presented for the locations. A truncated lognormal distribution was chosen for the impact angles of large aircraft and beta distributions were chosen for small aircraft. The cotangent of the impact angle was modelled using Weibull distributions for all aircraft types. Tabulated results were presented but no formulae or data were provided. Skid distances were represented by a Pearson VI distribution with cumulative distribution probabilities being tabulated.

The work at LLNL continued with a trial application of geographical information systems to accident locations around Salt Lake City, Utah, United States (Kimura et al., 1995). The paper provides a review of the earlier work and then developed the concept of an airport crash location model as a function of a radial distance from the runway's threshold and an angular distance from the runway's centre line. Extensive data analysis was undertaken for application around the main airport in Salt Lake City to derive accident rates per year onto a shopping mall, a school and a hospital.

One paper explained their analysis of high altitude en-route flight operations (Sanzo et al., 1996). High altitude operations were defined as above 18,000 feet. The data search for accidents was limited to US registered aircraft only. Whilst there are a considerable number of foreign aircraft operating international flights to the United States, many of the routes and destinations spend little time over the landmass of the continental United States. A twenty year time period (1975 to 1994) was taken for the accident search and resulted in seven events for the large passenger transport commercial operations.

There were a greater number of air-taxi accidents. The model is significant in that it attempts to address the distribution of crash locations that occur in modern air traffic control routes comparable with those in current use over the UK.

A paper that was designed to complement the high altitude en-route operations paper was published by employees of Science Applications International Corporation (Stutzke et al., 1996) and is reviewed in this section for convenience. The paper developed a mathematical model based on 1250 general aviation accidents within the continental United States extracted from the National Transportation Safety Board's database. Unusually, this dataset also included helicopter accidents. A product kernel method was used to produce a bivariate (latitude and longitude) probability density function of the crash site. Integration of the probability density function will yield the frequency of crashes within a specified area. Given sufficient data, this method should produce results that tend towards the true probability density function. The method gave results with a maximum non-airport accident frequency of 2.3×10^{-4} per year and minimum value of 6.1×10^{-6} per year.

Whilst this method may be reasonable for application to general aviation activities, it would not be useful for application in the event of limited datasets, such as commercial aircraft and military aircraft accidents. The method did not account for flight operational issues such as avoidance of nuclear installations by general aviation aircraft because of the prohibited airspace around them or the possibility of see-and-avoid for some forced landing accident scenarios.

1996 also saw the landmark publication of the LLNL aircraft crash risk analysis methodology (ACRAM) (Kimura et al., 1996). The analysis was based on data taken between 1973 at the earliest and 1995 at the latest. The analysis was broken down into flight phase to produce results of crash rates per departure, per aircraft flight hour, per mile flown and by airspeed for major airline traffic and air-taxi operations.

An extensive analysis based on all commercial jet accidents from 1950 to 1990 was carried out to make a crash location model for use around airports. Section 3 of the report analyses general aviation activity with a significant degree of segmentation. This segmentation was (i) single-engine piston, fixed wing, (ii) multiple-engine piston, fixed wing, (iii) turboprop, fixed wing, (iv) turbojet, fixed wing, (v) piston, rotary wing, (vi) turbine, rotary wing and (vii) other. The other category included hang gliders, gliders, balloons and other aircraft. Historically, the other category would not have included remotely piloted aircraft. Similar calculations to the airliners were carried out to derive a series of probabilities of an accident. Location modelling was carried out using a nonparametric bivariate estimation technique to derive crash locations and probabilities around airports.

Section 4 of the report presents an analysis of military aviation crashes based on fixed wing aircraft from the US Air Force and rotary wing aircraft from the US Army. Data from the US Navy and Marine Corps were rejected from the analysis. The fixed wing aircraft were segmented into large bomber, cargo and refuelling aircraft with small aircraft, including fighters and attack aircraft, as well as trainers being the other category. Crash frequencies for various units and locations were calculated.

The ACRAM model was converted into computer code to enable calculations to be made quickly and accurately for any specified location. A detailed analysis of the underlying mathematical expressions behind the computer code used to calculate the results has also been published (Glaser, 1988).

The use of tabulated results enables easy look-up of relevant values. The overall model was simple to use and with appropriate modification of data may be suitable for application by operators of licensed nuclear sites in GB.

Review Criterion	Review Comment
Location	Vicinity of a runway and background
Flight frequency	Considered
Fixed wing	Civil and military
Helicopters	Considered
Gyrocopters	Considered
Gliders	Considered
Airships	Considered
Balloons	Considered
UAVs	Not considered
Phases of flight	All relevant phases were considered
Impact scatter	Considered
Impact angle	Considered
Wreckage trail	Considered
Hazard scenarios	Standard accidents
Usability	Very simple to use
Usefulness	Worthy of consideration with possible change of data set

5.10 THE US DEPARTMENT OF ENERGY MODEL (1996 ONWARDS)

The United States Department of Energy (DOE) published a model, known as the DOE standard, in 1996 and the relevant part of concern to this project was updated in 2006 (DOE, 2006). The DOE standard was developed to assist in the evaluation of aircraft crashes into any hazardous facility, not just nuclear facilities. This model follows on as a development of the LLNL ACRAM model and caters for both accidents in the vicinity of an aerodrome and general background accidents.

The overall model considers the frequency of an aircraft impact into a facility; the structural response of the plant; the frequency of hazardous releases from the plant and finally the resulting harmful exposure. Only the first part of the overall model is of interest to this review. The model was developed to provide an approximate level of risk rather than to be a detailed risk analysis of a particular site. Uncertainty in the model was considered by providing an analytical margin rather than formal uncertainty analysis.

The DOE standard to examine aviation impact frequencies is applied in several stages. The first stage is a screening stage to see if the impact frequency is sufficiently below the acceptable impact frequency criterion as to not warrant further investigation. The suggested impact frequency criterion for the first stage screening is a frequency of fewer than 1×10^{-6} impacts per year. It is beyond the scope of this project to comment on the acceptability of this target level of safety for use at a licensed nuclear site in GB.

The annual frequency of impacts onto a site is built up from a four-factor formula. This considers the number of operations; the probability an aircraft will crash; the conditional probability that the aircraft will crash into a square mile where the facility is located; and finally the area of the facility.

An analysis was carried out to provide values for the background accident rate occurring onto every square mile of the continental United States such that only multiplication by the effective facility area is required to derive the estimated aircraft accident rate onto the site. The results include maximum, minimum and average values for commercial and military operations. The values for military activity do not include special manoeuvring and low-level operations which must be accounted for by local risk assessment. These were then published in a table (B-15) for various nuclear sites (not necessarily nuclear power plants) together with general continental values that could be used. The background crash rates were split into various classes of civil and military aircraft to allow a post-impact consequence analysis to be carried out.

Helicopter operations were not included in the background rate as they were considered to be insignificant contributors to the accident rate. The other classes of flying machines were not mentioned.

The accident rate for aircraft in the vicinity of an aerodrome was calculated using the formulae and the results were presented in a series of tables (B-1 to B-13) for application. The location of the site relative to the aerodrome was considered in the tables such that only a displacement along the runway's extended centre line and perpendicular to the runway's centre line were required for the analysis. The tables were then used to build up the contribution to the accident rate associated with civilian and military operations by various classes of aircraft.

A formula was provided to enable helicopter crash rates to be determined but this was by site-specific calculation rather than use of look-up tables.

The various other classes of flying machine were not mentioned for their contribution to aircraft accident rates in the vicinity of an aerodrome.

The calculations were valid for the general impact case and did not mention the "beyond design case", obstacle to safe flight and site boundary loss-of-service hazardous scenarios.

A building in the Nevada Test Site was the subject of an evaluation using the DOE model for military traffic. Civilian traffic may have been excluded through the prohibition of overflight for national security reasons and there are no nearby airports. The building area was modelled using formulae from the Solomon model (Solomon, 1988). Modifications were then made to the various dimensions of the building to take into account the structural hardening of the building against missile impacts.

This model was considered to be easy to use and to be useful as the basis for a model to apply in GB. The accident rates for various classes of aircraft may have to be modified and the results retabulated but the general principles involved in this model were worth further consideration.

Review Criterion	**Review Comment**
Location	Background and vicinity of an aerodrome
Flight frequency	Local data collection
Fixed wing	Civil and military; reasonable split of classes of aircraft for US operations that would take some reclassifying for GB
Helicopters	Formula provided for site-specific calculation
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Most considered but not low-level operations for civil and military

Impact scatter	Table provided for crash into square mile areas. Scatter for helicopters given
Impact angle	Impact angles given but not broken down by type of accident
Wreckage trail	Table provided for crash into square mile areas.
Hazard scenarios	Standard aircraft crash onto a site only
Usability/useful	Easy to apply by non-aviation specialists. Worthy of further consideration and development for application within Great Britain.

5.11 THE BYRNE MODEL (1997 ONWARDS)

The Byrne model is a generic name given to the evolution of models created by the British nuclear industry to examine aircraft crashes into nuclear facilities. Various studies were carried out collecting background crash rate data and a model for airport related crashes was created by Jowett and Cowell (1991). The Byrne revision was published in 1997 and it was updated by a revision of the accident data (Kingscott, 2002) with the latest version (ESR Technology, 2008) being applied as an acceptable means of compliance with the evaluation of aircraft crash requirements onto licensed nuclear sites in Great Britain.

The types of aircraft were split into five classes. Light civil aircraft were taken to be those of a maximum certificated take-off mass of up to 2300 kg. This covers most single engine aircraft and twin engine aircraft up to six seats. Military aircraft used by the University Air Squadrons and Air Experience Flights were also grouped into this category as they used similar aircraft.

All helicopters were grouped together in a single category. This would include light helicopters such as a Robinson R22 with a minimum mass of around 500 kilogrammes (Robinson Helicopter Company, 2013) through to the twin-rotor twin engine Boeing Chinook which can have a mass in excess of 22 tonnes (Boeing Defence, Space and Security, 2013).

The small transport category aircraft was comprised of fixed-wing aircraft with a mass range between 2,300 kg and 20 tonnes[3]. This included civil and military aircraft. The size of passenger planes in this category extends to encompass 50 seat turboprop regional airliners.

The large transport aircraft category extends beyond the 20 tonnes limit and those not included in the final category of military combat aircraft and jet trainers. One exception is the Shorts Tucano turboprop military trainer as this is a military training aircraft but has jet-like flying characteristics and was used to replace the Jet Provost trainer. The Tucano was included in the military jet trainer category.

No mention was made of gliders, gyrocopters, airships and balloons. Unmanned aerial vehicles were first discussed in the 2008 update.

The segregation of low mass, low speed, light fuel load aircraft from other groups appeared to be reasonable. However, heavy lift helicopters and the potential consequences of their loads did not appear to fit well into a general helicopter category. This concern was related to a potential screening out of the helicopter class based on their potential for low post-impact consequences.

[3] It should be noted that the Chinook helicopter may have a mass that exceeded even this category. The licensed site operator would have to carry out an analysis of the effects of a Chinook accident taking into account the mass characteristics. Although the helicopter may be relatively slow, it may carry a relatively dense external load, such as a 10 tonne artillery piece or military vehicle, which may have to be jettisoned in the event of an engine failure.

The classification of former military aircraft into a civilian category of below 20 tonnes appeared to be reasonable on mass considerations. However, given that they may operate similar speed/high profiles to current generations of military aircraft, it may have been reasonable to consider retaining them in a military category.

The large transport category aircraft range of potential mass and fuel load was considerable. If this class were not to be sub-divided further into, for example, narrow bodied airlines of up to 120,000 kg and wide bodied airliners above this mass range, then the post-crash consequence analysis would have to account for the wide range of potential outcomes. The Byrne model does not identify the “beyond design case” scenario class of aircraft and therefore, does not provide a calculation for its possible occurrence.

The debris from airborne aircraft discussion considers parts falling off airliners and military aircraft. Whilst it may not have occurred over mainland Britain in recent years, the possibility of an engine detachment was not identified as a significant piece of debris. The identification may only be important for completeness and then further analysis may show that the collision probability is insignificant when compared to other events. The detachment of weapons and external fuel tanks from military aircraft is rare but may need to be analysed as a dummy concrete bomb with a mass of approximately 450 kilogrammes impacting a plant at high speed may have different structural consequences than the relatively deformable aircraft structures.

Whole aircraft bounces and detached engine throw forward into a site were considered in the Byrne report and a range of values given (Byrne, 1994). The worked example of how to calculate the collision rate with a site in the appendix did not take this into account. Therefore, whilst it had been considered in the report, it did may not appear in the calculated hazard rate.

The mid-air collision hazardous scenario was considered from statistical data but no projection was given for future traffic scenarios. The probability of a mid-air collision increases disproportionately to an increase in traffic. The mid-air collision probability has reduced with the full implementation of collision avoidance technology and improved hazard identification by the air traffic control service providers. However, the distribution of likely collision points is not random and thus the contribution to background accident rates or below airway accident rates is not distributed evenly across GB. It may be reasonable to require the operator of a licensed nuclear site to provide at least a qualitative evaluation that the site is not particularly prone to this type of event.

The Byrne report provides a discussion of the effective site area that may be affected by an aircraft accident. Various factors are developed for different shielding scenarios. The shielding appears to assume that a shield building will provide total mechanical shielding from a second shadow building. However, there are some parts of an aircraft that might be considered as separate missiles and pass through the first building. This is particularly the case with jet engines striking buildings that do not have great structural strength.

The crash rate onto a site comprises four separate factors: the contribution from background flight activity, the contribution from airways, a contribution from being in the vicinity of an aerodrome and a contribution from military flight activity.

5.11.1 Civilian Aircraft Contribution to the Background Crash Rate

The data for accidents happening within the vicinity of the aerodrome are excluded if they were involved in the take-off, landing, go-around or circuit flying. The general definition of vicinity was taken to be within about five miles of the aerodrome. The definition was not precise in terms of distance but was made in terms of the phase of flight.

The background crash rate calculation method used by Byrne was based on a Poisson distribution. A discussion of the fundamental assumptions associated with Poisson distributions relating to stationary process, statistically independence and simultaneous events was included in the publication. The values published were for the 50% confidence level.

The data samples used were taken from statistics covering GB and appeared to be comprehensive. However, the number of events in some categories was very low, such as the two accidents recorded in the small transport aircraft category and the four accidents (including two military accidents) in the large transport aircraft category.

The use of local flying areas is discussed in the report. These are usually used for light aircraft training. The suggested method is only to include a factor to increase the light aircraft accident rate in these areas if they are busy. No significant analysis appears to have been undertaken to examine the distribution of light aircraft accidents from areas rarely flown over when compared to those areas that are frequented often. It may be advisable to increase the light aircraft background rate in all cases where a licensed site is below a local flying area and does not benefit from protective airspace provisions.

Forced landing accidents were screened out of the dataset by using an assumption that the pilot would be able to see-and-avoid the licensed nuclear site. No demonstration was provided that the conspicuity of a site was sufficiently high that a pilot would be able to detect and avoid the site during daylight; that the night lighting was sufficient to enable a pilot to detect the site and choose an alternative area to land on and that the cloud cover at any time of day or night would not prevent a pilot from detecting the site visually.

Crop spraying aircraft that crashed close to the fields that they were spraying were excluded from the crash data. This would be valid if the licensed site operator were able to ensure that such operations did not take place within the vicinity of the licensed site. This may not be applicable to all 37 sites currently licensed, or potential future sites. However, major nuclear sites may be able to establish prohibited airspace and control such activities. No other special low-level operations were considered in the report, including aerobatics.

A background helicopter crash rate was provided for the mainland of GB.

Gyrocopters, gliders, airships and balloons were not discussed in the report.

5.11.2 Military Aircraft Contribution to the Background Crash Rates

The background accident rate for military combat aircraft was calculated in a different manner as the distribution of accident locations was not considered to be random with some areas showing a relatively high concentration. A method was derived for calculating a background low concentration rate, a high crash concentration rate associated with intense military low-level and hard manoeuvring volumes of airspace and a transitional area between these two zones. The calculation of the crash rates did not appear to include military accidents that landed in the sea close to shore. If changes were made to close bombing ranges with significant flightpaths over the sea and there was a move to more intensive activities over the land (which may occur in a future strategy review with consolidation of aerodromes and closure of ranges) then the on-land accident probability per flight may increase. It is noticeable that the calculated background crash rate for the high intensity zones has a contribution of approximately three-quarters coming from the military combat aircraft activity.

The provision of the high concentration military crash areas is a first order simplification of the likely crash rate. The areas were considered to be relatively general and not necessarily related to the military activity rate, the type of activity and the associated accident probability. If a licensed nuclear site were to be proposed underneath a major military training route (without protective airspace provisions) then the background rate predicted using the Byrne model may be underestimated. The model does not present data for penetrations of the protective military airspace.

5.11.3 Below Airway Crash Rates

The calculation of below airway crash rates uses a model suggested by Phillips (1987). The assumption was made that the cross track deviation was normally distributed about the centreline of an airway with the standard deviation being equal to the airway's mean altitude. The airways were split into lower and upper airways, the boundary of which is at flight level 245 (an altitude of 24,500 feet above mean sea level if the barometric pressure is 1013.25 Hectopascals). The distribution of below airway crashes would appear to be made up of several different hazardous scenarios, each of which may have their own crash location distribution. Therefore, to make the assumption that a normal distribution applies may not be reasonable. However, it is recognised that until more research is done in this area to build a model for crash distributions for each hazardous scenario then an assumption of the distributions must be made.

The calculation makes reference to the structure of airways. This has changed fundamentally since the time of the original Byrne model with air traffic control giving more "direct to" clearances allowing the zig-zag routes associated with overflying ground-based navigation aids to be straightened out. Aircraft on busy routes may be subjected to radar vectoring to avoid coming into conflict with other aircraft. The military blocks of airspace may also be released to allow civilian aircraft to transit through them when not required for military activity under a concept known as flexible use of airspace. Therefore, the rigid route structure analysis is no longer valid. It may be more suitable to replace the formal route structure with a flight density map derived from surveillance data.

No method is suggested to account for holding patterns and the increased time spent above a licensed site. For example, the Lydd VHF omni-directional range navigation beacon is used by aircraft holding waiting their turn to approach Gatwick Airport under some circumstances. These aircraft can make several passes over the licensed site and are flying relatively slowly when compared with their full en-route transit speeds. This may increase the exposure time close to the plant considerably.

The report discusses the concentration of commercial flight activity around busy airports that are provided with terminal control area and aerodrome control zones as a form of protective airspace. The report states that there is no evidence to support an increase in the background and below airway crash rate (beyond five statute miles from an aerodrome) in these areas and that this may be related to the increased provision of air traffic control infrastructure and services. The lack of evidence may be based on historic data analysis rather than predictive hazard analysis. Only some types of hazardous scenario are assisted by the provision of air traffic control, for example mid-air collision and controlled flight into terrain. Structural failure and loss of control are not necessary reduced through the provision of air traffic control. There are some licensed nuclear sites within GB that lie within terminal control areas and have a relatively high traffic count within the vicinity of the site. The predicted accident rates at these sites may be underestimated by the Byrne model in this situation.

The model for crashes below airways included an analysis of "primary causal factor". The allocation of an event in an accident sequence between causal factor/ contributory factor or another observation category is the sole and subjective choice of the investigator-in-charge of the accident investigation (Gleave et al., 2013). No significant guidance is given as to how to allocate any particular event into each category. Therefore, a data survey extracting primary causal factors may not be indicative of current risk exposure.

The Byrne model discusses the relationship between primary causal factors for accidents that started in airways and then went on to crash. Almost half of the accidents had the outcome of a safe landing at an airport. This may be related to the classification of damage to systems that count as accidents but do not involve a "crash", such as catastrophic engine failure. The outcome of forced/emergency landing (on or off aerodrome) could be combined with ditching and may only reflect the probability of flightpath distribution over land/water. In some cases, such as a dense city environment, it may be preferable to ditch rather than hit a built up area (National Transportation Safety Board (NTSB), 2010).

The Byrne report discusses the in-flight break-up hazardous scenario. This is of particular importance when considering the area affected by an aircraft accident and the number of separate strikes that could occur across a site. A statement is given that in-flight break up accounts for less than 5% of the outcomes of airways related incidents. However, the table in Section 5.3 of the Byrne report includes outcomes of normal landing, forced landing and ditching all of which may not appear in the background/airway crash screening of accidents. If the in-flight break-up is considered with uncontrolled impact and controlled flight into terrain then the ratio increases to 16% which may be significant in terms of site area considerations.

The analysis of rates of small and large transport aircraft was equated with the slow and fast traffic distances flown data. The fast traffic was said to be equivalent to jet aircraft with slow traffic equivalent to turboprop aircraft. Byrne then correlates small transport aircraft with turboprop aircraft and large transport aircraft with jet aircraft. The crossover at the mass classification boundary is illustrated by the misclassification of the British Aerospace BAe 748 accident as a fast aircraft when it is in fact a slower turboprop type.

The calculated rates for aircraft crashes are expressed per km flown. The estimated total distance flown by large transport aircraft was $4.76\text{x}10^{9}$ km over a 12 year period in United Kingdom airspace. The amount flown over the mainland of GB would be less than this value. The number of accidents during this time period classified by Byrne as en-route (and thus below airways) was two. This gives an average value of approximately one accident per $2\text{x}10^{9}$ km which equates to a crash rate per km flown of approximately $5\text{x}10^{-10}$. Byrne quotes a Poisson statistical 50% confidence value for the crash rate per km flown of approximately $5\text{x}10^{-11}$, one order of magnitude lower than the mean value. The use of the Poisson 50% confidence value rather than the mean value, or another confidence level or even another statistical method for dealing with small data sets, ensures that the below airway crash rate is significantly lower than the background rate for most locations across mainland GB.

The lateral distribution of crashes below airways was given in the Byrne model as equation 10. The validity of this formula was not checked during this review.

5.11.4 Crash Rates in the Vicinity of Aerodromes and Helipads

The Byrne model also addresses the accident rate within the vicinity of an aerodrome. Polar coordinates were used originally in the United Kingdom Atomic Energy Authority models prior to Byrne, (Phillips, 1987) but this was updated to Cartesian coordinates for larger fixed-wing aircraft (Jowett and Cowell, 1991) to address the issue with large polar angles close to the runway.

The landing and take-off reliabilities for the groups of aircraft were calculated but they were published on a per movement basis. No account was made for the difference in accident probability per movement split between approach and departure accidents. Most airports do not have a 50:50 split between the directions of use of the runway because of prevailing wind and environmental considerations. Therefore, any difference in the probability of an accident between an approaching aircraft and a departing aircraft may affect the crash rate at a specified location on the ground.

The model did not appear to account for local variations in offset approaches, visual approaches and circling approaches as well as turns after departure, circuit variability and go-around flightpaths. Therefore, if a licensed nuclear site were to be located close to an aerodrome's flightpaths then the local routes may have to be considered in detail, rather than taking average crash location data into account. Light aircraft (below 2,300 kg MCTOM) were modelled using an older formula (Phillips, 1991). This was a polar coordinate model. The model did not appear to reflect local flight operational restrictions but was a generic model. The continued application of this model to a local site could be questioned.

Helicopter accidents were dealt with separately and an accident rate given for an area with a 200 metre radius around a helipad. This rate is particularly significant for licensed nuclear sites that have helipads as the blades of a helicopter can get thrown a considerable distance as well as just direct impacts. No account was taken of low-level hovering accidents suffered by helicopters. The reasons were not justified but the rotational energy contained within the blades and the combustible fuel loads would not be significantly different from the crash rate close to a helipad.

5.11.5 The Kingscott 2002 update

The 2002 update reviewed the background crash rate using data from 1991 to 2000 in the standard five aircraft categories of light aircraft, helicopters, small transport aircraft, large transport aircraft and military combat aircraft. No updates were made to the methods of calculating the crash rates associated with civilian aircraft activities.

This update did not re-examine the below airway crash rate or the crash rate in the vicinity of an aerodrome. The possibility of separating out aerobatic accidents from the background rate was discussed for the first time. Other low level civilian operations were not discussed. Once again, no consideration was given to the background crash rates associated with gyrocopters, gliders, airships and balloons.

The military high crash rate areas were redefined and moved slightly. It was not stated whether this was as a result of moving flight tracks or if it was the result of greater data being available. The zone boundary for the transition between high accident probability locations and background locations was increased from 40 km to 50 km in this update. It was noted that one licensed nuclear area was within the northern high crash zone and the transitional zone encompassed three licensed nuclear areas. The word area here has been chosen to indicate a general geographic location that may contain more than one nuclear reactor as some general areas have more than one licensed nuclear site status.

Figure Ten requires some careful inspection when looking at the combat aircraft accidents and Figure Seven should be taken as the authoritative version. The symbol used in Figure Ten to denote the corners of the high concentration crash areas appeared to be similar to the symbol for combat aircraft accident sites. The high concentration crash rate boundaries were not linked by a solid line and only denoted by the corner markers.

Ex-military jets flown by private pilots suffered four accidents and these were classified as small transport aircraft because of their mass. They accounted for half of the accidents in this category. The report did not justify why these aircraft should not continue within the military combat aircraft category that their flight operations may reflect. The update also provided figures examining the sensitivity of the large transport category to the variation of time bands and changes in confidence levels.

5.11.6 The ESR Technology 2008 update

The 2008 update reviewed the background crash rate using data from 1996 to 2006 in the standard five aircraft categories of light aircraft, helicopters, small transport aircraft, large transport aircraft and military combat aircraft. The method of calculating the crash rate contribution associated with civilian aircraft activities was not changed, only the data to be used in the calculations. The below airway crash rate was not mentioned and it was not clear if this was absorbed into the background rate by this stage of the Byrne model's development.

The crash rates in the vicinity of an aerodrome were also updated using data from the 1990 to 2006 timeframe (extended to January 2008 for the large transport category). The extension for the large transport aircraft was carried out to ensure that the data included an accident that occurred in January 2008 (AAIB, 2010). The methods of calculating the results were not changed in this update.

The crash rates for helicopters in the vicinity of an aerodrome or helipad stated that there was no crash location model for helicopters in the HSE aircraft crash risk methodology despite this being given as equation nine in the Byrne model. Furthermore, it was identified in this update that the only licensed nuclear sites of interested when considering helicopter operations near aerodromes would be those located at Dungeness. No consideration appeared to be given to helicopter operations near naval dockyards or to the provision and use of helipads at other licensed nuclear sites themselves. These licensed nuclear sites are detailed in the discussion of protective airspace (section 4.4).

The inclusion and exclusion of aerobatic flights and airshows from the vicinity of an aerodrome data was discussed with a modification value to the crash rates suggested.

The location of the high concentration crash area for military activity was retained as a similar area to the 2002 update. Whilst the military low flying hours were examined, the update did not contain a significant analysis of the use and location of low-level flying routes, bombing ranges and exercise areas. The projection that the high crash rate areas would remain in the stated location (based on flying routes) was not confirmed with reference to communications with military authorities. Three separate background rates were provided, as per the previous reports, but no attempt was made to define areas that had lower than average background crash rates despite the prohibition of combat aircraft activities in some areas.

For the first time, unmanned aerial vehicles (also known as remotely piloted vehicles) were commented upon. Indications were given of the current types in service. No projections of future types to enter military service were given, probably because of the security restricted nature of some of the developments. However, these will be of considerably greater mass and fuel load than those considered in the update. The conclusion that the unmanned aerial vehicle risk exposure level was so low that it would not alter the calculated rates may not be valid for extrapolation too far into the future.

The update included a review of the differences between the model developed by AEA Technology, as included in the Byrne model and updated, with models developed by NATS (reviewed in Section 6.12), DNV Technica (reviewed in Section 6.7), NLR (reviewed in Section 6.8) and GfL (reviewed in Section 6.16) for use in the vicinity of an aerodrome. The comparison concluded that the updated Byrne model was still valid and that other models had different problems but could be used as useful comparisons.

5.11.7 Summary

The Byrne model (and subsequent updates) provided an average background crash rate for civilian aircraft activities. The background crash rate in later updates of the model appeared to absorb the below airway crash rate from the original Byrne version. There was no requirement for adjustment to operations in busy terminal control areas and holding patterns. This meant that the background crash rate may be statistically valid as a value for mainland GB but that its application to a local site may lead to a significant under- or overestimate of the crash rate.

The model within the vicinity of an aerodrome did not appear to account for local conditions that may modify the accident rate per movement or to take account of the distribution of accident locations associated with local flightpaths.

Review Criterion	**Review Comment**
Location	Background and vicinity of an aerodrome
Flight frequency	National data collection
Fixed wing	Different models including: commercial aircraft above 2300 kilogrammes maximum certificated take-off mass, commercial aircraft below 2300 kilogrammes maximum certificated take-off mass, helicopters and military combat aircraft.
Helicopters	Considered for both background and vicinity of a helipad
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Considered but not thought to provide significant alteration to the background crash risk exposure
Phases of flight	All phases of airborne flight were considered but not necessarily segmented sufficiently finely to allow accurate local implementation.
Impact scatter	Considered
Impact angle	Considered
Wreckage trail	Considered
Hazard scenarios	Standard aircraft crash onto a site only. Mid-air collisions are not added to the locations around aerodromes with high-intensity operations. The site acting as an obstacle to safe flight was not considered. Aircraft accidents causing a loss of safety-significant services across the boundary of a licensed nuclear site were not considered.
Usability/useful	Equations can be applied by a person with some mathematical ability. Useful calculations of average exposure rates that can be applied by the operator of a current, or potential, licensed nuclear site if they can demonstrate that the local flight activities are below the average rate. Some sites may have considerably higher exposure rates that the Byrne model and updates cannot calculate accurately.

5.12 THE NATS MODEL (1997 ONWARDS)

National Air Traffic Services were commissioned by the Department of Transport to produce an airport crash location model (Cowell et al., 1997) and to suggest third party risk criteria (Evans et al., 1997) as part of the Terminal Five development at London Heathrow Airport. Data were taken from 464 airport accidents. Models were created for wreckage location after a take-off overrun, landing overrun, take-off non-overrun and landing non-overrun as well as for the point of first impact for take-off non-overrun and landing non-overrun accidents. An update to the model was published (Cowell et al., 2000) increasing the number of accidents locations considered by over 200. The third party risk criteria were developed into contours for public planning purposes after the 2000 model update (Kent and Mason, 2001). The model is scoped on the boundary limit of the smallest aircraft being considered as having a MCTOM of 4,000 kg. Under this mass limit, the model uses the AEA Technology (Philips, 1987) model which was a precursor to the Byrne model.

The model was developed to examine third party risk exposure, so it was essentially developed in four parts. The first part is the determination of crash rate for an aircraft operation within the vicinity of an airport. The second part is a crash location model. The third part is the consequence model examining the area destroyed. The final part of the model is the consideration of lethality to anybody in the destroyed area. For the purposes of this study, the consequential damage areas and the lethality are out-of-scope.

5.12.1 Calculation of crash rate

The calculation of a crash rate for a particular airport could be based on a top-down theoretical risk assessment based on hazard identification, hazard analysis and subsequent calculation of operational factors to arrive at the result. This theoretical exercise was rejected by NATS. A bottom-up analysis based on data analysis was chosen. The data were taken from historic accident reports and then analysed for the model. The disadvantage of this method is, whilst it may be statistically valid, it may have significant errors when applied to an individual site. Firstly, accidents may be included in the dataset that are irrelevant to the airport and runway under consideration. A controlled flight into terrain accident may be significantly more likely on approach to Katmandu airport than on approach to Amsterdam Airport Schiphol. Secondly, by taking a large dataset that includes significant local variables, it may over- or under-estimate the probability of an accident per approach. What was a significant incident, but with no accident, at one location, may well be an accident at another airport. Again, consider a deviation from a flightpath on approach to Amsterdam Airport Schiphol that may have no consequence because of the relatively benign terrain, obstacle and vegetation environment but a similar deviation could lead to a fatal controlled flight into terrain accident at a more geographically challenging location. Finally, the model for probability does not take into account local conditions at an aerodrome, such as weather variations and provision of local navigation aid infrastructure.

The model selected "first world" countries for their sampling of crash rates based on accident and movement rate data. The definition of the sample was not clear, on the basis that it might have referred to the country where the crash occurred, the country of registration of the aircraft, or the country of location of the aircraft operator. There are some countries that operate national aircraft registers that are favourable for tax reasons (similar to flags of convenience in shipping) or are favourable for aircraft lessors to be able to recover their aircraft (Ireland being an example).

The accident rates were calculated for various classes for aircraft. The aircraft types were split up based on the type of engine used. These were jet, turboprop and piston engine types. The reason given was that the engine reliabilities were different for the three types of engine. However, engine failure rate in itself is not a strong causal link to general accident rates.

The crash rates were calculated based on the number of movements at an airport. The movement rate was not adjusted for the number of go-arounds, or the increased likelihood of an accident during the go-around manoeuvre itself.

Jet aircraft accident rates were segregated according to a classification used by Boeing (Boeing, 2013) into the various technical generations of passenger jets. The analysis suggested that there was a significant difference between the accident rates, per flight, of the first generation and the subsequent (second to fourth) generations. The analysis suggested that the subsequent generations be classified together as they had similar accident rates. The recent statistics by Boeing show a marked difference between second generation and fourth generation aircraft. For example, the second generation Boeing 737-100/200 series of aircraft had an accident rate of 1.63 per million departures whereas the fourth generation Boeing 737NG series had an accident rate of 0.28 per million departures. The only aircraft types whose accident rate per departure increased as they were updated from second to third generation, was the DC-10 to MD-11 going from 2.97 to 3.52 accidents per million departures. The use of a grouped accident rate, based on the historic analysis might indicate a conservative figure being derived when applied to current flight operations in the UK.

The analysis determined the accident rate for scheduled passenger movement jets. An assumption was made that the rate for charter accidents would be similar. This broad statement would not necessarily be true for several reasons. Firstly, some charter flights are flown by non-first world operators and these may have a higher accident rate. Secondly, the whole flight risk includes a landing/departure from an airport that may not have the same infrastructure and operational environment as the airport for a capital city utilised by a scheduled flight. Finally, the crew familiarity with the airport may not be the same as for scheduled crews. For consideration of the risk exposure for an airport in the UK, the foreign operator factor may be the most significant.

The analysis of cargo/freight/positioning/maintenance/ferrying/training flights indicated a higher accident rate than for scheduled passenger flight operations by similar classes of aircraft. A factor of three was the suggested modification factor for relevant jets. This factor was adopted for turboprop freight aircraft too. This was despite the admission that a review by the Civil Aviation Authority (CAA) (CAA, 1998) suggested a combined increase in accident rate for aircraft above 5,700 kg MCTOM for jet and turboprop aircraft was a factor of six. Such differences may be significant when in the vicinity of freight hub airports, such as East Midlands Airport.

The data for smaller western built turboprops and turboprops built by second and third world countries were considered to be too sparse to calculate the relevant accident rates. The data for some of these should have been available from manufacturers and other sources but the main source used by NATS did not collect this data at the time. An accident rate for pre-1970s turboprops was used but the reasoning was not fully justified.

The rate for eastern built jets (usually considered to be Ilyushin, Antonov and Tupolev) was based on a single accident. Whilst the general loss statistics were available, the movement rates were difficult to determine for the analysts. It was stated that only 0.2% of scheduled passenger movements in the United Kingdom were made by these types of jets. The more in-depth analysis of these types would be necessary in the future as aircraft like the Antonov AN-124 and AN-225 are still used as large cargo transporters. The Antonov AN-124 has had several accidents despite the relatively low numbers of aircraft in the fleet and the relatively few flights per year carried out by each aircraft. There is only one

Antonov AN-225. However, the Tupolev-204 may continue to make regular appearances on freight flights into GB.

The executive jet accident rate was considered to be a factor of approximately 15 times higher than the scheduled passenger jet accident rate. Whist some of this may be down to the type of operations performed, no significant analysis appeared to have been performed to justify the use of that figure if operating from the same airport as a scheduled passenger jet where they would share the same infrastructure.

The accident rate for miscellaneous non-commercial flights was not analysed in detail. An assumption was made that the use of the piston-engine accident rate would be a pessimistic assumption. No justification was given for the inference that that assumption would turn out to be pessimistic and not optimistic.

5.12.2 Location modelling

The NATS model uses a different convention for location axes when compared with the David analysis. For landing accidents, the NATS convention is for negative y to be the distance before the threshold and positive y to be after the threshold. The x axis gives the distance perpendicular to the extended centre line of the runway. If distances in an accident report are given relative to the touchdown point of the aircraft, then this distance was assumed by NATS to be +225 metres from the threshold as the y coordinate. The distances for take-off accidents are measured beyond the threshold of the runway in the reciprocal direction. This does not necessarily account for the length of runway used in performance calculations as the reciprocal threshold direction is not necessarily the end of the runway for departures as it may not include any stopway or clearway.

The modelling of departure accidents does not account for the aircraft performance requirements, as opposed to the infrastructure provision by the airport operator. The airport operator declares the take-off run available (TORA), take-off distance available (TODA) and the accelerate-stop distance available (ASDA) for departure performance calculation purposes. The aircraft operator calculates take-off run required (TORR), take-off distance required (TODR) and accelerate-stop distance required (ASDR) for the intended flight. If the required value is equal to or less than the available value, the flight can proceed as planned, subject to changes in wind vector and other environmental factors. If the required value is higher than the available value then the flight has to be altered, either by waiting for environmental conditions to change (such as a temperature drop at night) or payload has to be removed (fuel, passengers, baggage, mail or freight).

The issue with modelling departure accidents as a distance from the end of the runway is that it does not account for the relationship of excess distances that may be provided between the required distance and the available distance. To illustrate the problem, consider an Airbus A319 operating from London Heathrow and London Gatwick to a common destination, such as Amsterdam Airport Schiphol, flown by the same aircraft operator and with similar aircraft engines, payload and furnishings. The take-off performance at London Heathrow will be very similar to London Gatwick as the temperature and air pressure will be similar. Gatwick has a slightly higher elevation above sea level but if this is ignored, then the performance will be similar. The aircraft do not need the 3000 metres at Gatwick and 4000 metres at Heathrow to operate, values closer to 1800 metres would be sufficient. If an aircraft were to crash 500 metres beyond the end of Gatwick's runway, this would be recorded as 500 metres before the end of Heathrow's runway. If the accident were to occur at Heathrow at 500 metres beyond the end of the runway, this would be similar to 1500 metres beyond the end of the runway at Gatwick. This variability in difference between runway lengths required and available can affect a crash location model significantly.

The NATS model is applied assuming that the arriving and departing aircraft maintain the extended centre line of the runway. No account was taken for offset approaches, circling approaches, visual approaches, circuit patterns and departures that turn after reaching a minimum height above the runway. Go-arounds (abandoning an approach) that follow a missed approach procedure's flightpath that was not straight-ahead were not taken into account. The documentation of the model is not clear as to how terrain related accidents were taken into account or how the model is to be applied in an obstacle-rich environment.

The various government departments with responsibility for transport policy around the countries that make up the United Kingdom have a requirement for airport operators to manage third party risk. The calculations are carried out under contract by NATS using their model. In addition, NATS are known to have carried out contracts at Jersey, Guernsey, Amsterdam and Frankfurt airports although these reports are confidential. The application to some of the busiest international aerodromes in Europe (when considering runway capacity) such as Heathrow, Gatwick, Frankfurt and Amsterdam did not lead to a modification to account for mid-air collision locations. The collision probability was calculated as being sufficiently high that it would have appeared in the contour map. The reports containing these details were kept confidential but one of the authors of this report was an author for those reports.

The NATS model has been applied by NATS within several external consultancy projects. The NATS model (1997) was used as the basis of part of the modelling of a more complete runway safety analysis by Roke Manor Research at Amsterdam Airport Schiphol and Copenhagen Kastrup Airports (Roke, 2003). The NATS model was supplemented by the use of the Instrument Landing System collision risk model (ICAO, 1980) as this additional model was able to provide an indication of risk relating to aircraft at runway holding points presenting themselves as obstacles to airborne aircraft close to landing.

The NATS model (2000) was used as the basis of third-party risk modelling for the three major airports in the Republic of Ireland: Dublin, Shannon and Cork. The model was applied by ERM Risk (David and Quinn, 2004) and validated by UMIST (Muldoon, 2002). The final report (ERM, 2005) appeared to be a straight application of the model with no significant modifications.

5.12.3 Conclusion

The NATS model suffers from a number of problems that affect the accuracy of results close to runways. The probability of an accident, when measured per flight, may be under- or overestimated by using the referenced data rates and may need to be modified for local conditions. The location section of the model did not account for aircraft performance and runway lengths. Flights other than directly along the extended centre line of the runway are not modelled so the crash contours for airports with significant early turns on departure, arrivals other than straight-in and go-arounds other than straight ahead may find that the contours do not extend adequately in the x direction.

	Review Comment
Location	Vicinity of an aerodrome
Flight frequency	Local data collection
Fixed wing	Commercial aircraft above 4000 kilogrammes maximum certificated take-off mass
Helicopters	Not considered
Gyrocopters	Not considered

Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Final approach, landing, go-around, take-off and initial departure.
Impact scatter	Considered
Impact angle	Not considered
Wreckage trail	Considered
Hazard scenarios	Standard aircraft crash onto a site only. Mid-air collisions are not added to the locations around aerodromes with high-intensity operations.
Usability/useful	Equations can be applied by a person with some mathematical ability. Limited use as it does not take operations other than along a runway's extended centre line into account. Other models in the vicinity of an aerodrome may be more accurate at the likely displacements between a licensed nuclear site and an aerodrome's boundary

5.13 TÜV SÜD MODEL (2001)

A German research organization contracted TÜV Süd to re-evaluate the aircraft crash probability onto the site in 2001 (the organization and site's location were not disclosed in the paper) (Weidl and Klein, 2004). The original risk assessment had been carried out in 1984 and substantial changes in military traffic and increases in civil aircraft movement rates since that time prompted the project. The military accident rate dropped significantly. Most of this was put down to the withdrawal of the Lockheed F-104 Starfighter, German nickname Witwenmacher ("The Widowmaker"), an aircraft with a very high accident rate, although the large scale withdrawal of NATO aircraft from Germany may have also had a significant effect on the accident rate. A new annual accident rate per square km was determined based on accident data from the previous 10 years.

A helicopter accident rate per square km was based on 12 years of data for the number of accidents per year and then the effective area of the site was based on the roof area alone. No account was taken of the research site acting as an obstacle to the flight path of a helicopter operating at low level.

The analysis of civil aircraft was considered to be "free air traffic" because the airport was approximately 18 km away. This is evidence of screening and was based on a German analysis from 1974 showing that the accident rate decayed away from an airport out to a distance of approximately nine km.

The same model for military aircraft and helicopters was used by TÜV Süd to investigate the frequency of aircraft crashes onto an industrial site near Berlin (Zapf, Weidl and Klein, 2006). However, a model was required for the crash contribution made by aircraft in the vicinity of an aerodrome. A search of aircraft crash frequencies was carried out and several different values were identified. Aircraft with a MCTOM of less than 20,000 kg were ignored (based on crash consequence considerations but not justified in the paper). The calculation appeared to use a value for en-route accidents rather than a take-off and initial climb specific phase of flight value. However, the exact location of the site and the local phase of flight conditions were not published to enable confirmation of an appropriate selection of crash rate.

The probability of an overflight on departure was calculated based on the flight routes and the required route conformance dispersion. The number of departures was based on an estimation related to wind direction. The actual number of departures, preferential routes and environmental considerations were not considered in the allocation of take-off direction.

The number of overflights on approach to the airport was estimated. No real data were used to confirm the assumptions. The assumptions were that the aircraft would establish on approach to the runway at a distance of ten to 18 kilometres (normal distribution applied) before the runway and that the lateral distribution was normal too.

The model attempted to include the influence of local flight routes but the assumptions could not be validated for application in Great Britain. The use of average crash rates for Germany may not be directly comparable, although similar to the expected values. Overall, the project team had a relatively low confidence in this model and it did not appear to offer a significant advance of the Byrne model.

Review Criterion	**Review Comment**
Location	Vicinity of an aerodrome and background
Flight frequency	Local data collection
Fixed wing	Civil and military
Helicopters	Considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	All relevant phases of flight were considered
Impact scatter	Considered
Impact angle	Not mentioned specifically. Helicopters were assumed to crash vertically.
Wreckage trail	Considered
Hazard scenarios	Standard aircraft crash onto and into a site only.
Usability/useful	REJECTED

5.14 THE LOUGHBOROUGH MODELS (2001 ONWARDS)

The work carried out by Loughborough into the area of aircraft accident probability, frequency and location has focused on the areas in the vicinity of an airport and at the airport, rather than accidents occurring en-route and contributing to background crash rates.

5.14.1 The Kirkland Thesis (2001)

The thesis examined aircraft overruns of runways for take-off, rejected take-off and landing cases. This thesis developed the concepts of using Normal Operations Data to estimate the probability of an individual flight suffering from an accident as well as the causal factors. This thesis also developed the concept of normalising the data and infrastructure to a common reference which could then be modified in a local application in an attempt to mitigate the small pool of aviation data that would be available for application to a specific site (Caves and Gosling, 1999). The atmospheric conditions of a "hot and high" airport, such as the main international airports in Mexico City and Johannesburg are very different from Anchorage in winter in terms of air temperature, humidity and pressure. These all affect aircraft in terms of air density for lift and thrust generation. By reducing the conditions to a common baseline, known as the International Standard Atmosphere, this would allow comparisons to be made between airports. Assumptions were made that the terrain around the airport was level and that the runway did not slope significantly to allow comparison between airports by removing topographical influences.

Some of the normalisation factors could be questioned on the basis of flight performance. The demonstrated distance to stop the aircraft on landing is based on a measured distance from an initial height of 50 feet to the point at which an aircraft comes to rest. The base airport has a height over the threshold of the runway in excess of 50 feet, because the nominal aiming point is further down each runway at this point. The distance for the aircraft to come to rest is “factored” in the performance calculations by a multiplication factor of 1.67 as a safety factor. This calculated value is then compared with the declared landing distance available at the airport. Approximate values of 1600 metres for the calculated value of factored landing distance of an Airbus A320 (just over 300 metres for the distance to touchdown, around 600 metres to bring the aircraft to a stop and then around 700 metres as the safety factor) were then compared with the 4000 metres of runway length. This gave a value of around 150% of excess landing distance. This did not reflect the actual situation associated with the marked touchdown zone on the runway, the distance of runway available after the touchdown zone as well as the pilot selection of low deceleration values at the base airport because of the long runways (as opposed to very harsh braking and deceleration in the test flights to derive the basic stopping distance). The mass values for aircraft did not necessarily reflect the landing and take-off mass limitations that may be reflected by the runways. Therefore, more aircraft may have been closer to the ultimate performance limit on some runways whereas it would not be possible for the Airbus A320 to reach this limit at the base airport.

A deceleration model was developed assuming constant deceleration, given an initial velocity. This would not necessarily be the case if the data included changes in the terrain’s load bearing ability; changes in the friction surface contamination by rubber, sand and various states of water; changes in aerodynamic drag with airspeed; changes in aerodynamic lift affecting the mass supported by the undercarriage with airspeed; impacts with solid massive objects and variations in aircraft configuration such as reverse thrust, flap setting, spoiler deployment, yaw angles, anti-lock brake deployment and tyre slip angles. Kirkland was aware of the limitations of his first order model and that further work would be necessary to develop more accurate results.

The thesis did make significant advances in modelling and demonstrated methods of how better models could be made with access to appropriate normal operations and accident data.

5.14.2 The Wong Thesis (2007)

The thesis used data from the USA to derive accident probabilities, frequencies and locations in the vicinity and at airports for all accident types of commercial aircraft: landing overruns, take-off overruns, landing undershoots and take-off and crash accidents. The thesis was the first application of multivariate analysis to the data that were collected. This was allowed by the normal operations database covering a multitude of operational and meteorological parameters along with the accident database that was developed. The normal operations data were better suited to the population of accidents used in the analysis than in the previous attempts by Kirkland (2001). Formulae were developed to determine the local risk factors, rather than generic runway risk factors. This analysis was carried out down to specific runways in use, not just for a specific airport. The possibility exists that some of the relationships are misleading and these may need to be tested further. In particular, the relationship between cloud ceiling and probability of an overrun did not appear to have any significant operational explanation of causality.

The airport design rules for runways in the USA are slightly different from those found in GB. This may mean that some of the factors would have to be re-evaluated prior to their application to locations in Great Britain. This would be particularly important for approach accidents in the vicinity of a runway. Wong also used normalisation of the data to enable comparisons to be made. This was achieved by adjusting the crash location distances from the start or end of a runway with a factor associated with the Landing Distance Available (LDA) or the Take-Off Distance Available (TODA).

The thesis examined two airports as example applications using a target level of safety of 10^{-7} per movement. The use of the formulae suggested in the thesis would allow for an improvement in the aircraft crash probabilities and locations calculated for the vicinity of an aerodrome when compared with the Byrne models by taking into account local operating conditions rather than average conditions across Great Britain.

5.14.3 Airport Cooperative Research Program Report 3 (ACRP 3) (2008)

The Transportation Research Board (TRB) of the National Academies in the United States commissioned work as part of the Airport Cooperative Research Program (ACRP) to examine runway overruns and undershoots as Project 4-01 and documented as ACRP 3 (TRB, 2008). The work was sponsored by the Federal Aviation Administration (FAA).

The ACRP work was heavily based on Kirkland's (2001) and Wong's (2007) theses as would be expected as four of the co-authors were from Loughborough University. Additional data were added to the basis of the Loughborough database and included some incidents as well as more accidents. The work only considered application to airports in the United States and did not take account of international airport design standards published by ICAO (2013) but only the FAA's design standards (FAA, 2012a) or the national modifications published for use in the United Kingdom (CAA, 2011a).

The data were normalised to International Standard Atmosphere conditions to allow for comparison between airports and similar models were produced to those in Wong (2007).

The model for overruns and undershoot locations was again given by an exponential distribution.

5.14.4 Airport Cooperative Research Program Report 50 (ACRP 50) (2011)

The work reported in ACRP 3 was further extended to include an analysis of arrester beds at the ends of runways and the provision of software to enable the formulae developed in ACRP 3 to be applied by airport management more easily. It also added a variable into the frequency models to capture the effect of runway criticality.

The arrester beds that were considered were made of a crushable foam type of concrete known as engineered material arresting system which was approved for use in the United States at the time of the investigations. The arrester beds have a design basis of a Boeing 737 entering at 70 knots and being brought to a stop without any significant damage to the aircraft and subsequent injury to the aircraft's occupants (FAA, 2012b).

The software requires data such as historic operations data, historic weather data, runway characteristics, runway safety area dimensions, obstacle data and projected operations data. The software outputs average risk values, probability of a movement being exposed to risk above the target level of safety and graphical outputs to enable visualisation of the runway safety areas required.

The report claimed to have developed a practical approach to assess the effect of runway distance available on the probability of overruns. However, the model did not appear to take account of many of the runway surface and runway design factors necessary to be able to make this claim.

Review Criterion	**Review Comment**
Location	Vicinity of an aerodrome
Flight frequency	Local data collection
Fixed wing	Commercial aircraft above 2,700 kilogrammes maximum certificated take-off mass
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Final approach, landing, go-around, take-off and initial departure.
Impact scatter	Not considered
Impact angle	Not considered
Wreckage trail	Considered
Hazard scenarios	Standard aircraft crash onto a site only. Mid-air collisions are not added to the locations around aerodromes with high-intensity operations.
Usability/useful	Equations can be applied by a person with some mathematical ability. The model would allow for a more local conditions to be considered for accidents in the vicinity of an aerodrome when compared with the Byrne model.

5.15 THE BIENZ MODEL (2004)

A group of residents to the South of Zurich Kloten airport commissioned a comparative risk study (Bienz, 2004) that examined the third party risk exposure for future runway options at the country's main international airport. The frequency model was based on an average accident rate for western built aircraft using a 1959 to 2000 study by Boeing, precursor to the current publication which updates the statistics to the end of 2012 (Boeing, 2013). The same accident probability was given to each runway end being considered.

The location model was based on expert judgement and the sizes of runway safety areas published by the Civil Aviation Authority and the Federal Aviation Administration. The resulting distribution was fan shaped for departures, showing that the flight routes were important and the conventional distribution shape for straight-in approaches.

The calculation of the distribution of accidents was simplified for the purposes of the comparative risk assessment. The requirement for a licensed nuclear site is not necessarily for a quantitative comparative risk assessment but for a quantitative absolute risk assessment, or at least quantitative absolute hazard analysis relating to aircraft crash rates. Therefore, the Bienz model was rejected as being suitable for use in the vicinity of major aerodromes.

Review Criterion	**Review Comment**
Location	Vicinity of a runway
Flight frequency	Considered

Fixed wing	Civil aircraft operating on commercial flights
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	Take-off, initial departure, landing
Impact scatter	Single location given for wreckage location
Impact angle	Not mentioned specifically
Wreckage trail	Not mentioned specifically
Hazard scenarios	Standard accidents
Usability	Only suitable for comparative risk assessment for individual airport but relatively easy to apply.
Usefulness	REJECTED

5.16 THE GFL MODEL (2006)

There are not many publicly available details in English for the Gesellschaft fur Luftverkehrsforschung (GfL) model. Loughborough University e-mailed the company to ask for further details of the model. No reply was received. The application of the GfL model to Frankfurt airport (GfL, 2006) was obtained with the text in German. The application was to examine the external risk associated with the expansion of Frankfurt airport and the provision of a fourth runway (which has now been built). Data were collected for the baseline situation (2005) and projections made for traffic distribution between the new runway system for 2020. The application was to determine the individual risk contour profile at the $1x10^{-5}$ level as well as elements of societal risk exposure.

The GfL model uses a Weibull distribution to model the probability of an accident along the flightpath and a Laplace distribution to model the lateral deviation from the intended flightpath. The historic accident locations were plotted and the distributions fitted. The plots showing the locations appeared to be symmetrical in their lateral distributions in that accidents to the left of the intended flightpath were mirrored and repeated on the right hand side and vice versa. The original data were not presented so it was not possible to determine if this affected the chosen distributions or was merely an error in the plotting process.

No explanation was given relating to accident location adjustment to take account of offset approaches and turning departures. No mention was made of accidents occurring during a go-around manoeuvre.
The GfL model as applied to third party risk around Geneva (Susini et al., 2008) describes an application of cluster analysis to identify a series of airports similar in movements to Geneva, air traffic control infrastructure and other factors that have statistical significance in their correlation to the airport being studied. Accidents that occurred at all of the cluster of airports were then considered, rather than worldwide data. Experts then filtered out accidents that could not occur at Geneva Airport because of unique obstacle or environmental conditions. No attempt was made to add an additional set of shadow accidents to the airport to account for the local conditions in Geneva that were not present at the other cluster airports in order to ensure that the results were not optimistic. For example, if Amsterdam and Geneva were considered to be in the same cluster (they are not), a flightpath deviation on approach to Amsterdam associated with the failure of navigation equipment on-board the aircraft may not have any significant controlled flight into terrain issue whereas the terrain around Geneva may present a

significant probability of an accident occurring. The model did not have any element of formal hazard identification or analysis techniques applied within it and was merely historic data driven.

Another element of the GfL model which is not present in other models (with the exception of the NLR model) is the modification of accident rates by comparison with other clusters of airports (Thiel and Fricke, 2008). The findings of some of their research (Susini et al., 2008) indicate that there is a correlation between the number of movements at an airport and the probability of an accident per flight.

The GfL model attempts to use local flightpaths to determine the accident probability at any specified location using (s,t) coordinates as per NLR. The specific flight routes by aircraft are taken into account through the use of radar data. This can work in the vicinity of a major airport where there are radar data but for a small airport with no surveillance coverage then this may not be an applicable method of data collection.

The post-impact analysis appeared to focus on the kerosene related damage rather than physical impact as well as consequential release of hazardous materials from industrial facilities.

The model appeared to be very similar to the NLR model without any significant additional benefits. The documentation of the GfL model was relatively poor and it could not be verified in this review. The model was rejected from further consideration.

Review Criterion	**Review Comment**
Location	Vicinity of a runway
Flight frequency	Considered
Fixed wing	Commercial aircraft
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	All relevant phases of flight in the vicinity of an aerodrome but some elements such as go-around may not have been given specific consideration.
Impact scatter	Not considered explicitly
Impact angle	Not considered explicitly
Wreckage trail	Not considered explicitly
Hazard scenarios	Standard accidents
Usability	Formulae provided
Usefulness	REJECTED

5.17 THE BERG MODEL (2011)

The Berg model (2011) was developed with the specific risk assessment objective of application to the unintentional aircraft crash onto a licensed nuclear site. The model included consideration of the structural response of the plant to an impact which was beyond the scope of this project.

The Berg model's consideration of civilian aircraft accidents is based on the air routes close to the site under consideration; small and medium sized aerodromes within 50 kilometres; and large aerodromes within 150 kilometres. The flights were split into three phase of flight categories: landing and take-off; en-route and holding pattern; and free air traffic. The aircraft were split into four mass categories: under 2000 kg, 2000 to 5700 kg; 5700 kg to 20,000 kg and greater than 20,000 kg and crash rates per unit distance flown were allocated for the en-route phase of flight.

An impact angle of 30 degrees was assumed for modelling purposes. Berg stated that this was a conservative assumption but without justification. The shadow area of the plant was calculated using this assumption. In addition, the crash of aircraft beyond the shadow area was accounted for by adjusting the hazard range by an extra 1000 metres. The impact rate for these crash and slide cases was modified by a factor of 0.2; the impact was assumed to be a single part; and the impacting mass was assumed to have a maximum mass of 2000 kg. No justifications were given for these values.

The vicinity of the aerodrome model was based on a formula derived from crash location plots. The formula did not account for the actual routes used and was published on an analysis first carried out in 1974 (Furste and Gulpe). Crashes more than ten kilometres from an aerodrome were assumed to be randomly distributed as free air traffic. En-route crashes were distributed with a Gaussian function perpendicular to the route. The continued use of these distributions was not justified by analysis.

The Berg model accounts for military traffic. The transport aircraft were treated as if they flew commercial routes outside the landing and take-off phases of flight. The accident rate for the fast-jet category of operations was determined looking at historic data since 1991. The accident rate in the previous decade was approximately double the rate since 1991 relating to aircraft type changes and frequency of flights over western Germany since reunification and withdrawal of some NATO fighter squadrons to their home countries. The model was not specific as to how it dealt with the hazard analysis of fast-jets but it did state that the analysis was broken down into general cruise accidents, accident rates in the vicinity of military aerodromes and a local modification factor relating to the history of flight accidents in a 30 km x 30 km grid around the nuclear power plant. The orientation of the grid was not given so the directions of the main axes of the grid were not known. Military helicopter accidents were not mentioned.

The future changes in aviation activity were considered in the paper. A statement was given that although the annual distance flown by airliners was increasing, there was no systematic increase in the accident rate. No analysis was given or referenced to justify this statement. The increase in expected en-route traffic was justified with reference to EUROCONTROL forecasts (2008) and a factor of 1.7 to 2.2 was quoted in the 2030 timeframe.

The paper considers the structural impact modelling and the case of an Airbus A320 collision was considered. The paper did not identify aircraft in the "beyond design case" class for the current structural design standards.

The model for aspects in the vicinity of an aerodrome were not considered as suitable for application in GB as the local flightpaths were not taken into account. The en-route aspects of this model were not considered as suitable for application to a site specific hazard analysis because it used a general background rate and thus would not be a significant improvement over the Byrne model in current use. The military aspects of this model were not considered to be an improvement over the Byrne model. Overall, the model was rejected from further consideration.

Review Criterion	Review Comment
Location	Vicinity of a runway and background

Flight frequency	Considered
Fixed wing	Civil and military
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered
Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	All relevant phases of flight
Impact scatter	Considered
Impact angle	30 degrees assumed with no justification
Wreckage trail	Considered
Hazard scenarios	Standard accidents
Usability	Formulae provided
Usefulness	REJECTED

5.18 THE ENAC MODEL

The Italian civil aviation authority (ENAC) sponsored the development of an accident location model with Sapienza University of Rome (Cardi et al, 2012) for use in Italy. The accident data were taken from 1996 to mid-2011 occurring to North American and Western European built aircraft. This would appear to exclude the significant number of regional jet and turboprop aircraft built by Embraer in Brazil. Alitalia operates Embraer aircraft as part of its fleet and other aircraft operators use these aircraft on flights to Italy, for example Flybe. Also excluded were "companies that have safety conditions and technologies not homogeneous to the Italian ones".

The accident locations were plotted after normalisation was applied. The normalisation process was not described fully but it involved a ratio with the length of the runway related to the accident. There is no aircraft performance, runway design, infrastructure provision or operational procedure justification given for this mathematical manipulation of the laws of engineering and physics.

The plotted locations are relative to fixed points on the normalised runway. No account of displaced thresholds, stopways, clearways, starter-strips and other aspects of runway design were explained in the definition of the locations.

It would not be possible to apply this model to the United Kingdom without an understanding of what data have been excluded on the basis of Italian conditions; what data needs to be added based on the exclusion of some aircraft manufacturers; how the normalisation processes were applied; and how the model should be used to reflect local conditions in the United Kingdom. Therefore, the model was rejected from further consideration.

Review Criterion	**Review Comment**
Location	Vicinity of a runway
Flight frequency	Considered
Fixed wing	Commercial aircraft
Helicopters	Not considered
Gyrocopters	Not considered
Gliders	Not considered

Airships	Not considered
Balloons	Not considered
UAVs	Not considered
Phases of flight	All relevant aerodrome phases considered
Impact scatter	Not mentioned specifically
Impact angle	Not mentioned specifically
Wreckage trail	Not mentioned specifically
Hazard scenarios	Standard accidents
Usability	The computer program was not evaluated. No equations were presented.
Usefulness	REJECTED

5.19 MODELLING METHOD REVIEWS

A paper reviewing aircraft crash location modelling methods (Haley et al., 1998) examined the NUREG-0800, Solomon, Sandia, Hornyik and DOE Standard models. The non-Hornyik models use similar methods to derive the general crash probability for a category of aircraft and then multiply by the number of flight operations in that category to derive an annual frequency. The annual frequencies for all of the categories are then summed to give the final result. The crash rate per mile of flight, crash density function and effective target area are used in the calculation. The paper identified that the Hornyik model was developed to assist in the calculation of aircraft accidents associated with military target towing operations. The comment is also given that Hornyik is not usually selected as the model of choice.

The review identified that NUREG-0800 has an additional factor in for airways modelling. The DOE standard model comments were related to its application across the continental USA.

The paper identified six improvements that could be made to the model. Firstly, changing the skid distance to a value associated with building penetration. This would require a structural analysis to take place before the effective skid area could be reduced. Secondly, changing the effective wingspan of the aircraft to be the distance between wing mounted engines. No account was given as to how rear-engine aircraft should be dealt with under this modification. No statement was made as to whether the dimension being considered should be between the centre of the engines or the outer element of their cowlings. Thirdly, considering the shielding protection received from other buildings. Again, this would require some consequence analysis to be carried out. Fourthly, a suggestion was made to take the building dimensions into account based on the direction of approach of the aircraft. This may appear to be reasonable. Another comment was given relating to terrain and the likelihood of an accident. The penultimate suggestion for improvement was the move to model flightpaths around an aerodrome explicitly rather than using orthonormal X and Y coordinates. This implied a move from Cartesian coordinates to curvilinear coordinates. The final suggestion was to improve the local crash rate analysis through the consideration of local topography.

The assessment of aircraft crash model applications in the final safety analysis reports of two nuclear power plants were compared (Jamali et al., 1998). The Seabrook nuclear power station used the Hornyik and DOE models with Millstone 3 nuclear power station applying NUREG-0800 and DOE models. The first comment by the reviewers related to the exclusion distance beyond which an aerodrome did not have to be considered as contributing to the crash rate. The second comment related to the assumed impact angle and the values chosen by the sites were considerably steeper than the DOE model suggested. The average skid distance chosen by Millstone was somewhat smaller than an average value balancing the likelihood of general aviation and commercial aviation accidents (by a factor of approximately two), even without biasing the distance to account for impact consequences associated with the heavier commercial aircraft. The third comment also related to the effective area of the sites because a more optimistic method was chosen in the Millstone analysis than would be suggested by application of the DOE method. The fourth comment related to the difference between the modelling carried out in the DOE method to represent the background accidents when compared with the Hornyik and NUREG-0800 methods. The reviewers considered that the DOE standard had a more credible method for predicting the crash rates given the changes to the air traffic control system with the move away from rigid airway structure use. The final conclusion was that the methods applied at the sites gave results significantly below those predicted by applying the DOE standard.

A comparison of models was carried out in a trial application to the site of a nuclear power plant with the use of the NUREG-0800 and DOE standard models (Kimura et al., 1997). A table illustrating the results for applying the two models to different areas of the plant is provided for a variety of projected aircraft movement rates. The different areas of the plant have different ground areas and vertical extents. The comparison of results between the models indicates that the NUREG-0800 model gives aircraft crash probabilities per year of approximately one order of magnitude higher than the DOE model.

The main comparison of accident models for use in the vicinity of an aerodrome was carried out by Piers (1998) and three categories were suggested:

"Category I: Models which effectively map historical accident locations on the area around the airport under investigation and calculate the location probabilities for large geographical segments directly as a percentage of all hits in that segment.

"Category II: Models which use historical accident location data to derive mathematical functions describing the impact probability for a particular location as a function of the angular distance between that location and the extended runway centerline and the distance that of that location to the runway threshold or as a function of the Cartesian (x,y) coordinates of the location relative to the extended runway centerline and the runway threshold. Effectively these models allow the calculation of the local accident location probability based on the polar or Cartesian coordinates of the location relative to the runway.

"Category III: Models which use historical accident location data to derive mathematical functions describing the impact probability for a particular location as a function of (longitudinal) distance to that location from the runway threshold along the intended route and the perpendicular (lateral) distance from the route to that location. Therefore, these models allow the integration of the influence of traffic routing in the risk calculation. Category I and II models lack this property."

Category I models were considered suitable if only a simple first indication of risk was required. However, for application in a licensed nuclear site safety case then the level of accuracy and precision required would require a more complicated model.

The review of Category II models examines Jowett and Cowell (1991) which was the precursor to the Byrne model. The advantages over Category I models of allowing calculation of the crash rate at any particular point around the airport and the greater data sets (associated with their later implementation) should give better results when combined with their ability to differentiate between take-off and landing crashes. The disadvantages highlighted include the assumptions that X-distribution and Y-distribution functions are independent which may not be a true representation of the flightpath data.

The Category III models examined included those by DNV Technica and NLR. These models attempted to ensure that the intended route of the aircraft was taken into account through the implementation of curvilinear coordinates. The data requirements for this type of model are more stringent than for the Category II models as the intended route has to be recorded and the model needs to be sub-divided into arrival and departure accidents with further splits into classifications such as take-off overruns and take-off and crash being required. The review concluded that the NLR model gave the best results for the predicted location. The remainder of the paper discussed the third party consequence analysis for accidents predominantly relating to urban environments and not particularly applicable to a licensed nuclear site.

Four separate reviews of the Byrne model and its application to the proposed expansion of London (Ashford) Airport near Lydd and the Dungeness licensed nuclear sites were identified. The suitability of the Byrne model for application at the Dungeness sites was investigated (ESR Technology, 2007) and subsequently updated (ESR Technology, 2009). The Byrne model was applied by the risk management consultancy AREVA RMC (Nicholls, 2009). The Lydd Airport Action Group published two reviews of the model (Pitfield, 2010; Trotta, 2012). The Health and Safety Executive commissioned Sandia National Laboratories to examine various models, including Byrne, and consider their application to the Dungeness sites (Hansen and LaChance, 2010).

The ESR Technology review included mentions of the 95% confidence limit for the crash data values in the discussion of the civilian aircraft contribution to the background crash rate and suggests a factor of approximately two higher than the 50% confidence level. The relatively low level of military flight activity in the area was used to justify the selection of the area of low crash concentration value selected for military aircraft crash contributions to the background crash rate. This appeared to be reasonable. However, some of the arguments as to the civilian background rate did not appear to stand up to scrutiny. The crash of a Viscount was discussed in the large transport aircraft category. An argument was presented that because the pilot had a degree of control, despite three out of four engines having failed, that the protection provided by prohibited airspace would have prevented the accident from occurring at a licensed nuclear site. No discussion was presented about pilot workload during such an emergency; the ability to locate the exact position of the aircraft and the presentation of prohibited airspace on the en-route charts for use with Instrument Flight Rules. The discussion also recognised that the use of an accident rate per departure may be a way of overcoming the limited dataset from operational experience in Great Britain. An accident rate per departure was derived from several sources of data but it did not appear to be correlated with the phases of flight that occur in the vicinity of Dungeness or the frequency of flights overhead. No attempt was made to demonstrate that the number of flights (or flight passes to account for the holding pattern overhead the Lydd navigation beacon for inbound flights to London Gatwick) gave an average or below average overflight rate.

The accident rates, expressed per movement, in the vicinity of an aerodrome are quoted with both 50% and 95% confidence levels. The balance between arrival and departure crash rates was not given. Various issues with modelling the crashes in the vicinity of an aerodrome were noted and the NATS model was used as a comparison. Mentions were made of some models that attempted to model curved departures without specifying which models were being considered and doubts about their validity. The importance of modelling local factors was highlighted with a quote of the relationship between approaches made with or without instrument landing aids. Unfortunately, it would appear that the relationship between visual approach, non-precision instrument approach and precision approach was not understood when quoting the results. Overall, the application of the NATS model to the operations at Lydd was suggested as preferable, despite the inability of NATS or Byrne models to deal with the local flightpath conditions.

The discussion of the below airways crash rate and the impact area model did not highlight any new deficiencies in the original model that had not already been identified.

The Pitfield review (2010) examined the application of the Byrne model with respect to runway directions and the overall crash rate. The review highlighted the need to assess landings on Runway 21 in addition to Runway 03 in the analysis of crash rates at Dungeness. In addition, the lack of the Byrne model's ability to cater for local variations was highlighted together with the statistical limitations associated with small sets of data. Suggested changes included the use of a wider set of data and the inclusion of modelling to account for go-arounds and birdstrikes.

The Sandia review (Hansen and LaChance, 2012) compared the application of the Byrne model with NUREG-0800, DOE standard and the IAEA requirements to Dungeness. The review indicated that the IAEA safety guidelines were met through the application of the Byrne method and no further consideration of the IAEA requirements was necessary. NUREG-0800 was recognised as being able to calculate the aerodrome and airway related components of the crash rate but not the background crash rate. The aerodrome-related accident rate was more than an order of magnitude lower using NUREG-0800. Quantification of the airway-related crash rate was not carried out. However, a statement was given that unless an airway was proximal to the Dungeness site, the contribution to the overall crash rate would be negligible. There are airways proximal to Dungeness that use the navigation beacon situation close to Lydd airport. The comparison with the DOE standard was similar to the NUREG-0800 comparison with the aerodrome-related crash rate being a factor of five to ten lower using the DOE standard. Once again, background and airway related accident rates could not be compared. It was concluded that neither of the American methods examined could deal with the local flightpath routes and airspace restrictions associated with the operations at Lydd any better than the Byrne model.

The Trotta review (2012) considered that the uncertainty in the background rate should be considered and suggested a confidence level of 99% would be reasonable and the resulting increase in accident rate would be a factor of two. The need to make significant extrapolations in the probability density curves as far out as the licensed nuclear sites implied that the uncertainty in the aerodrome-related risk may be as high as a factor of ten for those runway configurations considered. The relative location of the aerodrome and the licensed nuclear sites appeared to prevent the evaluation of landings on Runway 21 and departures from Runway 03 because they were beyond the range of applicability of the model. The lack of ability to cope with curved flightpaths was noted as was the relatively simple treatment of skid lengths in the application to the sites under consideration.

The four reviews did not appear to identify one significant issue with the Byrne model's application in the Dungeness/London Ashford Airport expansion case. The change in risk was considered to be an adequate measure and appeared to be based on a comparative hazard analysis. The base case was the Byrne model with the comparative case being the same value for background and below airway crash rate plus the change in the aerodrome-related risk. The background and below airway rate was considered to be approximately 90% of the base case exposure. However, the Byrne model does not appear to have been subjected to an examination of the relative contribution to crash rates made up from background, below airway and vicinity of an aerodrome. Therefore, inferences of the relative change in hazard occurrence rates associated with the expansion of an aerodrome through the application of the Byrne model may not be appropriate.

6 AIRCRAFT CRASH RATES FOR GREAT BRITAIN

6.1 BACKGROUND (OFF-AIRPORT) CRASH RATES

6.1.1 The Data

A report by ESR Technology (ESR Technology, 2008) provided a list of background aircraft crashes and updates to the background crash rates in England, Scotland and Wales for several aircraft categories, based on accidents that occurred between 1996 and 2006. Severe accidents involving fatalities or severe loss of aircraft control were included. The screening criteria meant that only those civil aircraft accidents that occurred over the UK mainland or within two miles of the coast were considered. As it appears that crashes occurring on Scottish islands, the Isle of Man and Jersey were included, it is believed that the crash rates refer specifically to the land mass containing England, Wales and Scotland (including the Scottish islands), i.e. Great Britain (GB), and some British Crown Dependencies. For clarity in this report, the crash rates presented in (ESR Technology, 2008) will be referred to simply as rates for GB (which includes GB and the British Crown Dependencies), rather than for the UK mainland.

In addition to the aircraft crash data listed for the period 1996 to 2006 (ESR Technology, 2008), background crash data for accidents that occurred in GB between 1985 and 1994 using similar screening criteria are available in an HSE report (HSE Research Report 150/1997, 1997), and between 1991 and 2000 in an AEA Technology report (AEA Technology, 1992). The aircraft categories used (HSE Research Report 150/1997, 1997; ESR Technology, 2008; Kingscott, 2002)) include:

(1) Light fixed-wing aircraft (<2,300 kg maximum certified take-off mass (MCTOM))
(2) Helicopters
(3) Small transport aircraft (≤ 20,000 kg MCTOM)[4]
(4) Large transport aircraft (airliners and military transport >20,000 kg MCTOM)

Tables A1 to A4 in Appendix A present the number of background crashes that occurred in GB for the above four aircraft categories, based on data reported in HSE Research Report 150/1997 (1997), ESR Technology (2008) and Kingscott (2002).

6.1.2 Statistical methods

6.1.2.1 Estimates of crash rates

It was assumed in the Byrne model (HSE Research Report 150/1997, 1997) that aircraft crashes may be represented as a Poisson process. This Poisson distributional assumption is commonly used to model the number of events occurring within a given time interval. For determining the background crash rates expressed at the 50% confidence level and per km^2, the following relationship between the chi-squared distribution and the Poisson-distributed crash rates was used in HSE Research Report 150/1997 (1997): if *r* is the number of crashes occurring in time period *T*, the chi-squared distribution relates the probability α that the mean is greater than or equal to a value θ, where

$$\theta = \frac{\chi^2_{1-\alpha,2(r+1)}}{2T} \qquad (1)$$

In this report, it is also assumed that aircraft crashes may be represented as a Poisson process with rate parameter λ (where λ represents the number of background crashes per year for a chosen area). The method used to estimate the background crash rate, however, is the maximum likelihood method, a

[4] *Ex-military jets in private operation fall into this category.*

standard method of estimating the parameters of a statistical model (which in this case is the parameter λ). This method selects the parameter value maximising the probability of obtaining the observed data. For the Poisson distributional assumption, the maximum likelihood estimate of λ is simply

$$\lambda_{ML} = \frac{1}{n} \sum_{i=1}^{n} k_i$$

where k_i is the number of crashes observed in year *i* and *n* is the number of years of observation. In comparison, the chi-square method used in HSE Research Report 150/1997 (1997) may not necessarily provide an estimate of the crash rate that maximises the probability of obtaining the observed data, but provides an estimated rate for which the probability of the true crash rate lying greater than or equal to the estimate is 50%. For calculating the confidence intervals around the estimated crash rates in this report however, the chi-square distribution is appropriate and will thus be used to provide 95% confidence intervals for the background crash rates.

In order to determine the crash rates per unit area, the land areas that were presented in previous reports will also be used for this report:

England	$1.304 \times 10^5\ km^2$
Scotland	$0.788 \times 10^5\ km^2$
Wales	$0.208 \times 10^5\ km^2$

A limitation of the Byrne model is the lack of treatment of uncertainty. Although the crash rates at the 50% confidence level were provided in HSE Research Report 150/1997 (1997) and ESR Technology (2008), the lack of treatment of uncertainty and absence of confidence bounds (which essentially state the range within which one has high confidence that the true crash rates lie) meant that there was no indication of how reliable the estimates of the crash rates were. In this section, lower 2.5% and upper 97.5% confidence limits will be presented in addition to the central estimates of crash rates.

Between 1985 and 2006, 84, 16 and 10 light aircraft crashes that met the screening criteria (HSE Research Report 150/1997, 1997; Kingscott, 2002; ESR Technology, 2008) occurred in England, Scotland and Wales respectively, resulting in a total of 110 background crashes involving light aircraft in GB.

Table 2 Estimates of annual background crash rates (95% confidence interval given in brackets) for between 1985 and 2006. Numbers in italics are the equivalent rates based on the shorter time periods used in ESR Technology (2008).

	Crash rate ($km^{-2}\ yr^{-1}\ 10^{-5}$)			
	England	**Scotland**	**Wales**	**GB**
Light aircraft (1985-2006)	**2.93 (2.34, 3.63)** *2.30 (1.58, 3.23)*	**0.92 (0.53, 1.50)** *1.04 (0.48, 1.97)*	**2.19 (1.05, 4.02)** *3.93 (1.80, 7.47)*	**2.17 (1.79, 2.62)** *2.02 (1.50, 2.65)*
Helicopters (1985-2006)	**1.39 (1.00, 1.90)** *1.53 (0.96, 2.32)*	**0.46 (0.20, 0.91)** *0.35 (0.07, 1.01)*	**1.31 (0.48, 2.85)** *0.44 (0.01, 2.44)*	**1.07 (0.80, 1.39)** *1.03 (0.67, 1.51)*
Small transport (1985-2006)	**0.31 (0.14, 0.60)** *0.35 (0.11, 0.81)*	**0.00 (0.00, 0.21)** *0.00 (0.00, 0.43)*	**0.22 (0.01, 1.22)** *0.44 (0.01, 2.44)*	**0.20 (0.10, 0.36)** *0.24 (0.09, 0.52)*
Large transport (1985-2006)	**0.04 (0.00, 0.19)** *0.04 (0.01, 0.21)*	**0.17 (0.04, 0.51)** *0.19 (0.04, 0.56)*	**0.00 (0.00, 0.81)** *0.00 (0.00, 0.89)*	**0.08 (0.02, 0.20)** *0.09 (0.02, 0.22)*

Table 2 presents the maximum likelihood estimates of the background crash rates along with 95% confidence intervals (given by the 2.5% and 97.5% confidence levels); for comparison, the equivalent rates based on the shorter time periods used in ESR Technology (2008) are presented in italics. For light aircraft, the estimated annual crash rate was highest for England (2.93 $km^{-2}10^{-5}$) and lowest for Scotland (0.92 $km^{-2}10^{-5}$), with Wales falling in between (2.19 $km^{-2}10^{-5}$). The difference between England and Scotland was statistically significant, with the lower bound of the 95% confidence interval for England lying above the upper bound for Scotland. In fact, the crash rate for England is that much higher than the rest of GB that even the estimate in ESR Technology (2008) for the UK mainland of 2.04 $km^{-2}10^{-5}$ falls below the lower 95% confidence limit of 2.34 $km^{-2}10^{-5}$ for England.

A comparison of the crash rates for the period 1985 to 2006, presented in bold, with the shorter time periods used in ESR Technology (2008), presented in italics, shows that the 95% confidence intervals are generally narrower for the former than the latter, which is an advantage of using a longer time period. However the inclusion of crashes as far back as 1985 to calculate a crash rate that is independent of time may only be appropriate if the crash rates have remain unchanged over time. The presence of such trends is investigated in Section 6.1.2.2.

ESR Technology (2008) reported an annual crash rate for light aircraft in GB of 2.04 $km^{-2}10^{-5}$ (50% confidence level), which falls within the 95% confidence interval for GB presented in Table 5. Although the use of this GB figure was recommended instead of the individual country values, it is recommended in this report that country-specific values are used for light aircraft, in particular for England where the GB figure may underestimate the true crash risk. In addition, the upper bounds of the 95% confidence intervals should be taken into account when evaluating the aircraft risk. Thus where the original value of 2.04 $km^{-2}10^{-5}$ (50% confidence level) (ESR Technology, 2008) would have been applied to evaluate the annual crash risk in England, the values of 2.93 $km^{-2}10^{-5}$ and 3.63 $km^{-2}10^{-5}$ (95% upper bound) are recommended for quantifying the upper bound of the risk.

For helicopters, the estimated annual crash rate was highest for England (1.39 $km^{-2}10^{-5}$) and lowest for Wales (0.46 $km^{-2}10^{-5}$). The difference between England and Wales was statistically significant. The GB estimate of 1.07 $km^{-2}10^{-5}$ is almost equal to the lower 95% confidence limit for England, which suggests that England-specific helicopter crash rates (rather than a UK mainland/GB rate) may be more appropriate for evaluating the crash risk from helicopters in England. There was little difference between the crash rates for helicopters in GB presented in Table 5 and that presented in (ESR Technology, 2008) of 1.05 $km^{-2}10^{-5}$.

For small transport aircraft, the estimates of the crash rates range from 0.00 to 0.31$m^{-2}10^{-5}$. As no significant difference was found between England, Scotland and Wales, the GB rate of 0.20 (0.10, 0.36) $m^{-2}10^{-5}$may be used.

For large transport aircraft, the GB estimate of 0.08 $m^{-2}10^{-5}$ and its upper 95% confidence limit of 0.20 $m^{-2}10^{-5}$ are recommended, due to the sparse data for the period 1985 to 2006. The GB rate of 0.11 $m^{-2}10^{-5}$ reported in ESR Technology (2008) lies within the corresponding 95% confidence intervals presented in Table 5.

The above estimates have not accounted for operational reliability. In future, an element of operational reliability may have to be added to these figures, as some routes are relatively dense, some sparse; a fact that had not been considered in the above analysis as it presented average crash frequencies over the landmass.

6.1.2.2 *Time trends in GB background crash rates*

The data on background crashes that occurred between 1985 and 2006 (Tables A1 to A4 in Appendix A) may be used to investigate whether any time trends in crash rates (expressed per unit area) were observed over that period. For the Poisson-distributed annual crash frequency distributed with mean λ, the following model may be used:

$$\ln(\lambda) = a + b \times (Year_i - 1985) \qquad (2)$$

i.e.

$$\lambda = e^a e^{b \times (Year_i - 1985)}$$

where $\lambda = E(N_i)$ and N_i is the number of crashes occurring in year i, $Year_i$ is the calendar year, e^a represents the 'best estimate' of the crash rate in 1985 (the baseline year) and e^b represents the multiplicative change in crash rate per year after 1985. The estimate of *b* can inform us whether the data show any evidence of a time trend; if the estimate is close to 0, the data would suggest no evidence. However a negative value of *b* may suggest that crash rates are declining.

Model (2) was fitted in R (R Core Team, 2013) for crashes involving light aircraft, helicopters and small transport aircraft in GB. The model was not fitted for large transport aircraft due to the sparse data. For light aircraft, helicopters and small transport, the estimate of *b* was not found to be significantly different from 0, i.e. **there was no evidence of a trend in background crash rates per unit area in GB based on data on crashes between 1985 and 2006, for light aircraft, helicopters and small transport**. This does not imply that there was no change in crash rates, but that the data did not show evidence of any trends in the crash rate per unit area. Furthermore, the number of small transport movements has increased over this period which may disguise an improvement in aircraft reliability for small transport aircraft.

This analysis on time trends did not consider historical trends in flight movements, i.e. that the number of flights over GB in some transport categories (such as large commercial transport) have gradually been increasing over time. Although no trends in crash rates per unit area were found, the actual background crash rate per flight movement or per km flown may actually have declined, but when combined with an increase in flight movements per km^2, any reductions based on total flight distance flown may not be observed when evaluating crash rates based on land area alone.

Data on distance flown by aircraft above GB should be obtained (which should include distance flown by foreign airlines flying above GB regardless of the state of operator/registration, but exclude the parts of the flights that were outside of GB) so that a background crash rate per km flown may be calculated. This method of calculation of background crash rates may be more appropriate for the following reasons:

1. Some areas of GB are areas of high flight activity, and a calculation of a background risk that is independent of the number of flights occurring within that area may substantially underestimate the true risk in these areas. The estimated background risk is an 'average' value and the local value may vary from almost zero to a much higher value than the estimate presented. Obtaining a crash rate per km flown along with total distance flown by aircraft in a particular region allows a more reliable estimate of the crash rate at a particular location to be calculated.
2. Annual estimates of background crash rates (per km flown) allow us to investigate trends in background crashes that have been adjusted for trends in flight activity, rather than assuming that the number of flights/distance flown above GB remains constant over time.

6.2 AERODROME-RELATED CRASH RATES FOR GREAT BRITAIN

6.2.1 The Data

The AEA report (AEA, 1992) and the ESR Technology report (ESR Technology, 2008) provided a list of aerodrome-related civil aircraft crashes and updates to the aerodrome crash rates in England, Scotland and Wales, based on accidents that occurred between 1979 and 1990 and 1990 and 2006 (between 1990 and 2008 for large transport) respectively. ESR Technology (2008) also presented the number of flight movements within the same period. Aerodrome-related accidents at military aerodromes were also presented, however only civil aircraft accidents will be analysed in this report.

An aircraft crash was deemed to be aerodrome-related if it met the following criteria (ESR Technology, 2008);

• The crash occurred within 5nm of the runway threshold on the approach or take-off phases. Note that for helicopters this includes planned landing sites, even if they are not recognised aerodromes or landing strips.

• The crash resulted from significant loss of pilot control where the pilot may be unable to avoid impacts with buildings or structures.

• The crash led to significant damage to the aircraft (often total hull loss) and/or major injury/fatality to crew or passenger.

• The aircraft overshoots or skids beyond the aerodrome boundary.

The following crash incidents were specifically excluded:

• Crashes or other impacts on the ground e.g. where taxiing or during towing.

• Helicopter crashes where the helicopter was hovering close to the ground[5].

• Fires on the ground, even if leading to total hull loss.

• Hard landings, veer offs, minor impacts or landing gear failures.

Tables A5 to A8 list the aerodrome-related crashes that occurred between 1979 and 2006 (1979 to 2008 for large transport), as reported in AEA (1992) and Kingscott (2002).

Table 3 lists the number of flight movements and the number of accidents that occurred in GB between 1979 and 2006 for light aircraft, helicopters and small transport aircraft, and between 1979 and 2008 for large transport aircraft.

[5] Many licensed sites allow helicopter operations at the site.

Table 3 Civil flight movement and accident data (GB) for light aircraft, helicopters, small transport and large transport, 1979 to 2006 (1979 to 2008 for large transport).

Year	Light aircraft		Helicopters		Small transport		Large transport	
	Number of movements (million)	Number of accidents	Number of movements (million)	Number of accidents	Number of movements (million)	Number of accidents	Number of movements (million)	Number of accidents
1979	2.76	2	0.53	2	0.35	2	0.744	0
1980	2.74	6	0.53	0	0.35	1	0.738	0
1981	2.64	1	0.51	1	0.34	0	0.712	0
1982	2.65	3	0.51	1	0.34	0	0.715	0
1983	2.81	3	0.54	0	0.36	1	0.758	0
1984	2.96	3	0.57	2	0.38	0	0.800	0
1985	2.95	3	0.57	0	0.38	1	0.797	1
1986	3.06	6	0.59	1	0.39	2	0.826	0
1987	3.28	9	0.63	0	0.42	4	0.885	0
1988	3.60	1	0.70	0	0.46	0	0.971	0
1989	3.95	1	0.76	1	0.51	0	1.067	1
1990	3.41	5	0.45	3	0.25	0	0.917	0
1991	3.41	5	0.45	1	0.27	2	0.974	0
1992	3.41	3	0.45	0	0.28	2	1.032	0
1993	3.41	2	0.45	0	0.30	0	1.089	0
1994	3.41	2	0.45	0	0.31	0	1.146	1
1995	3.41	4	0.45	0	0.33	3	1.203	0
1996	3.41	8	0.45	1	0.35	4	1.260	0
1997	3.41	7	0.45	2	0.36	0	1.317	0
1998	3.50	3	0.45	4	0.38	1	1.397	0
1999	3.35	10	0.45	0	0.40	1	1.463	1
2000	3.24	8	0.43	2	0.42	3	1.528	0
2001	3.34	11	0.46	0	0.45	3	1.634	0
2002	2.97	5	0.46	1	0.45	3	1.654	0
2003	3.27	7	0.42	2	0.46	0	1.675	0
2004	3.04	9	0.41	2	0.49	0	1.768	0
2005	3.03	10	0.46	3	0.51	0	1.863	0
2006	2.83	7	0.51	1	0.50	1	1.831	0
2007	-	-	-	-	-	-	1.831*	0
2008	-	-	-	-	-	-	1.831*	1
Total	89.29		14.12		10.82		36.43 (1979 - 2008)	

Flight movement data for 1990 to 2006 were obtained from the ESR Technology report (ESR technology, 2008). Data for 1979 to 1989 were obtained by scaling the estimated total civil aircraft movement data in AEA Technology (1992) by the percentage of total of movements in 1990 that were light aircraft (62.73%), helicopters (12.13%), small transport (8.07%) and large transport (16.93%).
*The number of movements in 2007 and 2008 for large transport was assumed to be the same as in 2006.

6.2.2 Statistical methods

6.2.2.1 Estimates of crash rates

As has been assumed for background crashes, it is assumed that aircraft crashes may be represented as a Poisson process (Kingscott, 2002). The chi-squared distribution was used to determine the aerodrome-related crash rates expressed at the 50% confidence level and per flight movement. If r is the number of crashes occurring from N flight movements, the chi-squared distribution relates the probability α that the mean is greater than or equal to a value θ, where

$$\theta = \frac{\chi^2_{1-\alpha,2(r+1)}}{2N} \qquad (3)$$

In order to determine the crash rates per flight movement, the following total flight movements were used (Table 3):

Light aircraft (1979-2006)	89,289,517	(89.290 million)
Small transport (1979-2006)	10,818,938	(10.819 million)
Large transport (1979-2008)	36,426,973	(36.427 million)

Between 1979 and 2006, there were 128, 10 and 6 light aircraft crashes in England, Scotland and Wales respectively, giving a total of 144 background crashes involving light aircraft in GB. Table 4 presents the estimates and 95% confidence intervals (given by the 5th and 95th confidence levels) of the light aircraft aerodrome-related crash rates between 1979 and 2006 for GB, England, Scotland and Wales.

Scotland was found to have the highest rate at 1.51 (95% C.I. [0.73, 2.78]) per million movements, with Wales the lowest at 1.46 (95% C.I. [0.54, 3.18]). However the 95% confidence intervals were wide and indicated no significant difference between the rates for England, Scotland and Wales. Thus the GB rate of 1.61 (95% CI [1.36, 1.90]) per million movements may be used for England, Scotland and Wales.

Table 4 Estimates of light aircraft aerodrome crash rates between 1979 and 2006 (95% confidence interval given in brackets)

	GB	**England**	**Scotland**	**Wales**
Number of accidents	144	128	10	6
Flight movements* (million)	89.29	78.57	6.61	4.11
Rate (per million)	1.61 (1.36, 1.90)	1.63 (1.36, 1.94)	1.51 (0.73, 2.78)	1.46 (0.54, 3.18)
*note that one movement is either a take-off or landing, so each flight may constitute two movements				

Table 5 presents the estimates and 95% confidence intervals of the aerodrome-related crash rates for GB for helicopters (based on data between 1979 and 2006), small transport aircraft (based on data between 1979 and 2006) and large transport aircraft (based on data between 1979 and 2008). The rate was significantly higher for helicopters and small transport aircraft , at 2.12 (95% C.I. [1.43, 3.03]) and 3.14 (95% CI [2.18, 4.39]) per million movements compared to 0.14 (95% CI [0.05, 0.32]) per million movements for large transport aircraft. There was no significant difference between the rates presented in this report and those reported in (Kingscott, 2002) based on 1990-2006, which lie within the 95% confidence intervals presented in this report.

Table 5 Estimates of helicopter, small transport and large transport aerodrome crash rates for GB (95% confidence interval given in brackets)

GB			
	Helicopters 1979-2006	**Small transport 1979-2006**	**Large transport 1979-2008**
Number of accidents	30	34	5
Flight movements* (million)	14.12	10.82	36.43
Rate (per million) ***[Ref. 2, based on years 1990-2006]***	2.12 (1.43, 3.03) *[2.96]*	3.14 (2.18, 4.39) *[2.40]*	0.14 (0.05, 0.32) *[0.144]*

*note that one movement is either a take-off or landing; each flight may constitute two movements

6.2.3 Time trends in GB aerodrome-related crash rates

Historical data on aerodrome crashes may be used to identify any time trends in crashes over the period of the dataset. Flight activity at aerodromes has increased in the last couple of decades with more flights now taking place than a few decades ago, thus the aerodrome crash rates may have to account for the recent increases in flight activity. Figure 2 shows the number of movements between 1979 and 2006 for light aircraft, small transport and large transport aircraft, along with the number of crashes involving aircraft.

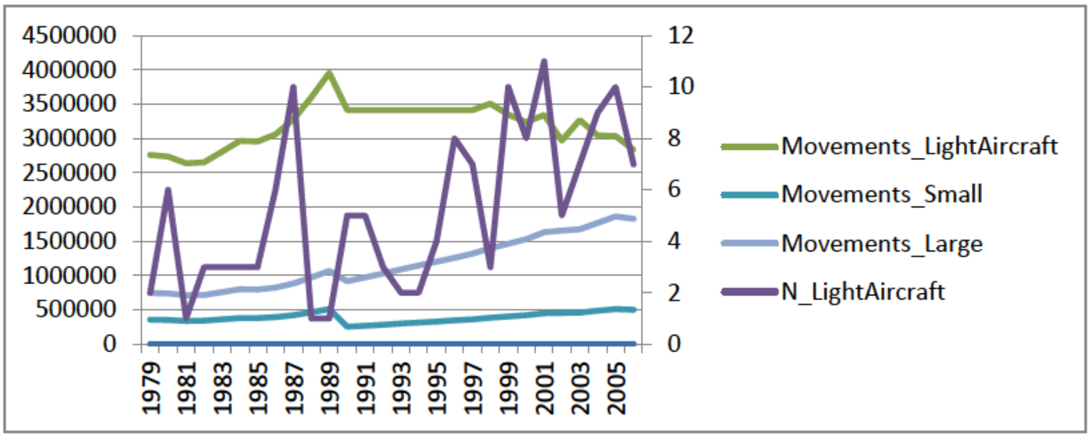

Figure 2 Flight movements and light aircraft accidents (N_LightAircraft) in GB between 1979 and 2006

Assuming that the number of crashes follows a Poisson distribution distributed with mean λ, the following model may be fitted:

$$\ln \lambda \ = \ln \ M_i \ + a + b \times (Year - 1979) \qquad (4)$$

where M_i is the number of flight movements, e^a represents the 'best estimate' of the crash rate in 1979 (the baseline year) and e^b represents the multiplicative change in crash rate per year after 1979.

The model was fitted to data for light aircraft, helicopters and small transport aircraft for the period 1979 to 2006. Due to the low number of crashes involving large transport aircraft, a time trend analysis was not carried out for this aircraft category. **For light aircraft, a statistically significant increase in the**

crash rate of 4.4% (95% CI [2.3, 6.6%]) per year was found (estimate of b=0.044). For helicopters, a statistically significant increase in the crash rate of 4.7% (95% CI [0.2, 9.3%]) per year was found (estimate of b=0.047). No significant time trend was found for small transport aircraft. Adjusting the rate for light aircraft and helicopters by the estimated trends of +4.4% and 4.7% per annum respectively give crash rates for 2014 of 3.89 (95% C.I. [2.51, 6.03]) per million movements and 5.16 (95% C.I. [2.19, 14.35]) per million movements.

6.3 TIME TRENDS FOR US AIRCRAFT ACCIDENT RATES

The National Transportation Safety Board (NTSB) 2012 aviation statistics provide information on US civil aviation accidents that occurred between 1993 and 2012 for air carriers regulated by 14 Code of Federal Regulations (CFR) Part 121, and commuter and on-demand carriers regulated by 14 CFR Part 135. Statistics available include the number of accidents by severity of accident, hull losses and aircraft hours flown. The phase of the flight during which the accident occurred (e.g. take-off, landing) was not available at the time of writing, however an analysis of the most severe accidents adjusted by aircraft hours flown may provide an indication of whether aircraft accident rates have changed over time, and how the trend compares to the GB accident rates for light aircraft. The NTSB accident severity classification scheme for Part 121 aviation divided accidents into four levels of severity, (i) major; (ii) serious; (iii) injury; and (iv) damage. Only major and serious accidents will be considered in this report, as accidents falling within these two categories have been identified to be the most comparable to those analysed in section 4 of this report.

A 'major' accident was defined as one where the aircraft was destroyed, OR there were multiple fatalities, OR there was one fatality and substantial damage to the aircraft.

A 'serious' accident was defined as one where there was a single fatality without substantial damage to the aircraft, OR at least one serious injury and the aircraft was substantially damaged.

Table 6 presents the number of accidents that were classified as major or serious, the aircraft hours flown, and the accident rate per million hours flown, for US carriers operating under 14 CFR Part 121.

Most air carriers regulated by 14 CFR Part 121 fly large transport-category aircraft however some haul cargo only. Although data on Parts 135 and 129 are not presented in this report, Part 135 applies to commuter and on-demand operations and has different regulatory requirements than those for Part 121 operators; Part 129 applies to foreign carriers operating in US airspace. The category 'general aviation' encompasses operations not covered by Parts 121, 135 or 129.

Table 6 Accidents and Accident Rates by NTSB Classification, 1993 through 2012 for US carriers operating under 14 CFR Part 121

Year	Accidents		Aircraft Hours Flown (millions)	Accidents per Million Hours Flown
	Major	Serious		Major
1993	1	2	12.706	0.079
1994	4	0	13.124	0.305
1995	3	2	13.505	0.222
1996	6	0	13.746	0.436
1997	2	4	15.838	0.126
1998	0	3	16.817	0
1999	2	2	17.555	0.114
2000	3	3	18.299	0.164
2001	5	1	17.814	0.281
2002	1	1	17.29	0.058
2003	2	3	17.468	0.114
2004	4	0	18.883	0.212
2005	2	3	19.39	0.103
2006	2	2	19.263	0.104
2007	0	2	19.637	0
2008	4	1	19.127	0.209
2009	2	3	17.627	0.113
2010	1	0	17.751	0.056
2011	0	0	17.963	0
2012	0	0	17.902	0

Major - an accident in which any of three conditions is met:

· a Part 121 aircraft was destroyed, or

· there were multiple fatalities, or

· there was one fatality and a Part 121 aircraft was substantially damaged.

Serious - an accident in which at least one of two conditions is met:

· there was one fatality without substantial damage to a Part 121 aircraft, or

· there was at least one serious injury and a Part 121 aircraft was substantially damaged.

Table 7 presents estimates of crash rates for scheduled and non-scheduled operations covered by 14 CFR Part 121 between 1993 and 2012, along with 95% confidence intervals. The crash rate for non-scheduled operations was 2.15 per million departures (95% CI [1.11, 3.75]), significantly higher than that for scheduled operations of 0.16 per million departures (95% CI [0.12, 0.23]).

Table 7 Accidents and accident rates for carriers operating under 14 CFR 121 between 1993 and 2012 (95% confidence interval given in brackets)

US air carriers operating under 14 CFR 121			
	Scheduled	Non-scheduled	Scheduled and Non-scheduled
Number of *fatal* accidents	32	12	44
Departures* (million)	196.073	5.590	201.663
Rate (per million departures)	0.16 (0.12, 0.23)	2.15 (1.11, 3.75)	0.22 (0.16, 0.29)

*Note that the number of departures is not comparable to the number of flight movements presented for GB, where one flight may constitute two movements

Table 8 presents the trends in aircraft accident rates for GB and the US. When considering just major crashes involving US carriers operating under 14 CFR 121 and adjusting by flight hours, a significant reduction of 7.5% (95% C.I. [0.2%, 13.1%]) per year was found. When looking at major and serious crashes combined, a significant reduction of 6.6% (95% C.I. [2.6%, 10.8%]) per year was found. Similar reductions were found when the crash frequencies were adjusted by the number of departures; for major crashes, a significant reduction of 6.5% (95% C.I. [1.1%, 12.1%]) was found and for major and serious crashes, a significant reduction of 5.6% (95% C.I. [1.5%, 9.8%]).

When considering major crashes involving general aviation (i.e. those that were not covered by 14 CFR Parts 121, 135 or 129) and adjusting by flight hours, a significant reduction of 1.3% (95% C.I. [1.1%, 1.4%]) per year was found. When looking at major and serious crashes combined, a significant reduction of 1.6% (95% C.I. [1.2%, 2.0%]) per year was found. Data on the number of departures were unavailable for the general aviation category.

These reductions seen in the US crash rates were not observed for GB (where either no trend, or an increase in crash rates were found), however a major difference between the two datasets used for the trend analysis is that the UK data included only light aircraft, helicopters and small aircraft (i.e. aircraft up to 20,000 kg) whereas the US dataset included aircraft operated under 14 CFR 121, of which a large proportion are aircraft greater than 20,000 kg maximum certified take-off mass. In addition, there were differences in the inclusion criteria; as an example, a crash had to result from significant loss of pilot control for it to be included in the GB accident dataset (see 4.1 for the GB accident inclusion criteria). The differences in trends may therefore be due to a variety of reasons: differences in the aircraft categories considered, the lack of reliable movement data for GB for light aircraft prior to 1996, differences in the inclusion criteria or differences in crash rates between the US and GB.

Table 8 Historical trends in GB and US aircraft accident rates

<table>
<tr><th colspan="5">GB</th></tr>
<tr><th></th><th colspan="2">Background</th><th colspan="2">Aerodrome</th></tr>
<tr><th>Light aircraft</th><td colspan="2">No trend</td><td colspan="2">Increase of 4.4% per year (95% CI [2.3, 6.6])</td></tr>
<tr><th>Helicopters</th><td colspan="2">No trend</td><td colspan="2">Increase of 4.7% per year (95% CI [0.2, 9.3])</td></tr>
<tr><th>Small transport</th><td colspan="2">No trend</td><td colspan="2">No trend</td></tr>
<tr><th>Large transport</th><td colspan="2">Not investigated due to sparse data</td><td colspan="2">Not investigated due to sparse data</td></tr>
<tr><th colspan="5">US</th></tr>
<tr><th rowspan="3">Aircraft operated under 14 CFR 121</th><th colspan="2">Denominator: flying hours</th><th colspan="2">Denominator: departures</th></tr>
<tr><th>Major accidents</th><th>Major and serious accidents</th><th>Major accidents</th><th>Major and serious accidents</th></tr>
<tr><td>Reduction of 7.5% per year (95% CI [0.2, 13.1]%)</td><td>Reduction of 6.6% per year (95% CI [2.6, 10.8]%)</td><td>Reduction of 6.5% per year (95% CI [1.1, 12.1]%)</td><td>Reduction of 5.6% per year (95% CI [1.5, 9.8]%)</td></tr>
<tr><th rowspan="2">General aviation</th><th>All accidents</th><th>Fatal</th><td rowspan="2" colspan="2">Data unavailable</td></tr>
<tr><td>Reduction of 1.3% per year (95% CI [1.1, 1.4]%)</td><td>Reduction of 1.6% per year (95% CI [1.2, 2.0]%)</td></tr>
</table>

Statistics provided in an IAEA report (IAEA, 2008) suggested similar total loss fatal accident rates for the period 1990 to 2000 between the US and JAA (The European Joint Aviation Authority). These rates were found to be significantly lower than the worldwide rate. It was shown that the worldwide rate has been declining between the years 1995 and 2004, however it is not certain whether this trend has been driven by recent improvements in aviation safety in certain regions outside of the US and JAA regions where aviation safety has historically been poorer, or whether reliability has improved across each geographical region.

Based on this limited evidence, the differences in trends between the US and GB are more likely due to the difference in aircraft categories used, rather than a difference between aircraft crash rates. If historical aircraft accident and flight movement data from other Western European nations can be obtained, further investigation and comparison of trends in accident rates may be carried out.

7 ANALYSIS OF CRASH LOCATIONS

7.1 THE DATA

The aircraft crash location data that were used to derive the location distributions used in the Byrne model are listed in a report by AEA Technology (Jowett and Cowell, 1991) and originated from three sources:

1. The United States Nuclear Regulatory Commission (USNRC) study into near aerodrome accident risks;
2. NTSB reports covering accidents which had occurred since 1977; and
3. The Royal Air Force (RAF) Inspectorate of Flight Safety in the UK.

All of these accidents occurred prior to 1992, meaning that there may be over 20 years' worth of accident location data that have become available since these location distributions were developed by AEA Technology, distributions which are currently used within the Byrne model. The USNRC data only included landing accidents whose impact locations were outside the aerodrome boundary, therefore the NTSB and RAF landing accidents were weighted to account for the omitted accidents.

In this report, rather than base the location distributions on the above data, a dataset containing information on US aircraft accidents and accident locations, compiled by Loughborough University, will be used. The database includes crashes that occurred in the US between 1982 and 2005 and will be referred to in this report as the 'US database'. A summary of the accident location data used in the development of the Byrne location models and the US database can be found in Table 9. The numbers of accident locations used in the AEA Technology report (Jowett and Cowell, 1991) (used in the Byrne location models) and the numbers used in the HSL analysis carried out in this report are presented in Table 10.

Table 9 Overview of aerodrome crash location data

	AEA (Jowett and Cowell, 1991)	US database (Loughborough University)
Years	1977 to 1991	1982 to 2005
Number of accidents	RAF: 31 NTSB: 36 USNRC: 54	549
Source(s)	Data compiled for a USNRC study into near aerodrome accident risks. NTSB reports covering accidents which had occurred since 1977. Data supplied from the Royal Air Force Inspectorate of Flight Safety in the UK.	Data compiled by Loughborough University
Screening criteria	Only studied crashes that occurred within five miles of an aerodrome. Only included accidents which involved fatalities or severe damage to the aircraft. Excluded accidents where the pilot retained a substantial degree of control over the aircraft.	Remove non US entries. Remove non fixed wing aircraft entries. Remove entries for airplanes with certified max gross weight <6000 lbs. Remove entries with unwanted FAR parts. Remove entries occurring in unwanted phases of flight. Remove all single engine aircraft and all piston engine aircraft entries. Remove all FAR Part 91 entries with a certified max gross weight <12,500 lbs. Remove entries where aircraft damage and injury levels were minor or less. Only accidents which directly challenged at least one ASA or impacting ground or obstacles within 10km of the landing or take-off runway threshold. This means that the aircraft has exited from the 'normal' areas of operation on the aerodrome (i.e. veering off the runway or hitting obstacles on landing or take-off. Cases do not have to include fatalities or hull loss to be included.
Aircraft types	All fixed-wing aircraft types over 2.3Te in mass (AEA Technology category 3,4 and 5 aircraft)	Airplanes with certified max gross weight >=6000 lbs
Accident type	1. Landing 2. Take-off	1. Landing undershoot (no initial ground contact on runway) 2. Landing overrun (initial ground contact on runway) 3. Take-off overrun, including rejected take-off overrun (not airborne at any stage) 4. Crash after take-off (airborne at any stage)
X and Y distances	The parallel distance from the runway threshold (x) and the perpendicular distance from the runway centreline (y) were recorded	Landing: Distance from runway threshold (x) Take-off: Distance from start of roll threshold (x). Perpendicular distance from the runway centreline (y).

Table 10 Number of aerodrome accident locations used in AEA (1991) and in the HSL analysis

	AEA (1991) (Jowett and Cowell, 1991)	**HSL (source: US database)** (accidents with known longitudinal locations)
Landings	80	Undershoots: 110
		Overruns: 153
Take-offs	41	Take-off overruns: 41
		Crash after take-off: 55

The data in the US database included the wreckage location and the point of first impact. For landing accidents, which include landing undershoots (LDUS) and landing overruns (LDOR), these locations are presented as the (longitudinal) distance from the runway threshold and the (lateral/perpendicular) distance from the runway centreline. For take-off accidents, which include take-off overruns (TOOR) and crashes after take-off (TOC) these are presented as the (longitudinal) distance from start-of-roll and (lateral/perpendicular) distance from the runway centreline. The landing distance available (LDA) and take-off distance available (TODA) were also provided. Of the 263 landing accidents used in the analysis presented here, 110 were undershoots and 153 were overruns. Of the 96 take-off accidents used, 41 were overruns and 55 were crashes after take-off.

The majority of nuclear sites are located over 20 km from the nearest licenced aerodrome hence the risk to the majority of nuclear sites from aerodrome-related crashes is considered to be relatively low, In comparison to the background risk. Flight activity at Lydd Airport presents the greatest risk of all licenced aerodromes, as its location approximately 5 km from Dungeness B results in a risk at Dungeness B that is potentially several orders of magnitude greater than that at the other nuclear sites. Hartlepool, Heysham 1, 2 and Sizewell are located approximately between 20 and 25 km from their nearest licenced aerodrome, hence there may also be increased risks in the vicinity of these sites. The remainder of this section investigates the distribution of crashes in terms of location, allowing quantification of the crash risk at a particular location relative to the runway.

7.2 STATISTICAL MODELS USED IN THE BYRNE MODEL

The crash location distributions for the longitudinal and lateral distances that were used in the Byrne model were assumed to be independent. For landing accidents (Jowett and Cowell, 1991)

$$FL_i\ x,y\ = \frac{(x+3.275}{3.24} e^{\frac{-\ x+3.275}{1.8}}\ \ \frac{56.25}{\overline{2\pi}} e^{-0.5\ \ 125y\ ^2} + 0.625e^{-\frac{y}{0.4}} + 0.05e^{-\frac{y}{5}} \quad (5)$$

$$FL_i\ x,y\ = 0\ \ for\ \ x < -3.275$$

and for take-off accidents

$$FT_i\ x,y\ = \frac{(x+0.6}{1.44} e^{\frac{-\ x+0.6}{1.2}}\ \ \frac{46.25}{\overline{2\pi}} e^{-0.5\ \ 125y\ ^2} + 0.9635e^{-4.1\ y} + 0.08e^{-\ y} \quad (6)$$

$$FT_i\ x,y\ = 0\ \ for\ \ x < -0.6$$

Uncertainty in these fitted distributions had not been considered. Contour plots (on the $\log_{10}$ scale) of the probability density for landing and take-off accidents used in the Byrne model are shown in Figures 3 and 4. These will aid comparison of the Byrne location distributions with the HSL distributions that will be presented later in this section.

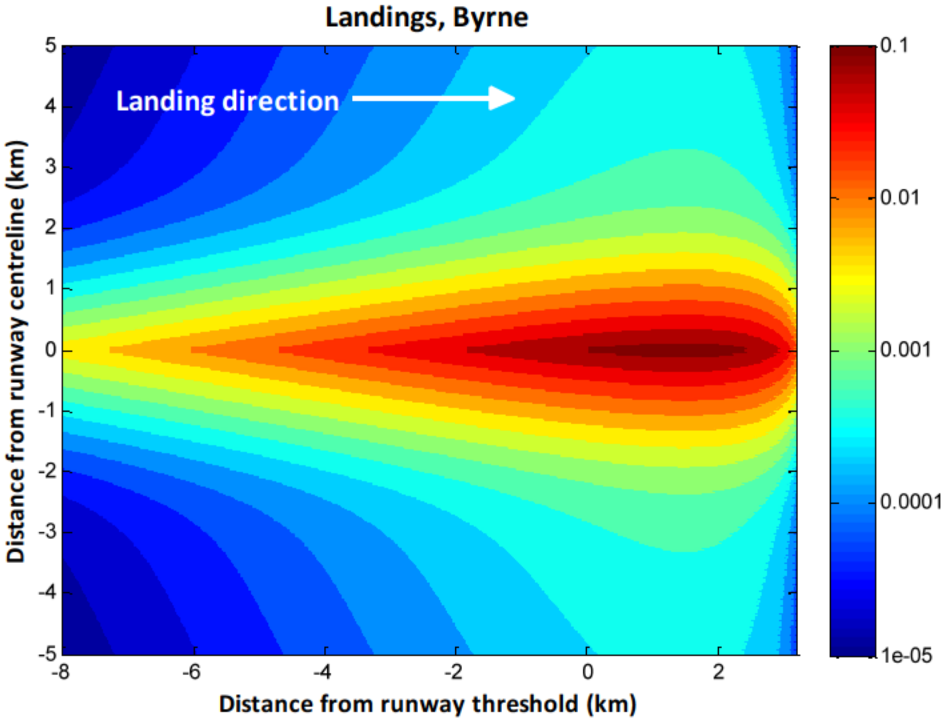

Figure 3 Contour plot of probability density for landing accidents (Byrne model (Jowett and Cowell, 1991)

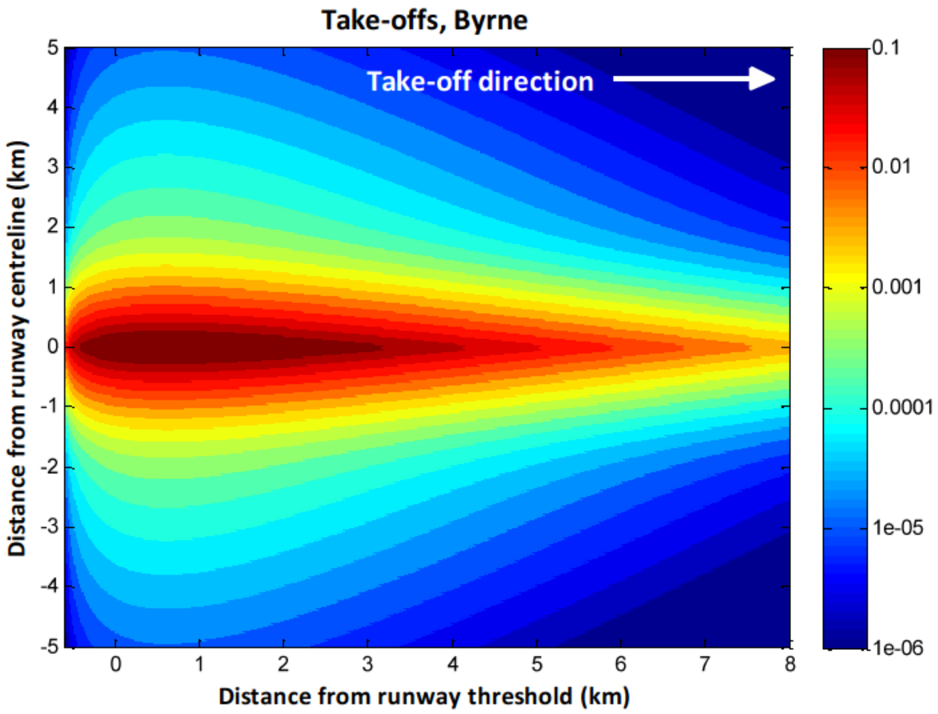

Figure 4 Contour plot of probability density for take-off accidents (Byrne model (Jowett and Cowell, 1991))

7.3 CRASH LOCATION DISTRIBUTIONS

7.3.1 Statistical Analysis

The location of aircraft crashes have been recorded in the US database in terms of the point of first impact and the final wreckage location. For landing accidents, the distances included are the longitudinal distance from the runway threshold, the lateral distance from the centreline, and the elevation of the point of first impact/wreckage site relative to the runway threshold. For take-off crashes, the distances included are the longitudinal distance from the start of roll threshold, the lateral distance from the centreline, and the elevation of the point of first impact/wreckage site relative to the runway threshold. In the HSL location modelling (and following the Byrne and Wong models), only the longitudinal and lateral distances have been considered.

The majority of crashes have a recorded wreckage location that is further away from the runway threshold than the recorded location of point of first impact; in these cases, once a plane has impacted upon the ground during either take-off or landing, the plane or its wreckage may have continued to slide or skid along the runway. The decision was made to use the final wreckage location to derive the longitudinal and lateral distances for use in the HSL location models if the wreckage distance from the 'origin' (defined in this report as the point on the runway threshold where it meets the runway centreline) was greater than or equal to the distance of the point of first impact from the origin, otherwise the location of the point of first impact was used. Thus although sliding or skidding is not considered explicitly in this report, they are considered implicitly through the use of the final wreckage location for certain accidents.

The steps taken to derive the relevant longitudinal (x) and lateral (y) distances from the US database for use in the location models were:

1. For each accident, extract the x and y distances for the point of first impact, the wreckage location, the LDA (if landing accident) or TODA (if take-off accident) along with their units of measurements.

2. For distances measured in feet and miles, convert distance to km. If distances are blank, or recorded as unknown or NA, set to 'NAN' for calculation purposes.

3. Determine the *critical location*. If the final wreckage distance from the origin is greater than or equal to the distance of the point of first impact from the origin, the critical location is the final wreckage location. If the point of first impact distance is the greater of the two, the critical location is the point of first impact.

4. Determine the *critical x* and *critical y* distances. The critical x distance is the longitudinal distance of the critical location from the runway threshold (or for take-off accidents, the start of roll threshold); the critical y distance is the lateral distance from the runway centreline.

In sections 7.3.1.1 and 7.3.1.2, the marginal probability distributions for these critical x and y distances will be investigated for take-off and landing accidents, i.e. ignoring any dependencies between them. In section 7.3.2, more refined bivariate distributions that account for correlations will be fitted.

7.3.1.1 Landing accidents

The generalised extreme value (GEV), gamma, Weibull and lognormal distributions were fitted to the x and y distances for landing undershoots with critical locations before the runway threshold. A comparison of the fit of the CDFs for the x distance can be seen in Figure 5. Up to about 10 km, there was little difference between the gamma and Weibull distributions however the cumulative probability for the gamma distribution was consistently around 0.01 higher between 15 to 20 km. The uncertainty in the gamma and Weibull CDFs can be seen in Figure 6, where even at distances of up to 20 km from the runway threshold, there is considerable uncertainty in the CDF and thus considerable uncertainty in the probability that a crash will occur at x distances >20 km from the runway threshold. For the gamma distribution, the 95% CI ranges from approximately 0.5% to 6%; for the Weibull distribution, the 95% CI ranges from approximately 1% to 8%.

Figures 7 to 14 show comparisons of the fit of the distributions to the data for the other types of landing accidents and crash locations relative to the runway threshold.

From the figures, the gamma distribution appears to result in a better fit to the data, thus the remainder of the location analyses will assume a gamma distribution for both the x and the y distances.

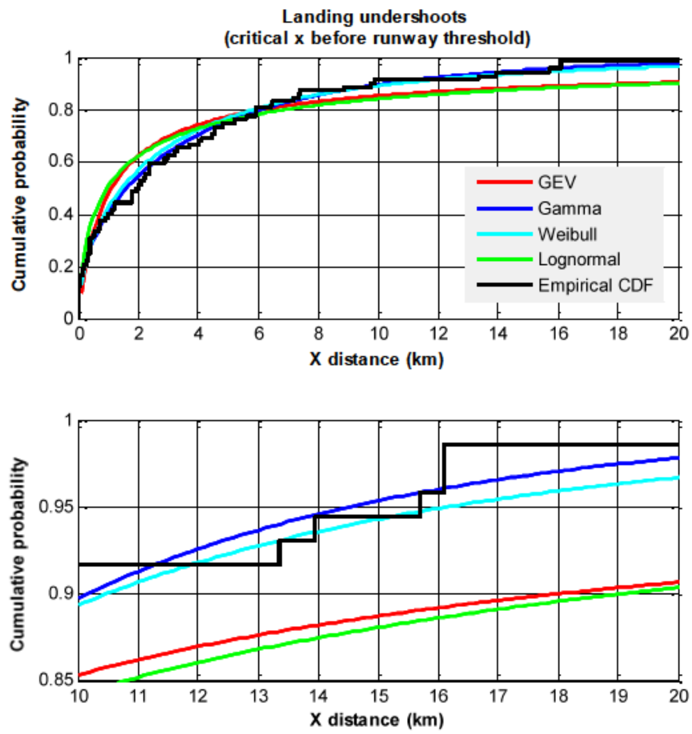

Figure 5 Cumulative distribution function for x: landing undershoots; x<0

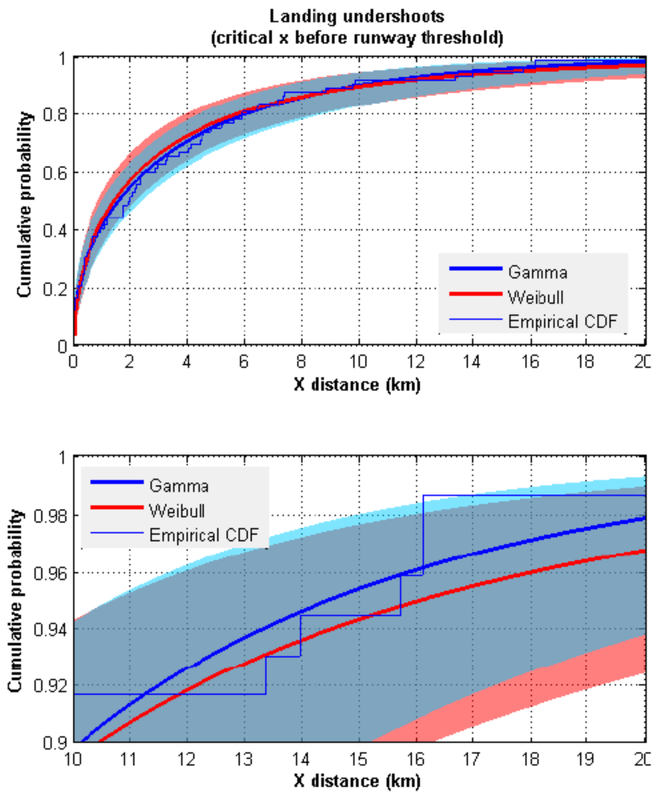

Figure 6 Comparison of Gamma and Weibull cumulative distribution functions for x: landing undershoots; x<0 (shaded area = 95% CI)

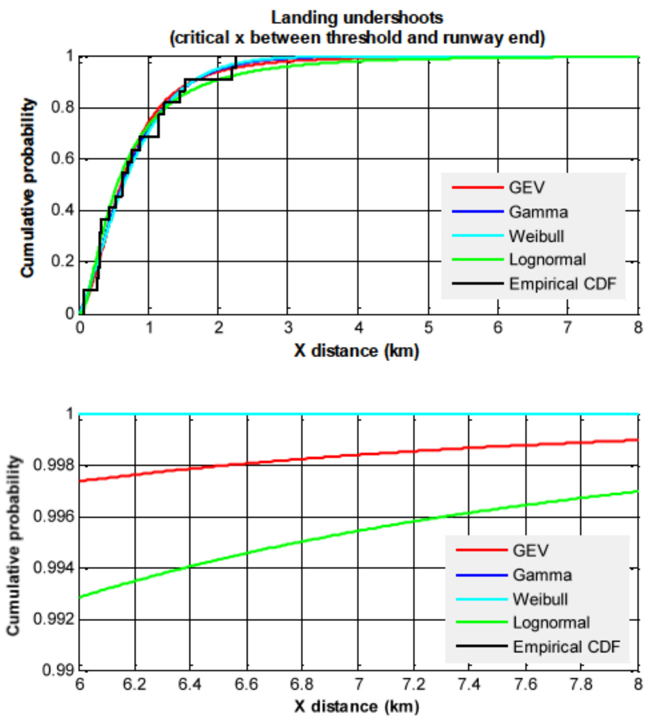

Figure 7 Cumulative distribution function for x: landing undershoots where 0≤x<LDA

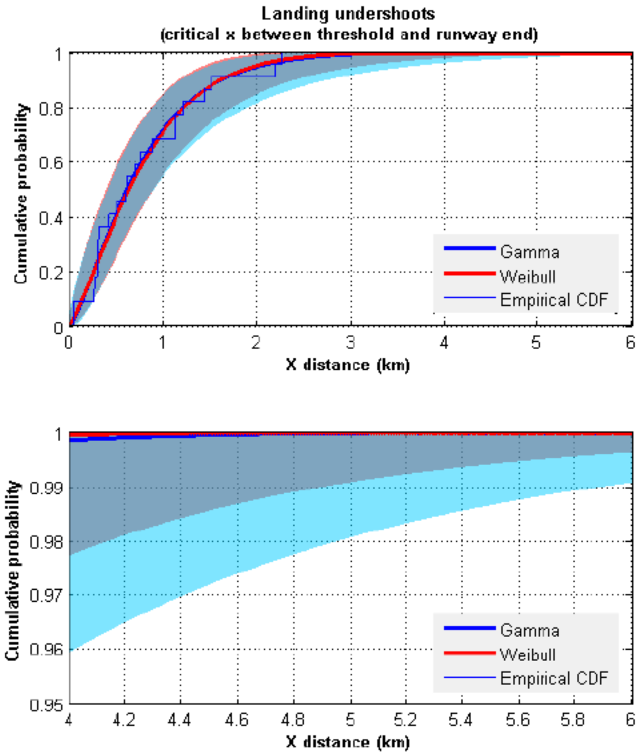

Figure 8 Comparison of Gamma and Weibull cumulative distribution functions for x: landing undershoots where 0≤x<LDA (shaded area = 95% CI)

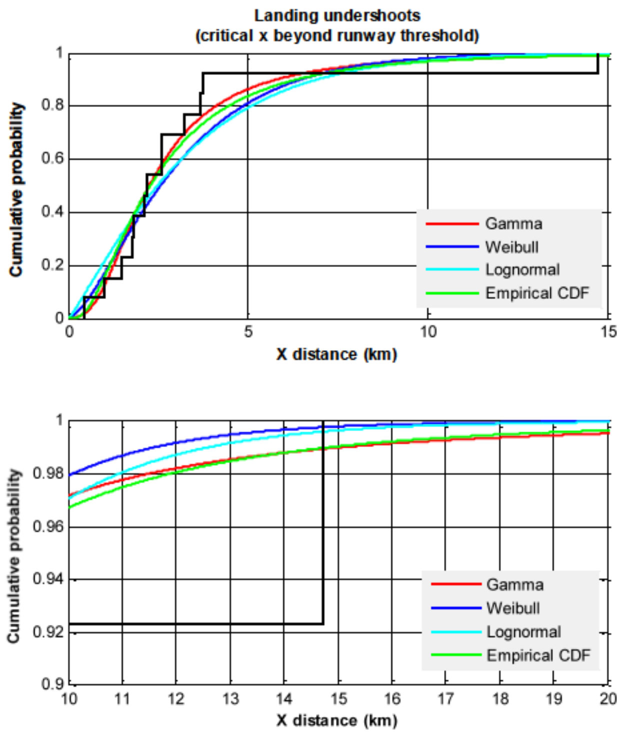

Figure 9 Cumulative distribution function for x: landing undershoots where x≥LDA

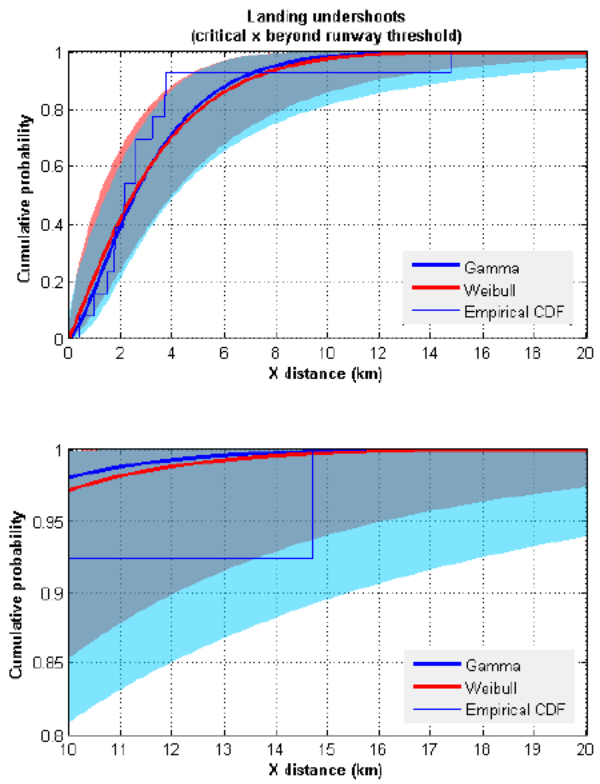

Figure 10 Comparison of Gamma and Weibull cumulative distribution functions for x: landing undershoots where x≥LDA (shaded area = 95% CI)

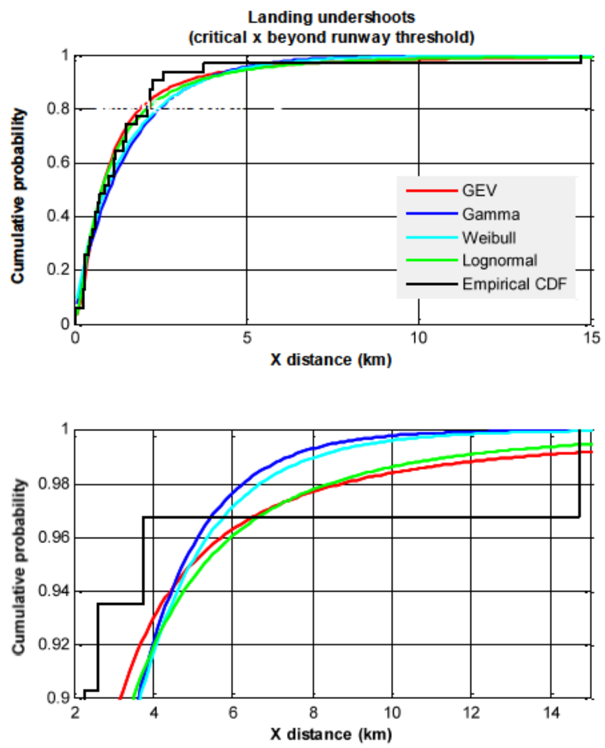

Figure 11 Cumulative distribution function for y: landing undershoots

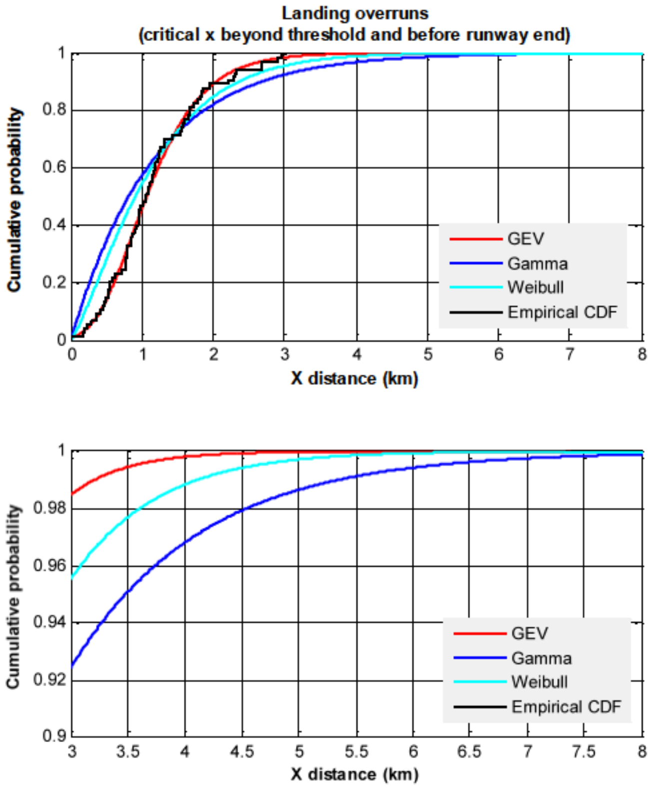

Figure 12 Cumulative distribution function for x: landing overruns where 0≤x<LDA

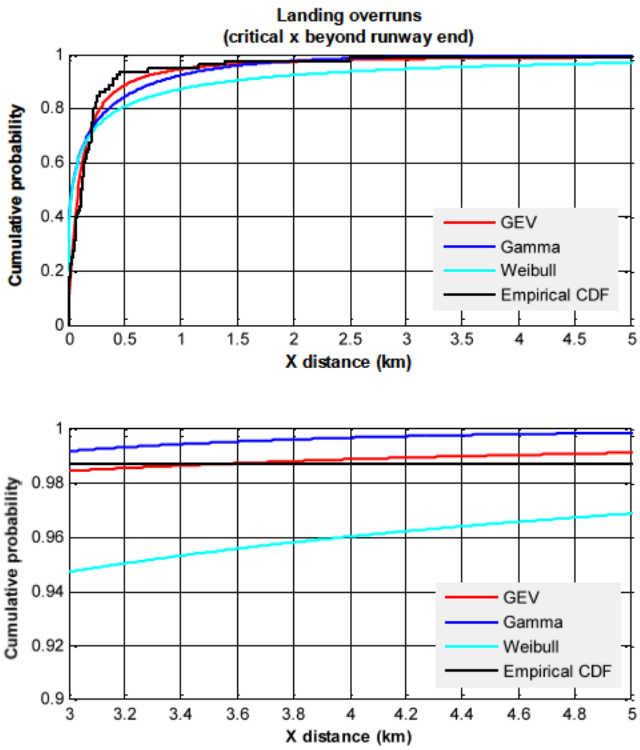

Figure 13 Cumulative distribution function for x: landing overruns where x≥LDA

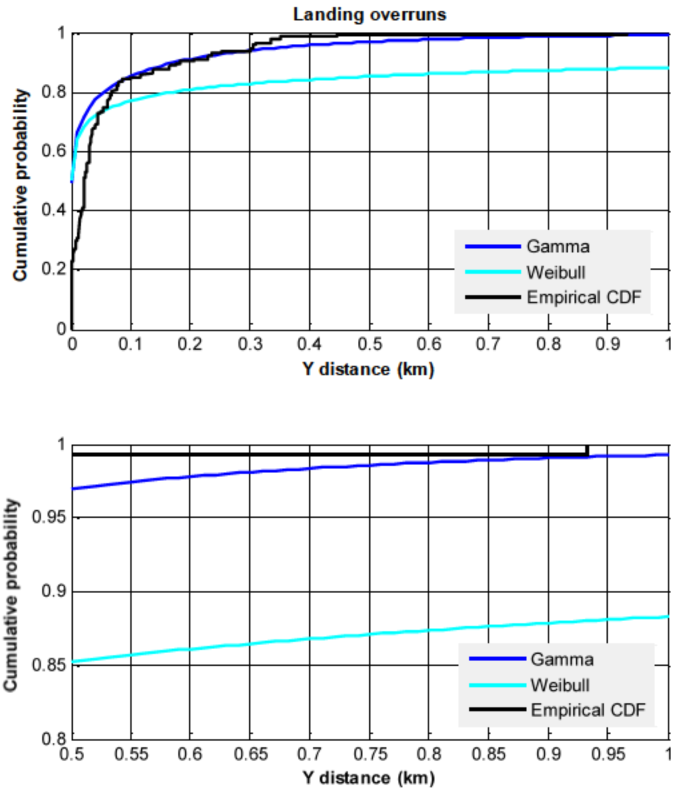

Figure 14 Cumulative distribution function for y: landing overruns

7.3.1.2 Take-off overrun accidents

The generalised extreme value (GEV), gamma, Weibull and lognormal distributions were fitted to the critical x and y distances for take-off overrun accidents. Of the 41 take-off crashes, 17 occurred before the end of the available distance for take-off (i.e. the critical x distance was less than the TODA). The other 24 crashes occurred after the end of the available distance for take-off (i.e. the critical x distance was equal to or greater than the TODA). The two sets of crashes were analysed separately, as this greatly improved the fit.

Figure 15 shows a comparison of the cumulative distribution functions (CDFs) for the x distances for take-off accidents that occurred before the end of the TODA. There was little difference between the gamma and Weibull distributions, however the cumulative probability for the GEV and lognormal distributions were lower than both the gamma and Weibull distributions at x distances greater than 3 km. As an example, whilst the cumulative probability under the gamma and Weibull distributions of a crash occurring up to 6 km from the threshold was close to 1 (i.e. the probability of a crash occurring at x distances >6 km was almost 0), the GEV and lognormal distributions resulted in around 1% and 2% of crashes occurring at x >6 km[6] respectively.

[6] At large distances from the runway, the operational reliability may not be reflected in these models; the terrain collision hazard may vary between aerodromes.

For crashes occurring after the TODA (Figure 16), the Weibull distribution resulted in lower cumulative probabilities at large x distances than the gamma and GEV distributions; whilst the probability under the Weibull distribution of a crash occurring at x >1.5 km from the end of the TODA was >2.5%, the gamma and GEV distributions resulted in around 1% and <0.5% of crashes occurring over this distance respectively. Although not presented in this section for take-off overrun accidents, plots of the uncertainty ranges of the fitted distributions indicated considerable uncertainty, particularly with increasing distances from the runway where data is sparse.

Figures 17 to 20 show comparisons of the fit of the GEV, gamma, Weibull and lognormal distributions to the data for take-off overruns (y distance), and crashes after take-off (x distances). From these figures, the gamma distribution appears to provide a better fit to the data. The remainder of the location analyses will assume a gamma distribution for both the x and the y distances.

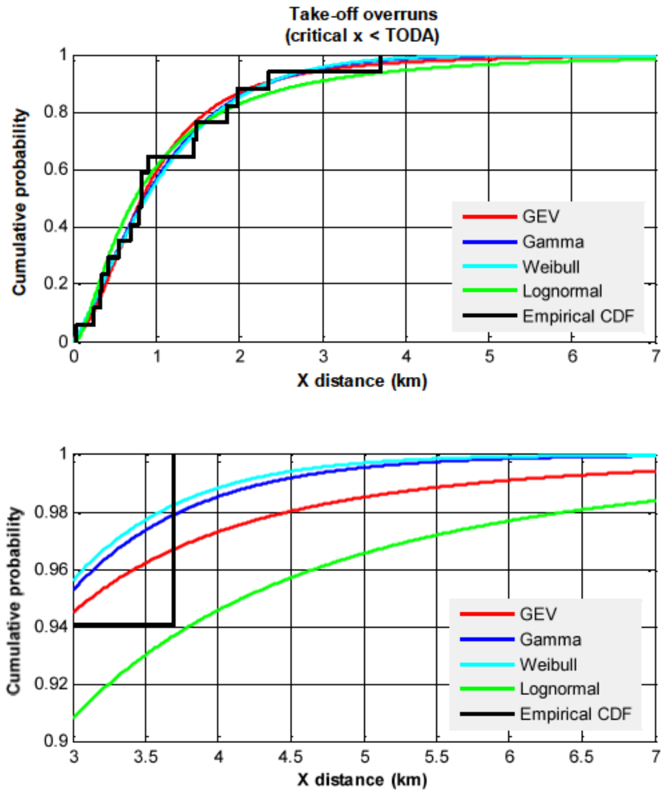

Figure 15 Cumulative distribution function for x: take-off overruns where x<TODA

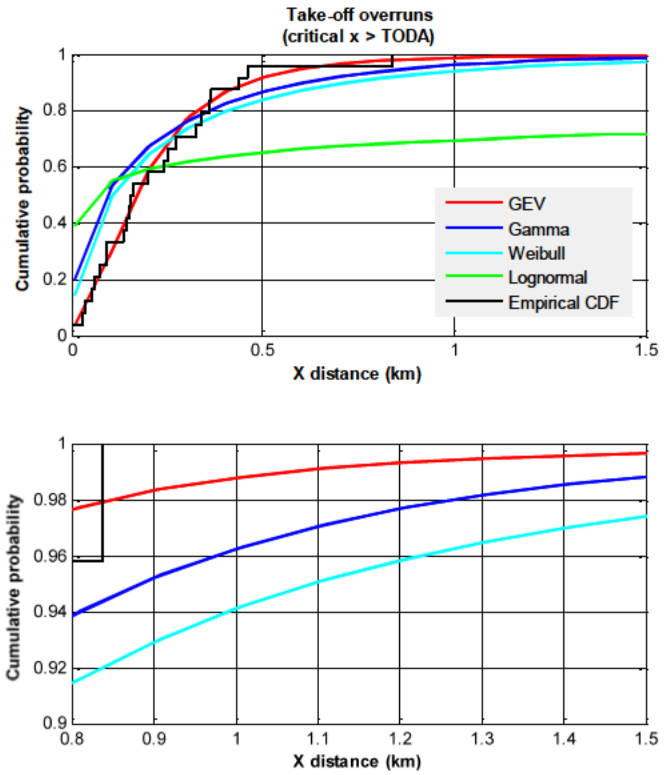

Figure 16 Cumulative distribution function for x: take-off overruns where x≥TODA

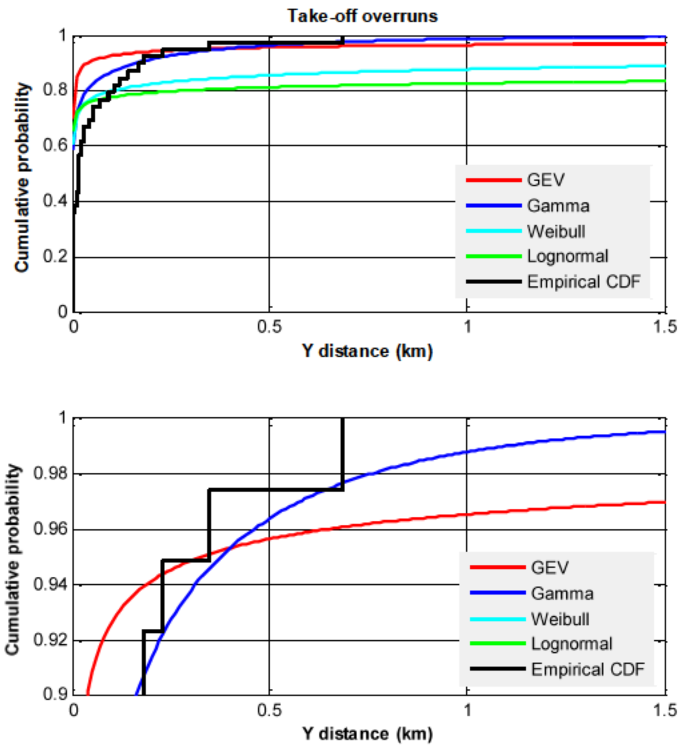

Figure 17 Cumulative distribution function for y: take-off overruns

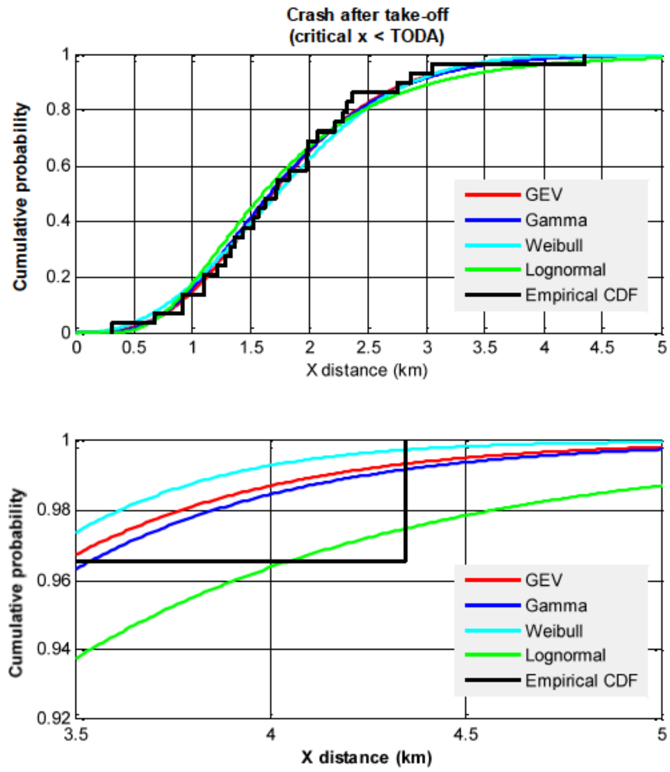

Figure 18 Cumulative distribution function for x: crashes after take-off where x<TODA

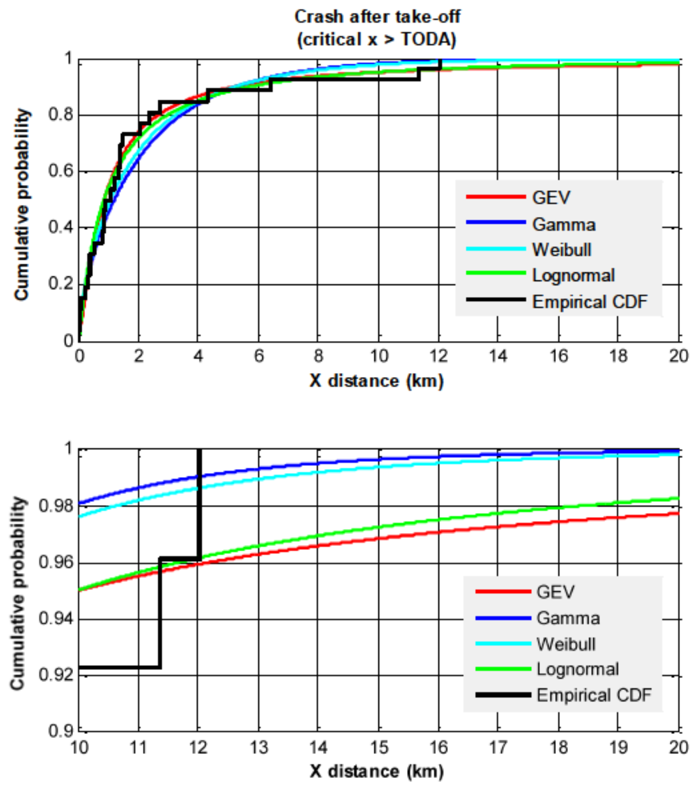

Figure 19 Cumulative distribution function for x: crashes after take-off where x≥TODA

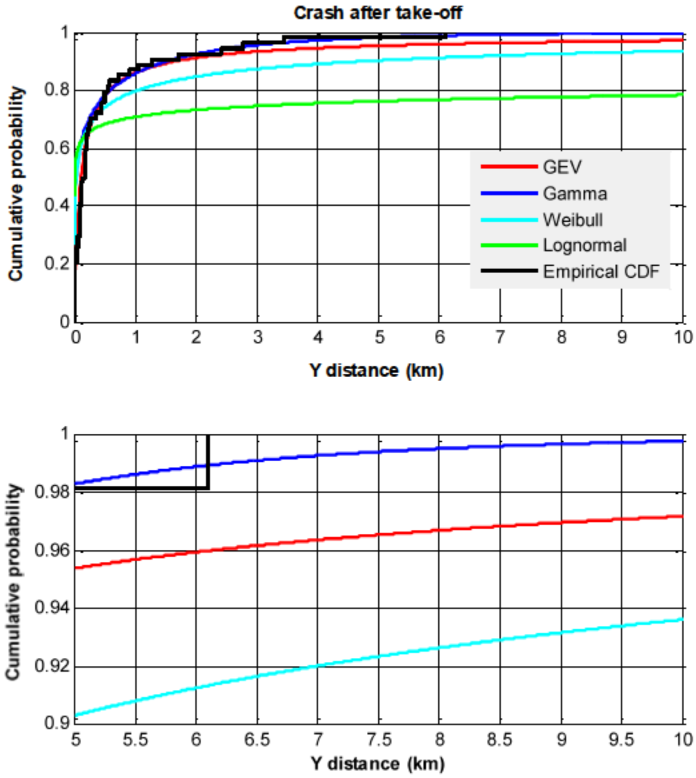

Figure 20 Cumulative distribution function for y: crashes after take-off

7.3.2 Correlations between lateral and longitudinal distances

In the analysis presented thus far, the longitudinal and lateral distances have been treated independently. Intuitively it might be expected that the further a crash is longitudinally from the runway threshold then the greater the likelihood of a substantial lateral deviation. The correlation between the lateral and longitudinal distances of crashes listed in Jowett and Cowell (1991) (based on those accidents with fatalities or severe aircraft damage) and crashes listed in the US database that have been used in the HSL analysis have been calculated and are presented in Tables 11 and 12 respectively.

The correlation coefficients presented in Table 11 indicate weak/moderate correlation of the x and y distances of crashes on which the Byrne model was based. In contrast, the x and y distances in the US database used in the HSL analysis (Table 12) exhibit much greater dependencies for certain accident types. For landing undershoots where the critical x distance was before the runway threshold, landing overruns where the critical x distance was beyond the LDA, and crashes after take-off where the critical x distance was beyond the TODA, the correlation coefficient was found to be 0.68, 0.77 and 0.67 respectively, indicating strong correlation between the x and y distances. There may be several reasons why the correlations seen in the US database are greater than those seen in the AEA data. A large proportion of the crashes in the AEA data involved (RAF) military aircraft whereas the US database excluded those operated by US military forces. Accidents that did not exit from normal areas of operation (such as the runway) were excluded from the US database; these accidents may have had small lateral distances but potentially large longitudinal distances had they been included, thus their exclusion may have artificially inflated the correlations observed. In section 7.3.4, the location distributions under the assumption of dependent longitudinal and lateral distances will be compared with those where these distances are assumed independent.

Table 11 Correlation between longitudinal distance from runway threshold (x) and lateral distance from runway centreline (y); data up to 2008 from Jowett and Cowell (1991)

	Landing		**Take-off**	
	Number of crashes	Pearson's correlation coefficient	Number of crashes	Pearson's correlation coefficient
Before runway/start of roll threshold	67	0.10 (weak)	3	0.27 (weak)
After runway threshold/start of roll	13	0.35 (moderate)	38	0.39 (moderate)
All x distance	80	0.11 (weak)	41	0.41 (moderate)

Table 12 Correlation between longitudinal distance from runway threshold (x) and lateral distance from runway centreline (y); data from the US database

	Landing			**Take-off**		
	Landing type	Number of crashes	Pearson's correlation coefficient	Take-off type	Number of crashes	Pearson's correlation coefficient
Before runway/start of roll threshold	LDUS	72	0.68 (strong)	-	-	-
Runway veer-offs/before runway end	LDUS	25	0.35 (moderate)	TOOR	17	-0.36 (moderate)
	LDOR	73	0.30 (moderate)	TOC	29	-0.30 (moderate)
After LDA/TODA	LDUS	13	-0.18 (weak)	TOOR	24	-0.19 (weak)
	LDOR	80	0.77 (strong)	TOC	26	0.67 (strong)

7.3.2.1 Gaussian copula

The location models used in the Byrne model (Byrne, 1997; Jowett and Cowell, 1991) assume independence of the longitudinal and lateral locations. This assumption of independence can be advantageous in that it allows the probability distribution of the longitudinal distance to be fitted without the need to consider how it affects the behaviour of the lateral distance, and vice versa. This means that the independent distributions may be fitted much more easily than joint probability distributions. However, if the assumption of independence is incorrect, it may result in underestimation or overestimation of crash probabilities in certain areas away from the origin.

Although joint distributions can be relatively simple to fit if the distances are normally distributed (Gaussian), they become more difficult when other distributions such as the gamma and Weibull are involved. One method for dealing with this is through the use of Gaussian copula. A copula is a way of describing the joint behaviour of two or more variables and contains all the information on the dependence structure, whilst preserving the marginal distributions of these variables. In statistical terms, a copula is a joint cumulative distribution function with uniformly distributed marginal distributions. The Gaussian copula is one such copula, constructed from a multivariate normal distribution.

In this report, the dependence between the x and y distances were investigated using the Gaussian copula. For the marginal distributions, the gamma distributions fitted in section 8.3.1 were used.

7.3.2.2 *Take-off overrun accidents*

The dependence between the x and y distances was investigated by assuming a gamma distribution for the marginal x and y distances, and through the use of a Gaussian copula. The distribution for crashes before the runway end was considered separately from that for crashes that occurred beyond the runway end, as the correlation coefficients in Table 12 suggested a possibly weaker dependence between x and y for crashes that occurred beyond the runway end (-0.19) than those before the runway end (-0.36).

Figure 21 shows the probability density for take-off overrun locations (on the $\log_{10}$ scale), given that a take-off overrun accident has occurred. The highest risk occurs at y distances close to the centreline, between 0 and 4 km longitudinally from the runway threshold. With runways generally being 2 to 5 km in length, the highest risk occurs on or just after the runway end, with the risk gradually decreasing with increasing distance from the centreline.

A limitation of the use of the US database is that crashes that occurred on the runway and remained on the runway were excluded. No indication is provided as to how many crashes (or the proportion of crashes) this criterion excluded, and the contour plot in Figure 21 does not take into account the missing on-runway accidents.

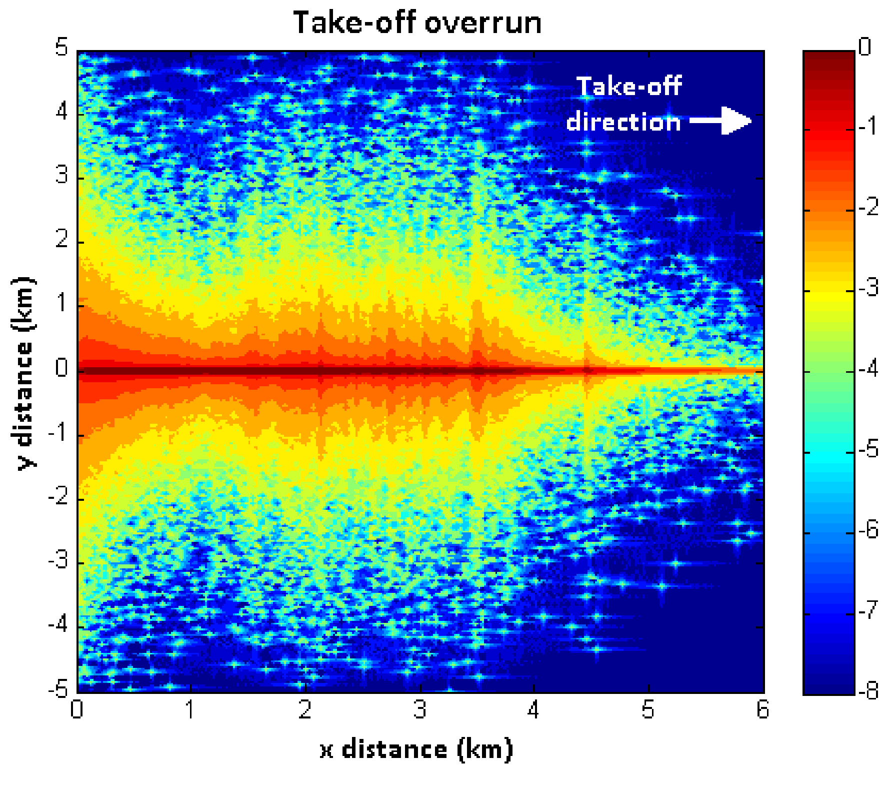

Figure 21 Probability density for take-off overrun accidents ($\log_{10}$ scale)

7.3.2.3 *Take-off and crash accidents*

As was investigated for take-off overrun accidents, the dependence between the x and y distances was investigated by assuming a gamma distribution for the marginal x and y distances, and a Gaussian copula. The distribution for crashes before the runway end was considered separately from that for crashes that occurred beyond the runway end, as the correlation coefficients in Table 12 suggested a strong dependence between x and y for crashes that occurred beyond the runway end (0.67) than those before the runway end (-0.30).

Figure 22 shows the probability density for take-off and crash locations (on the $\log_{10}$ scale), given that a take-off and crash accident has occurred. The highest risk occurs at y distances close to the centreline, with the greatest density around 1 km to 3 km longitudinally from the runway threshold. With runways generally being 2 to 5 km in length, the highest risk occurs on or just after the runway end, with the risk gradually decreasing with increasing distance from the centreline.

As discussed in 7.1, a limitation of the use of the US database is that crashes that occurred on the runway were excluded, and the contour plot in Figure 22 does not take into account these missing on-runway accidents.

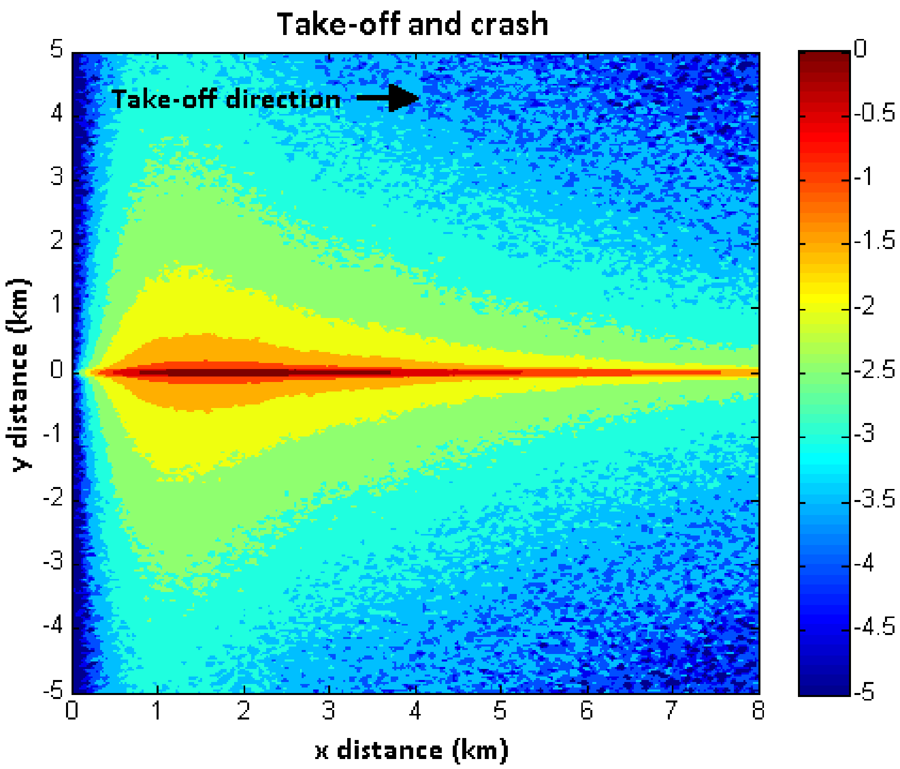

Figure 22 Probability density for take-off and crash accidents ($\log_{10}$ scale)

7.3.2.4 Landing undershoot accidents

As was investigated for take-off overrun accidents, the dependence between the x and y distances was investigated by assuming a gamma distribution for the marginal x and y distances, and a Gaussian copula. The distribution for crashes before the runway end, between the threshold and before the runway end, and after the runway end were considered separately, as the correlation coefficients in Table 19 suggested a strong dependence between x and y for crashes that occurred before the runway threshold (0.68) but weaker correlations elsewhere.

Figure 23 shows the probability density for landing undershoot locations (on the $\log_{10}$ scale), given that a landing undershoot accident has occurred; the contour lines represent locations of equal probability for landing undershoot accidents. The highest risk occurs at y distances close to the centreline, with the greatest density between approximately 2 km before and 1 km after the runway threshold. The risk gradually decreases with increasing distance from the centreline, however the probabilities are not symmetric about the runway threshold. For example, for a given y distance, the probability of an accident 2 km before the runway threshold is not necessarily the same as the probability of an accident 2 km after the runway threshold, due to separate distributions being fitted for crashes occurring before and after the runway.

As discussed in 7.3.2, a limitation of the use of the US database is that crashes that occurred on the runway were excluded, and the contour plot in Figure 23 does not take into account these missing on-runway accidents.

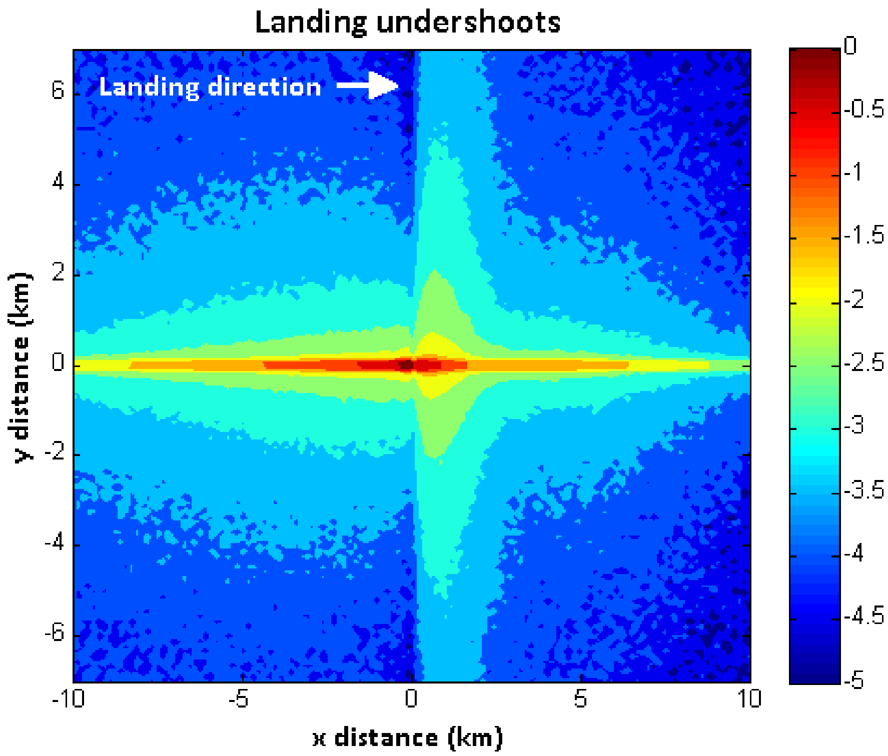

Figure 23 Probability density for landing undershoot accidents ($\log_{10}$ scale)

7.3.2.5 *Landing overrun accidents*

The dependence between the x and y distances was investigated by assuming a gamma distribution for the marginal x and y distances, and through the use of a Gaussian copula. Crashes before the runway end were analysed separately from those that occurred beyond the runway end, as the correlation coefficients in Table 19 suggested a stronger dependence between x and y for crashes that occurred beyond the runway end (0.77) than those before the runway end (0.30). The correlation parameter of the copula was found to be 0.38 (moderate correlation) before the runway threshold and 0.32 (moderate correlation) for locations after the runway end. For consistency with the other types of accidents, the correlation parameters have been retained in fitting a joint probability density function.

Figure 24 shows a contour plot (on the $\log_{10}$ scale) of the probability density for landing overrun locations, given that a landing overrun accident has occurred; the contour lines represent locations of equal probability for landing overrun accidents. The highest risk occurs at y distances close to the centreline, with the greatest density between 0 km and and 2 km after the runway threshold. The risk gradually decreases with increasing distance from the centreline.

As discussed in 7.3.2, a limitation of the use of the US database is that crashes that occurred on the runway were excluded. No indication is provided as to how many crashes (or the proportion of crashes) this criterion excluded, and the contour plot in Figure 24 does not take into account these excluded crashes.

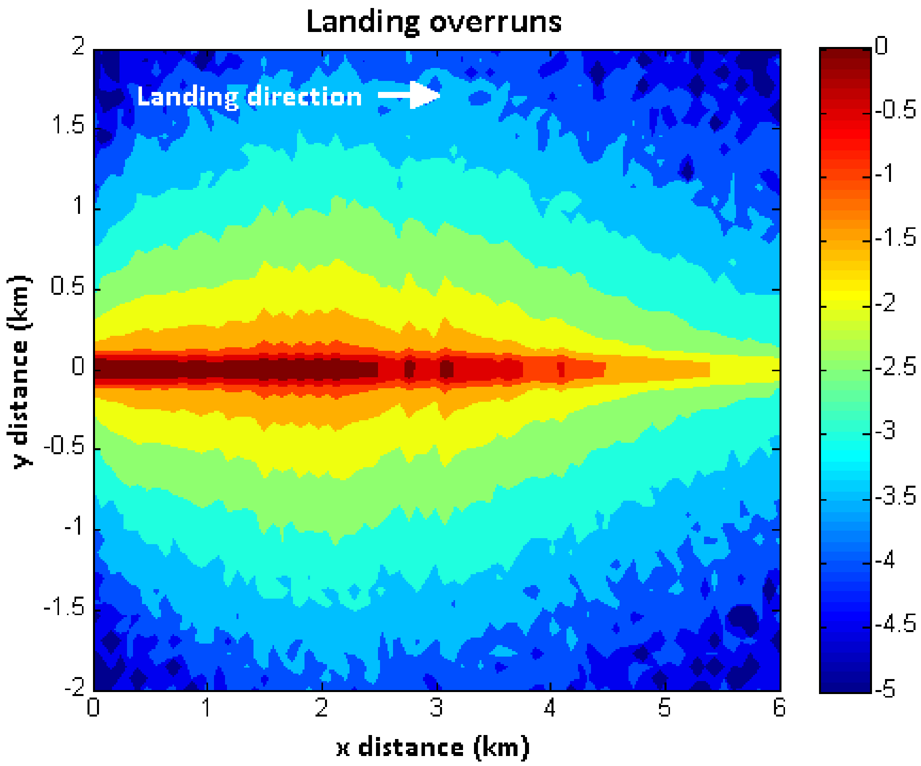

Figure 24 Probability density for landing overrun accidents ($\log_{10}$ scale)

7.3.3 Sensitivity of the location distributions to missing on-runway accidents

In fitting the gamma distribution to the x and y distances, it was assumed that all crashes on the runway were included. However there is likely to be a proportion of crashes that occurred and remained on the runway, and were thus removed from the US database. As it is unclear how many or the proportion of accidents that have been removed due to this exclusion criterion, the sensitivity of the probability density function for crashes after take-off and landing undershoots to the proportion of crashes p that are excluded has been investigated.

The probability density for p=0, 0.1, 0.2, 0.3, 0.4 and 0.5 have been compared at eight selected locations within the vicinity of an airport, between 1 and 4 km from the runway. The actual proportion is likely to be closer to 0 to 0.1 and unlikely to be as high as 0.4 to 0.5; these values have been included nevertheless.

Across all the selected locations for take-off accidents, the probability density decreased by approximately 10% for each 0.1 increase of p, e.g. when p=0.5, the probability density at that location was approximately 50% lower than when p=0. This indicates that unless the number or proportion of crashes that were excluded can be quantified, there is great uncertainty in the crash risk at locations near a runway. Nevertheless the assumption that no crashes were excluded has likely resulted in an overestimation of the crash risk at locations off the runway and is thus a conservative assumption to make; in addition, as it is thought that only a small proportion of crashes on the runway had been removed, the true risk and the estimated risk are likely to be of the same order of magnitude.

7.3.4 Impact of assuming independence of longitudinal and lateral distances

In 7.3.2, the correlation between the x and y distances were investigated through the use of Gaussian copula. For some types of aerodrome-related accidents, the y distance was found to be highly correlated with the x distance; for others, the correlation was found to be very weak or negligible. Therefore the assumption of independence between the x and y distances will likely have a greater impact on those accidents where the correlation is moderate/strong, and failing to model the correlation may overestimate or underestimate the risk of an accident at certain locations in the vicinity of an aerodrome.

In this section, the impact of assuming independence between the x and y distances for crashes after take-off and for landing undershoot accidents is investigated by comparing the probability density under the assumption of independence, with the probability under the assumption of dependent x and y distances (i.e. where correlation is modelled). Crashes after take-off and landing undershoot accidents have been selected for investigation as the y distance was found to be strongly correlated with the x distance in certain locations in the vicinity of the runway.

The first step of this comparison was to obtain a joint probability density function assuming dependent x and y distances using the Gaussian copula, f_{corr}. Then, separate probability density functions were obtained under the assumption of independent x and y locations; the product of these two independent functions is denoted by f_{nocorr}.

Figures 25 and 26 show contour plots of the ratio of the two probability densities, for crashes after take-off and landing undershoots respectively:

$$\frac{f_{no\_corr}}{f_{corr}}$$

Areas that are red indicate the areas where f_{no_corr} is greater than f_{corr}; areas that are blue indicate the areas where f_{corr} is the greater of the two. Within the green areas, the difference between f_{corr} and f_{nocorr} is relatively small.

In Figure 25, the main area in which f_{nocorr} is substantially greater than f_{corr} (i.e. where assuming independent x and y leads to a greater probability density) is near the origin. Close to the runway threshold at increasing values of y, f_{corr} is substantially the greater of the two densities where the difference can be up to two orders of magnitude. In addition, there are some areas around x>6 km and y>3 km where f_{corr} appears to dominate (i.e. where assuming independent x and y leads to a lower probability density); in these areas, ignoring the correlation may lead to an underestimation of the true crash probability.

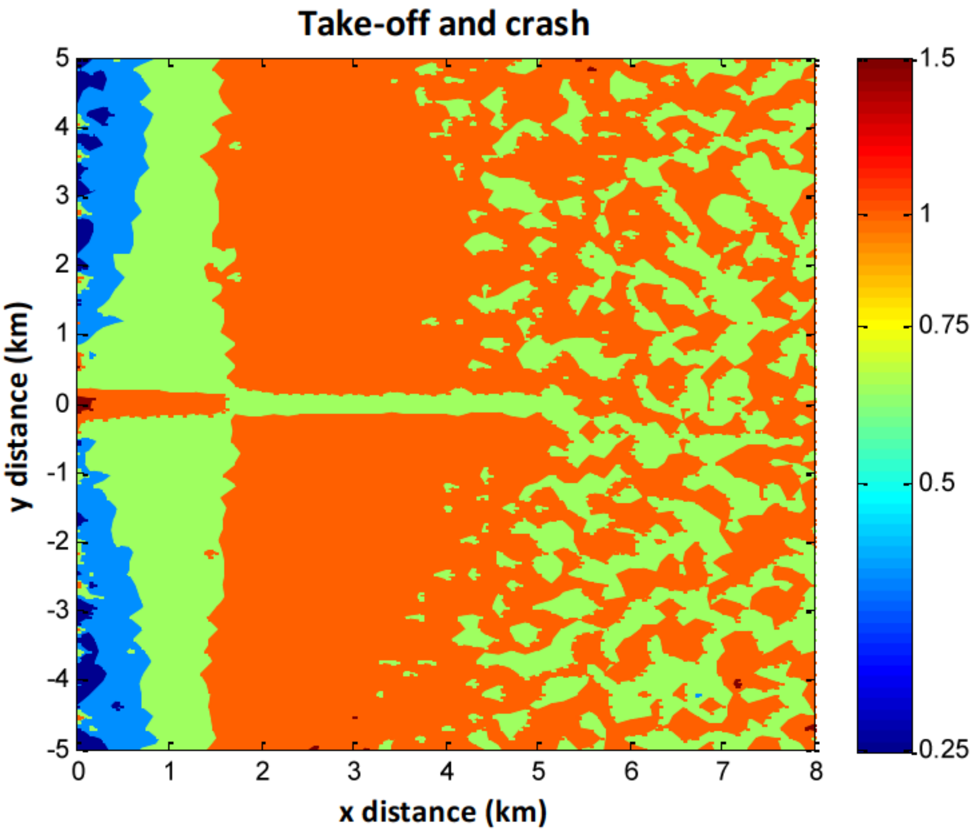

Figure 25 Contour plot of the ratio of probability densities for take-off and crash accidents

The probability of a crash after take-off within a 1 km^2 area centred at location x=2.5, y=3.8 was found to be approximately 24% higher when x and y were assumed independent, than when correlation was modelled, meaning that the assumption of independence is conservative at this location. However, when considering the crash risk of take-offs at locations further from the runway, the correlation should be modelled so as to avoid potential underestimation of the true probability.

In Figure 26, it can be seen that in areas along the runway threshold (x=0), the probability of a crash under the assumption of independent x and y distances is consistently greater than when correlation is modelled, most notably at large y distances where the difference can be up to two orders of magnitude. Further along from the runway threshold at large negative x distances and large y distance, the blue patches appear to dominate; in these areas, ignoring the correlation may lead to an underestimation of the true crash probability in these areas.

The probability of a landing undershoot within a 1 km^2 area centred at location x=-2.5, y=3.8 was found to be approximately the same for both cases, however when considering landing undershoots at locations further from the runway, the correlation should be modelled so as to avoid potential underestimation of the true probability.

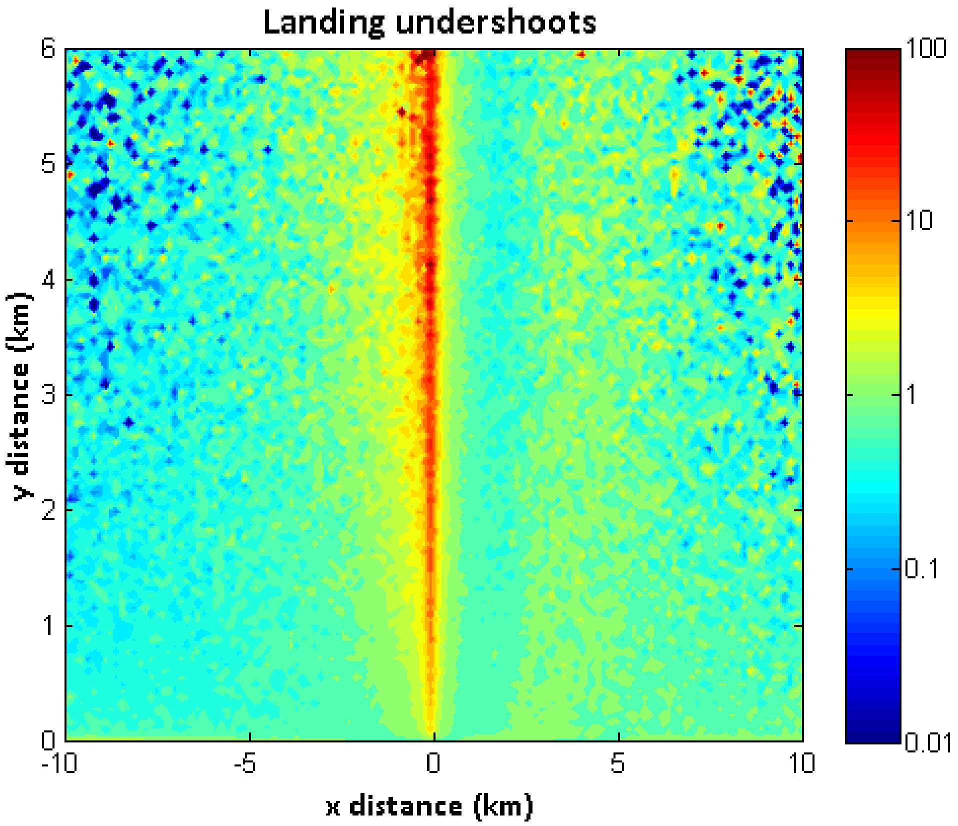

Figure 26 Contour plot of the ratio of probability densities for landing undershoot accidents

8 FREQUENCY OF AN AIRCRAFT ACCIDENT IN THE VICINITY OF LYDD AIRPORT

This section presents a series of calculations to assess the risk of an accidental aircraft crash at a location in the vicinity of Lydd Airport. The main calculations use the crash frequencies and location distributions derived in this report in conjunction with a Monte Carlo method in order to quantify the uncertainty in the overall crash probability. For comparison, crash probabilities calculated using the Byrne and Wong models are also presented.

The frequency of an aerodrome-related crash, *G*, within the vicinity of Lydd Airport can be calculated using the general formula:

$$G = NRf(x,y)$$

Where *N* is the runway movements per year, *R* is the probability per movement of a landing or a take-off accident and *f(x,y)* is the probability per unit ground area (x,y) of suffering an impact, given that an accident has occurred. As discussed in section 8, the probability of an accident in the vicinity of an aerodrome is a function of the longitudinal and lateral distances from the runway and is also dependent on the type of accident considered (e.g. landing undershoot, take-off overrun). Generally the risk of an aerodrome-related crash decreases with increasing distance from the runway.

At Lydd Airport, the wind direction favours Runway 03 around 30% of the time and Runway 21 around 70%. In deriving the annual crash frequency at Lydd Airport, an assumption is made that 2,500 landing movements by small transport aircraft take place on Runway 03 (i.e. heading in a north easterly direction) and 5,000 take-off movements take place on Runway 21 (i.e. heading in a south westerly direction); these figures are estimates and are used to demonstrate the steps required to derive overall aerodrome-related crash frequencies, to enable comparison between the HSL, Byrne and Wong models, and to provide an indication of the potential magnitude of the crash frequency based on the assumed number of flight movements. For more reliable crash frequencies, the calculations presented in this section should be based on actual or projected flight movements on Runways 03 and 21. The estimated aerodrome-related crash rate (comprising the landing and take-off components) is combined with the background crash rate in order to derive an overall probability for accidental aircraft crashes.

The steps required for deriving the crash frequency of small transport aircraft within a 1 km^2 area centred at 2.5 km before the runway threshold of Runway 03 (or 2.5 km from the stop end of Runway 21) and 3.8 km perpendicular to the runway centreline at Lydd Airport are presented in this section. For landings on Runway 03, this location corresponds to (-2.5, 3.8) using the (x,y) coordinate system used in Section 6 for landings, taking the runway threshold as the origin. Using the Byrne coordinate system (where positive x relates to distances before the runway threshold), this location corresponds to x=2.5 and y=3.8. The assumption is made that the flights do not follow a curved path either on take-off or landing, and that the rate of a background crash at Lydd Airport may be represented by a rate derived for England (as presented in section 6.1.2.1).

Whilst only calculations for small transport aircraft are presented in this section, similar calculations for crash frequency can be carried out for light aircraft and heavy transport aircraft. However the location distributions presented in section 8 were based on aircraft with maximum gross mass over 6,000 lbs, comparable to the small and large transport categories (>2,300 kg MCTOM), but greater in mass than the light aircraft category (<2,300 tonnes MCTOM). For application to light aircraft crashes, the location distributions should ideally be refitted to accident location data on light aircraft crashes.

The probability per landing movement of an accident, R_L, and the probability per take-off movement of an accident, R_T are derived. In section 6.2, the probability per movement of an aerodrome-related accident (3.14 per million movements) was presented, which was based on both landings and take-offs. However statistics suggest that accidents are more prevalent during the landing phases than take-off phases. The statistics in a recent Boeing report (Boeing, 2013) show that 16% of fatal accidents and onboard fatalities occur during the take-off and initial climb phases, and 41% occur during the final approach and landing phases. The assumption is made that of all aerodrome-related accidents, the same proportion applies, i.e. 16/(16+41)x100% = 28% of aerodrome-related accidents occur during take-off and 72% during landing. Uncertainties in these proportions are not considered. Assuming that the annual number of take-off movements equals the number of landing movements in the movement data presented in Table 3, the following probabilities are obtained:

Probability per million landing movements $\mathbf{R_L = 4.52}$ (95% CI [1.26, 2.46])

Probability per million take-off movements $\mathbf{R_T = 1.76}$ (95% CI [3.24, 6.32])

These probabilities need to be further split by type of landing and take-off accident.

8.1 LANDING UNDERSHOOT AND OVERRUN ACCIDENTS

8.1.1 Crash frequency per landing movement

Landing accidents are assumed to fall under two categories: undershoots (LDUS) and overruns (LDOR), thus the probability of a landing accident is the sum of the probability of a LDUS and LDOR. Using the Wong model (Wong, 2007), and considering medium aircraft crashes and the reference categories for the variables in the models (i.e. no precipitation, no crosswinds etc.), LDUS accidents are 9% more likely than LDOR accidents, thus the following probabilities are obtained:

Probability of an undershoot per million landing movements, $\mathbf{R_{LDUS} = 2.36}$, and

Probability of an overrun per million landing movements, $\mathbf{R_{LDOR} = 2.16}$ (the sum of R_{LDUS} and R_{LDOR} equals R_L)

8.1.2 Location distribution of landing accidents

Distributions for the longitudinal and lateral distances from the runway were presented in section 7.3 For landing accidents at Lydd Airport, landing undershoots may occur at x=-2.5 relative to Runway 03.

The location distribution for LDUS accidents comprised three distributions corresponding to three distinct areas: (i) before the runway threshold ($x<0$), (ii) $0\leq x<LDA$, (ii) $x\geq LDA$. The chosen location of interest lies 2.5 km before the runway threshold and 3.8 km from the centreline on Runway 03. Thus the relevant area to consider is (i), which allows us to obtain the probability of an undershoot accident occurring at (-2.5, 3.8), *given that the accident occurred before the runway threshold*. Note that the x distance is negative as the location of interest lies before the runway threshold. The location probability then has to be multiplied by the probability of a landing undershoot accident occurring before the runway threshold, to give a probability of a landing undershoot accident occurring in a 1 km^2 area centred at (-2.5, 3.8).

Due to the intensive nature of the Gaussian copula and the bootstrapping method used for modelling uncertainty (section 7.3), independence between the x and y locations has been assumed in determining the uncertainty in crash locations in this section. This assumption should have relatively little impact on the overall crash rates around location x=2.5, y=3.8 (justification can be found in 8.3.4).

The relevant probabilities for the calculation of the crash frequency are provided below:

P(x=-2.5, given that a landing undershoot has occurred and x is before the runway threshold) = 0.091 (95% CI [0.079, 0.108])

P(y=3.8, given that a landing undershoot has occurred and x is before the runway threshold) = 6.7e-03 (95% CI [4.6e-03. 8.9e-03]) (the density at Y=3.8 has been divided by two to account for crashes of equal probability on either side of the runway)

P(x=2.5, y=3.8, given that a landing undershoot has occurred and x is before the runway threshold) = 6.1e-04 (95% CI [4.1e-04, 8.5e-04])

Of 110 landing undershoot accidents, the critical x was before the threshold for 72 accidents, therefore

P(x before threshold, given landing undershoot has occurred) = 72/110 = 0.65

Therefore, given that a landing undershoot has occurred, the probability that the critical distance lies within a 1 km^2 area centred at (2.5, 3.8) = 0.65 x 6.1e-04 = 4.0e-04 (95% CI [2.6e-04, 5.5e-03]).

Multiplying this by R_{LDUS} and accounting for uncertainty in its value gives

Frequency of a landing crash on Runway 03 with a crash location within a 1 km^2 area centred at (-2.5, 3.8) = 9.5e-04 (95% CI [5.5e-04, 1.5e-03]) per million landing movements.

8.2 TAKE-OFF OVERRUN ACCIDENTS AND CRASHES AFTER TAKE-OFF

8.2.1 Crash frequency per take-off movement

Take-off accidents are assumed to fall under two categories: overruns (TOOR) and crash after take-off (TOC), thus the probability of a take-off accident is the sum of the probability of a TOOR and TOC. Using the Wong model (Wong, 2007), and considering medium aircraft crashes and the reference categories for the variables in the models (i.e. no precipitation, no crosswinds etc.), TOOR accidents are three times more likely than TOC accidents, thus the following probabilities are obtained:

Probability of an overrun per million take-off movements, $\mathbf{R_{TOOR} = 1.32}$, and

Probability of a crash after take-off per million take-off movements, $\mathbf{R_{TOC} = 0.44}$ (the sum of R_{TOOR} and R_{TOC} equals R_T)

8.2.2 Location distribution of take-off accidents

8.2.2.1 Take-off overrun

For take-off accidents at Lydd Airport, take-off overruns and crashes after take-off may occur at location 2.5 km after the stop end of Runway 21 and 3.8 km from the centreline. The location distribution for take-off overrun accidents comprised two distributions corresponding to two distinct areas: (i) x distance 0≤x<TODA, (ii) x≥TODA. The chosen location of interest (2.5, 3.8) lies 2.5 km after the end of

Runway 21, so the relevant distribution is (ii), which allows us to obtain the probability of an overrun accident occurring at (2.5, 3.8) *given that the accident occurred after the take-off distance available* (for ease of calculation, it is assumed that the end of the TODA for aircraft on Runway 21 coincide with the end of Runway 21). This probability then has to be multiplied by the probability of a take-off overrun accident occurring after the end of the TODA, to give us a probability of a take-off overrun accident occurring in a 1 km^2 area centred at (2.5, 3.8).

As discussed in Section 8.1.2, the x and y locations have been assumed in determining the uncertainty in crash locations in this section. Although it was found in 8.3.4 that the independence assumption led to a greater probability density around x=2.5, y=3.8, the impact this assumption has on the crash rates is that it may result in a conservative estimate of the overall crash rate at x=2.5, y=3.8.

P(x=2.5, given that a take-off overrun has occurred and x>TODA) = 1.7e-3 (95% CI [2e-11, 1.2e-2])

P(y=3.8, given that a take-off overrun has occurred and x>TODA) = 5.7e-5 (95% CI [3e-7, 5.5e-4]) (the density at Y=3.8 has been divided by two to account for crashes of equal probability on either side of the runway)

P(x=2.5, y=3.8, given that a take-off overrun has occurred and x>TODA) = 3e-08 (95% CI [4e-16, 2.7e-6])

Of 41 take-off overrun accidents, the critical x distance was greater than the TODA for 24 accidents, therefore

P(x after TODA, given take-off overrun has occurred) = 24/41 = 0.59

Therefore, given that a take-off overrun has occurred, the probability that the critical distance lies within a 1 km^2 area centred at (2.5, 3.8) = 0.59 x 3.6e-08 = 2.1e-08

Multiplying this by R_{TOOR} and accounting for uncertainty in its value gives

Frequency of a take-off overrun crash on Runway 21 with a crash location within a 1 km^2 area centred at (2.5, 3.8) = 2.4e-08 (4e-16, 2.1e-06) per million take-off movements.

8.2.2.2 Crash after take-off

As has been assumed for TOOR accidents, the location distribution for TOC accidents comprised two distributions corresponding to two distinct areas: (i) x distance 0≤x<TODA, (ii) x≥TODA. Our chosen location of interest (2.5, 3.8) lies 2.5 km after the end of Runway 21, so the relevant distribution is (ii), which allows us to obtain the probability of an overrun accident occurring at (2.5, 3.8) *given that the accident occurred after the take-off distance available* (for ease of calculation, it is assumed that the end of the TODA for aircraft on Runway 21 coincides with the stop end of Runway 21). This probability then has to be multiplied by the probability of a TOC accident occurring after the end of the TODA, to give us a probability of a TOC accident occurring in a 1 km^2 area centred at (2.5, 3.8).

P(x=2.5, given that a crash after take-off has occurred and x>TODA) = 0.11 (0.086, 0.14)

P(y=3.8, given that a crash after take-off has occurred and x>TODA) = 0.007 (0.002, 0.011) (the density at Y=3.8 has been divided by two to account for crashes of equal probability on either side of the runway)

P(x=2.5, y=3.8, given that a crash after take-off has occurred and x>TODA) = 7.5e-04 (95% CI [2.5e-04, 1.3e-03])

Of 55 crashes after take-off, the critical x distance was after the TODA for 26 accidents, therefore

P(x after TODA, given a take-off and crash has occurred) = 26/55 = 0.47

Therefore, the probability of a crash after take-off with a critical distance within a 1 km^2 area centred at (2.5, 3.8) = 0.47 x 7.5e-04 = 3.5e-04.

Multiplying this by R_{TOC} and accounting for uncertainty in its value gives

Frequency of a crash after take-off on Runway 21 with a crash location within a 1 km^2 area centred at (2.5, 3.8) = 0.47 x 3.5e-04 = 1.6e-04 (5.2e-05, 3.0e-04) per million take-off movements.

The frequency of a take-off related crash on Runway 21 can now be calculated as the sum of the TOOR and TOC frequencies, however as the contribution from TOC accidents is significantly higher than from TOOR accidents, the overall take-off crash frequency on Runway 21 is essentially the TOC frequency of 1.6e-04 (5.2e-05, 3.1e-04) per million take-off movements.

UNCERTAINTY IN THE CRASH FREQUENCIES

An important aspect of deriving the crash rates is the treatment of uncertainty. In the method adopted in this report, uncertainty arises from several sources, including the background crash rates, the aerodrome-related crash rates, the proportion of accidents that occur during the different phases of flight and the location of the crash. Whilst it is not possible to eliminate the uncertainty, it may be quantified using statistical methods, resulting in a range within which it is believed with high confidence that the true crash frequency may lie.

In calculating overall crash rates, uncertainty in the aerodrome-related crash rate has been propagated through the model using Monte Carlo simulation and sampling from the appropriate chi-square distribution. Uncertainty in the location distributions have been modelled using bootstrapping. The 95% C.I. of the overall crash frequency that will be presented in this report therefore encompasses uncertainty in the aerodrome-related crash rates, and the uncertainty in the probability of a crash at that location.

8.3 COMPARISON OF CRASH FREQUENCIES

The overall crash frequency per year comprises the background frequency and the aerodrome-related frequencies. Table 13 presents these frequencies under the HSL, Byrne and Wong models, although only the aerodrome-related frequency has been derived under the Wong model. Calculations for deriving the Byrne and Wong crash frequencies can be found in Appendix B. As aircraft type and meteorological conditions were factors in the Wong model, the calculations in Appendix B and the frequencies presented in this section using the Wong model apply to medium aircraft in the absence of snow, rain, strong winds, fog etc.

The HSL crash frequency (per movement) for landing accidents is significantly higher than for take-off accidents with non-overlapping 95% confidence intervals, however the frequencies are of the same order of magnitude. The Byrne crash frequency (per movement) at x=2.5, y=3.8 for landing accidents is lower than for take-off accidents, however again the two frequencies are of the same order of magnitude. As the base aerodrome-related crash frequencies per movement for take-offs and landings are the same under the Byrne model, this difference between landings and take-offs is due to the differing location distributions. The Wong frequencies for landing accidents and take-off accidents are the lowest of the three methods and lie below the HSL 95% confidence intervals, however if adjustments were made to the crash probabilities to account for factors such as precipitation, crosswinds and low visibility (which have not been accounted for in the calculations), the Wong crash frequencies are likely to be higher than those presented in Table 13 and may push them within the HSL 95% confidence intervals.

In order to be able to express the aerodrome-related frequencies in terms of annual frequencies at Lydd airport, an assumption of 2,500 landings on Runway 03 and 5,000 take-offs on Runway 21 has been made, by small transport aircraft, per year. The use of these figures provides us with an estimate of the annual crash frequency in a 1 km^2 area centred at x=2.5km, y=3.8 km of 3.0e0-6 (95% C.I. [1.5e-06, 5.1e-06]) from aerodrome-related crashes. For the background crash rate, the assumption is made that the background crash frequency in the vicinity of Lydd Airport may be represented by the GB rate of 2.4e-06 (95% C.I. [1.2e-06, 5e-06]). These estimates suggest that the background frequency and the aerodrome-related frequency of a crash at this particular location are comparable. If the assumed number of flight movements were to increase, the contribution from the aerodrome-related frequency would begin to dominate.

Under the Byrne model, the probability of an aerodrome-related crash provides the greater contribution (4.7e-06 compared to 2.6e-06 from background crashes), however both frequencies lie within the HSL 95% confidence intervals of (1.6e-06, 5.3e-06) and (1.2e-06, 5e-06) for aerodrome-related and background crashes respectively. The aerodrome-related frequency using the Wong model is the lowest of the three. At 4.7e-07, this frequency lies outside the HSL 95% C.I..

A comparison of the total crash frequency per year using the Byrne model with the HSL method shows that although the individual contributions from landing and take-off crashes differ, for the location being considered the differences cancel each other out when the risk from background crashes, landing movements and take-off movements are combined; the HSL method estimates a total crash frequency per year of 5.6e-06 (95% CI [2.8e-06, 1.0e-05]) and the Byrne model produces an estimate of 7.3-06, which lies within the HSL 95% C.I..

Table 13 Comparison between HSL, Byrne and Wong models: Crash frequency in a 1 km^2 area centred at x=2.5, y=3.8

	HSL	Byrne	Wong
LANDING Runway 03 **Crash frequency per million movements**	9.5e-04 (5.5e-04, 1.5e-03)	4.2e-04	1.6e-04
TAKE-OFF Runway 21 **Crash frequency per million movements**	1.6e-04 (5.2e-05, 3.0e-04)	7.3e-04	3.0e-05
Aerodrome-related crash frequency per year (assuming 2,500 landing movements on Runway 03, 5,000 landing movements on Runway 21, and 5,000 take-off movements on Runway 21)	**3.2e-06** **(1.6e-06, 5.3e-06)**	**4.7e-06**	**7.1e-07**
Background crash frequency per year	**2.4e-06** **(1.2e-06, 5e-06)**	**2.6e-06**	*Assume HSL rate of 2.4e-06 per year*
Total crash frequency per year (assuming 2,500 landing movements on Runway 03 and 5,000 take-off movements on Runway 21)	**5.6e-06** **(2.8e-06, 1.0e-05)**	**7.3e-06**	*3.1e-06*

In deriving the crash frequencies presented in this section, it was assumed that the x and y distances are independent of each other; the results in Section 7.3.4 suggest that this is a reasonable assumption to make and that it has little impact on the overall derived crash frequency, or introduces an element of conservatism. The analysis should be repeated with correlations between the x and y distances taken into account, and compared with the crash frequencies in Table 13 to quantify the impact of the independence assumption.

9 SUITABILITY OF THE BYRNE MODEL FOR CONTINUED APPLICATION

The continued suitability of the Byrne model for application to determine the crash rate onto and into a licensed nuclear site in Great Britain was examined by considering: how each of the hazardous scenarios was addressed; the scope of the flying machines that were covered; accident data and how local operational factors may vary the crash rates from the average value for Great Britain; how models could be merged to present the accident probability along a flight path; how the statistical uncertainty in calculated results could be addressed; how the usability of the model could be improved; and a consideration of the results of applying different models to flights using London (Ashford) Airport (Lydd) which is in the vicinity of the Dungeness A and B licensed nuclear sites.

9.1 CONSIDERATION OF THE HAZARDOUS SCENARIOS

No formal hazard identification project was carried out as part of the project. Therefore, the operators of licensed nuclear sites will have to carry out their own validation exercises that the scenarios discussed include all of the relevant types of aviation-related external hazards for their sites.

Aircraft accidents beyond the structural design requirements

None of the models identified the “beyond design case” scenario and provided analysis of the likelihood of this occurring. Whilst the likelihood of this accident may be relatively low, the project team considered that it should still be addressed within a safety case for a licensed nuclear site by demonstrating that appropriate safeguards had been introduced. Further discussion of this hazardous scenario is not published within this document for reasons of national security.

Civilian aircraft crashes directly onto a site

The Byrne model accounts for civil aircraft crashes directly onto a site, as do the other models. This was achieved by Byrne through the modelling of a background rate, a below airway rate and a vicinity of an aerodrome rate.

It was recognised that there may be an element of double counting within Byrne by considering both background accidents and below airway rates. However, the benefit of double counting with this method is that it would lead to a conservative estimation of the crash rate onto a unit area if a historic accident data point were included in both analyses.

The classification of fixed-wing aircraft into different groups was done on the basis of how data were collected by different agencies. It may be more reasonable to determine which classes of aircraft can be excluded from analysis based on the post-impact consequences to a site and then derive the data classes from that point. Splits of maximum certificated take-off mass around 2,000; 2,300; 5,700; and 20,000 kilogrammes were used in different models with difficulties arising with boundary cases such as large helicopters over 20,000 kilogrammes and the boundary between large turboprop and regional jet transport aircraft.

The Byrne model appears to suffer from generalisation of the traffic distribution over Great Britain that could lead to the calculated result for a specific location being optimistic. Some areas above Great Britain have relatively intensive operations by civilian aircraft, for example around southeast England, and these combine a significant number of overflights by cruising traffic; climbing and descending traffic away from the immediate vicinity of their departure and arrival aerodromes; as well as traffic in holding patterns awaiting further onward clearance. There may also be relatively intense general aviation activity below the airways skirting around the low level airspace restrictions associated with the major London airports.

The Byrne average calculated exposure, subject to statistical confidence interval treatment, could be used as a local value by the operator of a licensed nuclear site if they could demonstrate that their exposure was at or below the average level implied by the aircraft operations considered by Byrne and later updates. However, the details of the actual flight distributions across Great Britain are not given in the model and the operators of licensed nuclear sites may not collect data about local flight operations. Therefore, the argument that the application of Byrne leads to a reasonable result may not be justified in this case.

The background and below airway rates are based on relatively few accident data points for transport category aircraft (both large and small) so this leads to a significant element of uncertainty in the statistically derived rate (section 6.11.3). For example, the quoted below airway crash rate, expressed per km flown, using the Poisson 50% confidence level was approximately one order of magnitude below the average mean value.

Each of the models capable of calculating the below airway crash rates generated different lateral distribution crash densities. There did not appear to be a significant recent analysis of the lateral distribution of the crashes that took place outside the vicinity of an aerodrome to validate any of the models in particular. The issue relating to the greater use of direct air traffic control clearances rather than the flight plan route was not addressed by any of the models in a satisfactory way.

The background distribution for general aviation accidents may have enough data points to justify a different type of analysis rather than a general averaging process. Work carried out in the development of the ACRAM model included analysis of over a thousand general aviation accidents across the continental United States of America (Stutzke, Haley and Barto, 1996) and derived a non-uniform distribution rate for use as a background value. This type of retrospective analysis may be suitable for use across Great Britain if a great enough time span of accidents were considered.

Different models were available for accidents in the vicinity of aerodromes. These were classified into three different generations of model (as discussed in section 10.19) (Piers, 1998) of which Byrne represented an early stage second generation evolution. Light aircraft were dealt with by Byrne through the continued use of an earlier first generation model (Philips, 1987). The primary difference between second and third generation models was the change in coordinate system from conventional (x, y) to curvilinear (s,t) in order to allow for the more accurate modelling of local curved flightpaths around the aerodrome being considered.

The review team considered that a three stage approach to modelling the aerodrome-related crash frequency onto a licensed nuclear site was desirable after gathering local flight operational data. Firstly, a calculation of the crash frequency; secondly an adjustment of the crash frequency for local operational factors; and finally an application of a relevant crash location distribution model.

The modification of crash frequencies through the application of factors discussed in Wong (2007) and ACRP 3 (TRB, 2008) models provide some useful information. However, some of the probability modification factors may not be directly applicable to flight operations in Great Britain. For instance, very few aerodromes in Great Britain would meet the Federal Aviation Authority's criteria for being a hub airport or have 'significant terrain' within six miles of the aerodrome reference point. Similarly, whilst the analysis of the United States-only data suggested that flights with foreign origins or destinations ran a greater risk of take-off overruns, it is not clear how this might translate to Great Britain. The probability modification factors relating to meteorological conditions, particularly rain, crosswinds and visibility, were considered to be the most reliable for application to Great Britain. A useful sensitivity analysis would be to use the probability modification factors for meteorological conditions to predict the variation in accident rates between a small number of geographically diverse aerodromes in Great Britain. This would provide a lower bound to the extent of variation between aerodromes.

The Byrne model's treatment of accidents within the vicinity of an aerodrome does not take local flightpaths into account. The flightpath variations that are not accounted for include holding patterns, air traffic control vectoring to shorten routes or for traffic conflict management or capacity sequencing, offset approaches, circling approaches, visual approaches and turning departures. Rather than continued use of Byrne to predict the crash locations in the vicinity of aerodromes, in the short term it may be more appropriate to use a third generation model that can account for the intended flight tracks (for example, NLR) together with normalisation and normal operations data adjustments from the Loughborough models. These approaches to modelling curved flight paths should be investigated further to determine their suitability for use with the HSL location distributions or to aid development of alternative methods for addressing curved flight paths. In addition, an attempt should be made to recalculate the crash locations in the US database along the actual flight paths or intended flight paths; these or other relevant data may be contained within the NTSB accident reports. The longitudinal and lateral location distributions may then be refitted, providing distributions based on the location of crashes relative to the actual flight path, rather than on the assumed flight path on the extended centreline. In assessments of the crash location probability distributions in the vicinity of particular aerodromes, the generic crash location distribution should then be adjusted to account for the local flight paths.

In the longer term, it may be more appropriate to use a fourth generation crash location model. The next generation of crash location model will take into account aerodrome design factors (that move the relative location of approach undershoot accident locations and the take-off accident locations to account for the actual design of the runway) and aircraft performance factors (that account for engine derated take-off, reduced thrust take-off engine power settings, actual take-off mass, runway contamination and local weather conditions) to give a much more accurate prediction of crash location associated with operations on a specific runway. A fourth generation model is in the early stages of development at Loughborough. Other fourth generation models may be under development elsewhere. Once these models are published then comparison against the method in use at the time (either Byrne or the suggested short term change) should be considered. The continued application of Byrne by the operator of a licensed nuclear site to large and small transport aircraft accidents in the vicinity of aerodromes would have to be accompanied by adequate justification that it represented a pessimistic or accurate result given its shortfalls in the ability to adjust local operational factors and the inability of the crash location distribution model to take into account some flight operational aspects, such as turning departures, offset approaches, circling approaches, visual approaches and go-arounds.

The ability to model general aviation accidents in the vicinity of an aerodrome did not appear to have developed beyond the DOE Standard although a model such as this would be a better short-term alternative than the continued use of the Philips equations within the Byrne model.

The crash location distributions presented in this report (Section 7.3) may not be considered representative of light aircraft under 6,000 lbs (approximately 2,700 kilogrammes) maximum certificated take-off mass, due to the distributions being derived from data on crashes of aircraft certified maximum gross mass over 6,000 lbs. This report has identified 106 light aircraft crashes in the vicinity of aerodromes in Great Britain that have occurred between 1979 and 2006. An attempt should be made extend the data set to include more recent accidents; to collate the crash locations with the intended flightpaths; and analyse these data to determine suitable crash location distributions for this category of aircraft. However until the analyses have been carried out, the benefits of such work to nuclear safety remain unclear. In addition, the location distributions have been based on aerodrome-related accidents that occurred at distances of up to approximately 20 km from the runway. These distributions have then been applied to aerodrome crash rates that were based on accidents that occurred within approximately eight km from the runway threshold. As such, there is inconsistency as to the cut-off distance used to classify a crash as aerodrome-related, and a more consistent approach should be sought.

The collection of local flight operations data will require the capture of surveillance data, probably using transponder and flight plan information, as well as surveys of military and general aviation activity. Aircraft surveillance transponder information alone will not necessarily capture some general aviation aircraft as they are not required to be fitted and in the vicinity of some sites, the transponder is not required to be operated if the aircraft is at relatively low altitudes. Aircraft under 2,000 kilogrammes maximum certificated take-off mass are not required to file flight plans with EUROCONTROL, although they may do, and the flight routes given may still be varied from the planned route. Depending upon the location of the site of interest, some air traffic control surveillance monitoring may not be optimal for capturing passing general aviation traffic and local monitoring may have to be provided by a third party contractor. This would provide aircraft track, altitude, speed and aircraft type information for use in the crash models. It would also provide a file of data for quality assurance purposes.

Military aircraft crashes directly onto a site

The analysis of military crashes within the Byrne model is unusual in that it provides a low, medium (transition) and high crash rate area whereas other models either perform site specific evaluations or have a more general background rate. This goes some way to addressing local factors but the changes to military operating routes, including bombing ranges, appears to lead to retrospective changes in the high probability and transition zone areas. The areas of high crash concentration published by Byrne (1997) were not the same as the latest version of the model (ESR Technology, 2008). The problem with this high concentration area analysis is that it is retrospective which gives the operators of licensed nuclear sites a problem with forward risk projections as it is liable to move in ways that are not easy to extrapolate considering the historic versions of the model alone. The modelling may not account for future changes in military operations and the subsequent alteration in background crash rate frequency at a specified location. The operator of a licensed nuclear site should be able to predict if their location will move from a low or transition area into a higher probability area. This is not possible with the current Byrne analysis method.

To improve the Byrne model then it may be necessary to improve the knowledge relating to those military flight routes used historically and those projected to be used in the future. This may allow a more accurate evaluation of crash location densities to be established. The distributions may have to be segregated into low-level flight corridors used to transit the country; training areas where manoeuvres associated with pilot skill development take place; and combat areas where significant interaction between aircraft may take place. The crash distribution associated with a transit corridor may be significantly different from the other areas.

The classification of aircraft as either civilian or military may need further reconsideration with the increasing use of private finance deals and the purchase of former military aircraft for use by civilians for private purposes. Most of the small transport category accidents in the last few years have been ex-military jets but with their relatively high speeds and structural density compared with civilian small propeller driven airliners, the consequence analyses may be distorted with the reclassification. The largest aircraft operated on the civilian register but performing military operations is the Airbus A330 Voyager that has taken over the long-haul troop transport and air-to-air refuelling roles from aircraft such as the VC-10 and TriStar. It may be more appropriate to consider any civilian registered aircraft operating for military purposes under the military grouping. Similar considerations may also apply to contracted-out operations for HM Maritime and Coastguard Agency as these operations are relatively distinct from normal civilian operations.

The licensed nuclear site as an obstacle to safe flight

There were attempts to model the probability of a collision between an aircraft and an obstacle to safe flight in the Hornyik model. No validation of the suggested theory appeared in the search of published literature. None of the other models addressed this hazardous scenario. Intuitively, the likelihood of this hazardous scenario may be relatively low but collisions with obstacles have occurred in Great Britain and licensed nuclear sites may have a significant vertical extent when compared with the local terrain.

In order to undertake a local hazard analysis, it would be necessary to gain an understanding of the types of low-level traffic that may operate in the vicinity of a site and the reasons that they may fly low over the site itself. The conspicuity of the site would have to be examined in order to address the see-and-avoid factor. It may be that a site is relatively inconspicuous as part of a security strategy. Alternatively, the site may be marked in conspicuous contrasting colours and well lit in an attempt to inform pilots of its location. Any consideration of conspicuity would have to consider the variation between day and night, the possibility of low cloud and fog, the effects of rain and other factors that may reduce forward visibility including direct sunlight at low sun elevation angles as well as the ability of a pilot to detect a slender structure during daylight hours but with full cloud cover reducing the ambient sunlight conditions.

The conspicuity factor could be addressed by changing the dataset of accidents being considered to include those for all forced landings, not just fatal outcomes. This would also have the benefit of removing a dependency factor that may bias the data associated with using fatal accidents. The obstacle factor could be addressed through a local hazard analysis that involved suitable aviation expertise.

The dependency factor is related to the potential for double counting (leading to an optimistic calculation of hazard occurrence rates) of accidents/incidents associated with landings/crashes outside aerodromes that were not fatal. For example, an aircraft may have a loss of control accident but be of an ex-military type and fitted with ejector seats leading to a non-fatal outcome. The flight crew would not be on-board in order to steer the aircraft away from a licensed nuclear site. Another example would be an engine failure in a single engine aircraft. Whilst it may undertake a forced landing safely, by virtue of flying in daylight with no cloud and over open land, the same outcome may not result associated with flying above a licensed nuclear site, in cloud with a low cloud ceiling and at night.

The local factor associated with the provision of airspace restrictions, and subsequent granting of exemptions to allow aircraft to penetrate any such airspace, was not taken into account by any of the models. It was understood by the review team that if such airspace protection was provided then it was not claimed as a calculated risk reduction factor but was only quoted in the safety argument as a factor to demonstrate the application of risk management principles associated with “As Low As Reasonably Practicable”.

Safety-significant services crossing the boundaries of a licensed nuclear site
Licensed nuclear sites are required to have robust safety arguments demonstrating that the loss of safety-significant services that cross the site's boundaries have adequate contingency infrastructure and procedures to cater for the loss of these services. This may include grid power to import/export electricity and tertiary cooling water supplies.

A flying machine may have the capability to disrupt these cross-boundary services, even if it does not crash directly into the licensed nuclear site. For example, electrical grid transmission lines strung between pylons may be struck by a hot-air balloon requiring the power lines to be shut down.

The loss of any of these cross-boundary services should include aviation-related events within their initiating event frequency and loss of service outage time calculations, or a demonstration that the aviation-related contributions to these values are insignificant.

Shadow shielding of a site
The Byrne model considers how a building, structure or terrain may provide some degree of shielding from impact by projection of a protective shadow over another area. Some other models developed for the analysis of aviation-related external hazards to nuclear sites, rather than models developed to determine third-party risk in the vicinity of an aerodrome, also consider this issue.

The models are particularly sensitive to the angle of descent chosen when they are applied. Different types of aircraft accident may have different descent angles. An aircraft flying low level colliding with a tall chimney on-site may have a horizontal flightpath whereas an aircraft suffering a stall-related loss-of-control accident may have a very steep angle of descent. Whilst the Byrne model provides three equations (numbered 13 to 15) it may be appropriate to update the data as it was last analysed 24 years ago (Jowett, 1990).

The structural integrity of a building and its ability to shadow another has to be demonstrated in the impact analysis. This element is beyond the scope of the Byrne model and this report.

The size of the aircraft also has to be considered with standard geometric consideration of the semi-span of the aircraft. The suggestion that only the measurement between wing-mounted engines be considered as the critical aircraft measurement (Haley et al, 1998) may not be a significant improvement to the Byrne model.

Sliding or skidding into a site
The Byrne model considers this issue as do some other models including Solomon, LLNL ACRAM and its development into the DOE standard model, Loughborough and Berg. The distances travelled between point of first impact (or the point of leaving a runway) and the point at which the aircraft comes to rest can vary considerably. The variables include aircraft speed at impact, angle of impact, the aerodynamic drag, the lift generated by the aircraft during deceleration, the braking and reverse thrust forces, terrain slope, integrity and use of undercarriage, scooping forces generated by wing-mounted engines digging into the ground, the basic strength of the terrain and the obstacle/vegetation environment.

The Byrne model only uses the assumption that the coefficient of friction between the aircraft and the ground is the sole retardation force. Byrne equation 16 is the basic Newtonian mechanics equation assuming constant deceleration. Values for the coefficient of friction are not given but a value of nearly 5,000 metres is suggested for a skidding distance with an initial impact speed of 200 metres per second.

The implied value of the coefficient of friction is slightly above 0.4. The values derived from this single example in Byrne do not correlate well with the values derived by Solomon (1974). The continued use of the Byrne model equation 16 may be conservative but it may require some justification in safety argument documentation with referencing to other documents or analyses. It may be appropriate to update the calculated friction factor or to move to a more comprehensive model of deceleration that takes terrain, ground strength and ground friction factors into account.

Aircraft crash outside a site but with projectile bounce into a site

The Byrne report identified this issue (Byrne, 1997 Section 8.4) whereas other models did not. The models for aircraft crashes in the vicinity of an aerodrome that considered post-impact wreckage spread did not provide separate models for built-up urban areas with relatively dense structures and open areas such as safety areas around runways. These other models may have considered bouncing projectiles but only implicitly.

The data and analysis were derived by Byrne (1994) but this study may benefit from an update as it has been 20 years since its publication. In addition, the scope of the study may benefit from being widened to consider military accidents in other countries that operate similar types of aircraft to increase the dataset.

A simple model was derived by Byrne (1994) but this was not published in the main report (1997) but an example was given which quoted the values to be used and the result, without providing any formulae or exhaustive list of assumptions. The appendix containing worked examples of the Byrne model did not include consideration of the bounce scenario.

Projectiles falling from an aircraft

The Byrne report addressed this issue and considered that the relative frequency of events and the relative mass of the projectiles were both low such that this could be discounted from further analysis. The updates published to Byrne since 1997 did not include updates to the projectile analysis. An update to the projectile rate and mass considerations may be worth consideration to ensure that Byrne's statement that this hazardous scenario could be discounted was still reasonable.

Hazardous materials

Any aircraft may be carrying hazardous materials as part of its payload. There are no additional restrictions to flight operations imposed on the routes of these aircraft to keep them away from licensed nuclear sites.

The aircraft itself may contain materials as part of its structure that are hazardous to health after an impact or post-impact fire, such as depleted uranium.

It was beyond the scope of this project to consider the additional on-site and off-site consequence to human health associated with these issues.

9.2 CLASSIFICATION OF FLYING MACHINES AND SCOPE OF THE MODELS

This review was required to review models for the external hazards associated with flying machines. The generic types of flying machines were broken down into fixed-wing aircraft, helicopters, gyrocopters, gliders, airships, gas balloons, hot-air balloons and unmanned aerial vehicles. All of the models included fixed wing aircraft but they did not necessarily segment these into single or multiple power plants; piston, turboprop or jet propulsion. Classifying aircraft in terms of their number and types of power plant may assist in gaining a greater understanding of the accident rate. Some of the accidents are directly associated with engine failure and some are related to a loss-of-control after engine failure because of asymmetric flight conditions.

The sub-divisions may be required by the operator of a licensed nuclear site as they may be able to screen out various types of traffic because their structural and other defences against impact and post-impact consequences were adequate. However, none of the models provided a quantification of the rate for the “beyond design case” accident for which current structural hardening requirements for new build power plant may be inadequate.

The models attempted to account for commercial aircraft movements, some models only doing so within the vicinity of an aerodrome. The lower mass limits differed between models but this was more a function of input data. The use of a decade’s worth of national data could be questioned as to whether it captured all of the relevant hazardous scenarios. For example, during the period covered by the original Byrne model, the mid-air collision frequency for a specific point above Great Britain was calculated as being several orders of magnitude higher than the Byrne model would predict. The reports detailing the calculation are not available in the public domain. The probability and frequency of the mid-air collision has been reduced over time because of the predictive risk assessment and also the retrospective analysis of several incidents led to changes being made in the airspace structure. In addition, the further developments of both Short Term Conflict Alert (implemented on air traffic control surveillance displays) and traffic collision avoidance systems fitted to aircraft have reduced this accident frequency. Therefore, the crash location frequency peaks may not all be detected through the application of the Byrne model and the operator of a licensed nuclear site would have to demonstrate that they were not located at one of these locations.

Helicopter operations were considered by some of the models, including the Byrne model. However, most of the models specifically excluded the hover phase of flight just before touchdown or just after landing. Given that some licensed nuclear sites have helipads authorised for helicopter entry into the restricted airspace, it would seem appropriate that the hover phase accidents were included in the safety analyses carried out for those locations. However, if a licensed nuclear site operator could justify the exclusion of helicopters on post-impact consequence grounds, then this would not be an issue. The size of visiting helicopters in the consequence analysis may have to take military helicopters into account if that was part of the security response plans. The size of visiting search and rescue helicopters may have to be taken into account if they could be considered as part of an evacuation strategy.

The Byrne model did not provide any formulae for the calculation of gyrocopter related hazardous scenarios. The ACRAM model contained data for rotary wing and “other” types and it was likely that gyrocopter accidents were placed into one of these two categories. The ACRAM model was the only model that appeared to consider gyrocopters. Whilst most gyrocopters have relatively low mass, low structural density, low fuel loads and low speeds when compared with helicopters and fixed wing aircraft they should be considered in any comprehensive analysis of aviation hazards. It would be up to the individual operator of a licensed nuclear site to discount their consideration on post-impact consequence grounds after suitable analyses had been undertaken.

The Byrne model did not provide any formulae for the calculation of glider related hazardous scenarios. The ACRAM model contained data for gliders (within the “other” category) and it was the only model that appeared to do so. Whilst most gliders have relatively low mass, low structural density, no fuel (apart from self-launching motor gliders) and low speeds when compared with fixed wing aircraft they should be considered in any comprehensive analysis of aviation hazards. It would be up to the individual operator of a licensed nuclear site to discount their consideration on post-impact consequence grounds after suitable analyses had been undertaken.

The Byrne model did not provide any formulae for the calculation of airship related hazardous scenarios. The ACRAM model contained data for airships (within the "other" category) and it was the only model that appeared to do so. Whilst most airships have relatively low mass, low structural density, no fuel (apart from self-launching motor gliders) and low speeds when compared with fixed wing aircraft they should be considered in any comprehensive analysis of aviation hazards. It would be up to the individual operator of a licensed nuclear site to discount their consideration on post-impact consequence grounds after suitable analyses had been undertaken. The future size of airships may change radically with the current development of cargo carrying and surveillance platforms and should be taken into account in when carrying out predictive risk analyses.

The Byrne model did not provide any formulae for the calculation of gas balloon and hot-air balloon related hazardous scenarios. The ACRAM model contained data for balloons (within the "other" category) and it was the only model that appeared to do so. Most balloons have relatively low mass, low structural density and low speeds when compared with fixed wing aircraft. The ignition of hydrogen gas within gas balloons and the ignition of propane or other liquefied gases within hot-air balloons may have different initiation mechanisms and consequences when compared with fuels used in reciprocating and turbine engines fitted to other flying machines. The dropping of ballast from a balloon and the impact with electrical grid transmission lines may have to be considered in any comprehensive analysis of aviation hazards. It would be up to the individual operator of a licensed nuclear site to discount the consideration of all types of balloon on post-impact consequence grounds after suitable analyses had been undertaken.

The latest version of the Byrne model considered unmanned aerial vehicles but did not provide any formulae for their hazardous scenarios. Their mass, structural density, fuel loads and speeds will increase over the next few years to the extent that their post-impact consequences may be similar to military fast jets. The operators of licensed nuclear sites may have to take future developments into account in the near future.

9.3 MERGING MODELS FOR DIFFERENT PHASES OF FLIGHT

The Byrne model suffers from being a generalised model for predicting aircraft crash rates onto a location when actually the exposure of a specific location is required. The four components of background, below airway, aerodrome-related and military are each relatively generalised models and so the summation of results predicted by each of these four different contributions cannot be relied upon to give an accurate mean exposure rate at a specific location.

It should be possible to calculate an accident probability distribution along the whole length of a flightpath, including local modification factors; determine the number of flights operating locally and the relevant phase of flight when in the vicinity of a licensed nuclear site; and make a calculation of the subsequent accident rate for a specific location.

The development of a probability distribution along a flightpath may require national data to be collected relating to the length of flightpaths flown in each aircraft type grouping and each phase of flight to aid in the calculation of the denominator. More research is required into the lateral distribution of accidents when compared to their nominal flightpath too. Ultimately it may be possible to produce a model whereby the operator of a licensed nuclear site has to collect local flightpath data (or contract that work out) and this could then be imported directly into a crash model to calculate a historic exposure rate. This would have to be supplemented with a demonstration that the local exposure calculated using this method was not going to vary significantly in the short term because of local operational changes within the aviation community. If such changes were forecast, then the model could be adjusted through the addition of dummy data to represent the future additional movements and a new exposure value calculated.

9.4 STATISTICAL CONFIDENCE LIMITS

Whatever methods were selected to calculate "best estimate" of the aircraft crash frequency onto a specific location, it was considered as essential to quantify the overall uncertainty in the results. Therefore, continued use of the Byrne model without additional statistical considerations of the confidence intervals was not considered best practice.

An analysis of crash location data supplied by Loughborough University was undertaken with a number of distributions investigated. Although a Gamma distribution was judged the best fitting, other distributions including the Weibull and generalised extreme value distributions provided reasonable approximations to the data. The differences in the probability of a crash between these distributions were considerable, particularly with increasing distances from the runway. For landing undershoots at distances of up to 20 km from the runway threshold, there was great uncertainty in the cumulative probability and thus great uncertainty in the probability that a crash will occur at distances greater than 20 km from the runway threshold. This uncertainty may be related to the change in the phase of flight that usually occurs around this distance from the aerodrome. For the gamma distribution, the 95% confidence interval ranges from approximately 1% to 6%; for the Weibull distribution, the 95% confidence interval ranges from approximately 1% to 8%. These crash location distributions were not considered representative of light aircraft under 2,700 kilogrammes maximum certificated take-off mass.

Correlations between lateral and longitudinal crash distances were determined and the bivariate distribution of these distances modelled using a Gaussian copula. The strength of correlation varies according to the type of crash and is strongest for crashes after take-off after the runway end and landing undershoots before the runaway threshold. The influence of this correlation on the crash probability therefore varies according to the location being considered. For landing undershoots, ignoring correlation led to greater estimated crash probabilities along the runway threshold but lower estimates at greater lateral and longitudinal distances from the runway threshold and centreline. These differences, being up to two orders of magnitude, were substantial.

9.5 USABILITY

The reviewers considered that the easiest model to apply, given suitable data, was the format of the DOE standard model as this would allow non-aviation specialists to take account of site-specific factors more easily than applying the Byrne model and the Philips model if light fixed wing aircraft had to be accounted for. However, all of the models suffered from either an inability to consider all types of aircraft, or they may not take local flightpaths into account if the site was within the vicinity of an aerodrome. The DOE standard model included a tabulated set of data that was relatively easy to apply to a site but it would also be possible to expand the concept to a Geographic Information System to highlight the aviation risk exposure over the whole of Great Britain. Such risk maps exist in the Kingdom of the Netherlands for third party risk exposure to the population from industrial, nuclear, aviation and water related hazardous scenarios. A Geographic Information System would have the benefit of being relatively easy to use for reference purposes and it would be a major advance in public understanding of aviation risk exposure across Great Britain. However, the boundary of regulatory responsibility associated with aviation risk exposure being shared between the Health and Safety Executive and the

Civil Aviation Authority as well as the operator accountability may have to be explored further before any such system could be implemented in the short term.

9.6 COMPARISON OF MODELS APPLIED TO LONDON (ASHFORD) AIRPORT (LYDD) AND THE DUNGENESS LICENSED NUCLEAR SITES

The majority of licensed nuclear sites are located over 20 km from the nearest licensed aerodrome. Hence the crash frequency from aerodrome-related accidents is relatively low when compared with the background accident frequency (either civil and/or military). Flight activity at London (Ashford) Airport (Lydd) may present the greatest probability of an accident per flight onto a licensed nuclear site that was originating or destined for a licensed aerodrome as its location is approximately five km from the Dungeness B nuclear power plant. The relative probability of licensed aerodrome-related accidents may be several orders of magnitude higher than at other licensed nuclear sites.

The revised crash rates and location distributions determined in this study were used to estimate the probability of an accidental aircraft crash at a location in the vicinity of London (Ashford) Airport (Lydd). Separate calculations were made per take-off and landing movement for light transport aircraft only. The calculated uncertainty was substantial with approximately a three-fold difference between the lower and upper 95% confidence limits for the accident probability posed by take-offs and a six-fold difference for the accident probability posed by landings. Application of the existing Byrne and Wong models gave crash probabilities outside of these ranges. The annual aerodrome-related crash frequencies using the Byrne model and an assumed number of take-off movements on Runway 21 and landing movements on Runway 03 were similar to those calculated using the HSL method. Hence although the landing and take-off probabilities under the Byrne model were lower than and greater than the HSL landing and take-off probabilities respectively, these differences cancel each other out when landing and take-off crash frequencies are combined.

10 DISCUSSION

The Byrne model did not account for the hazardous scenario of the licensed nuclear site acting as an obstacle to an otherwise safe flight. Whilst the Hornyik model attempted to address this hazardous scenario, the model was not validated. The difficulties in validating any model may be around the identification of the frequency of low-level flights in the vicinity of the licensed nuclear site; determining the daily variability in weather conditions; accounting for protective airspace; and determining the conspicuity of the site and any slender structures.

The Byrne model addressed the shadow shielding of part of a site by structures on another part of a licensed nuclear site. The structural integrity of the shadowing building was not discussed in detail but this was considered to be a post-impact consequence management issue. The updating of the assumptions relating to aircraft impact angles may assist in improving the quality of the calculated results as the last analysis was 24 years ago.

The Byrne model addressed the skidding of an aircraft into a licensed nuclear site. However, there were significant differences in the general friction factors assumed to bring an aircraft to rest between various models. The updating of the friction factor based on additional data may help to improve the quality of the calculated results.

The Byrne model addressed the projectile bounce of an aircraft making its initial impact outside a licensed nuclear site but then projectile impacting the site. However, the formulae to calculate relevant results were not in the main Byrne model but in an earlier paper by the same author (Byrne, 1994). The worked examples within the Byrne model did not include this scenario. The updating of the assumptions relating to bounce projectile motion may assist in improving the quality of the calculated results as the last analysis was 20 years ago.

The Byrne model addressed projectiles falling from aircraft. The updating of assumptions relating to the frequency with which projectiles fall from aircraft, their mass and speed may assist in improving the quality of the calculated results. However, if the mass and speed of projectiles falling from aircraft can be discounted as a trivial case from their impact and post-impact consequence analyses, then updating would not add any significant knowledge.

The Byrne model did not address issues relating to hazardous materials carried on-board the aircraft and hazardous materials used in the structural composition of the aircraft. These were considered to be post-impact consequence issues and not addressed further within this report.

Most of the models addressed commercial aircraft movements but with different lower mass cut-off points as a function of their selected data sets. Not every hazardous scenario was captured through the use of a decade's worth of aircraft accident data, particularly when considering the stringent target levels of safety for licensed nuclear sites. The peak exposure for aircraft accident frequency onto specific locations may not be captured by the Byrne model.

Helicopter operations were considered by some models. Most models that did include helicopters did not include accidents in the hovering phase of flight. This was not consistent with the authorisation for helicopter operations to take place at some licensed nuclear sites.

The Byrne model did not appear to consider gyrocopters, gliders, airship, gas-lifting balloons and hot-air balloons. These were considered in the ACRAM model that then developed into the DOE standard model. The exclusion of these types of flying machine on the grounds of mass, speed, structural rigidity and fuel carried may be reasonable but no evidence was provided to the team during the project to justify their exclusion from consideration by every operator of a licensed nuclear site.

The most recent update of the Byrne model addressed unmanned aerial vehicles and concluded that they posed an insignificant risk. However, future developments will see an increase in mass, speed, fuel payload and structural rigidity to the stage where they cannot be excluded on the grounds of consequence analysis alone.

The Byrne model was considered to be a generalised area model suitable for calculating average crash frequencies over a nation, but not a good model for predicting the crash frequency onto a specific location.

The DOE standard model was considered the easiest model to apply for non-aviation specialists. The development of an aviation-related risk map for the whole of GB may be significantly easier to use but would take considerably greater resources to develop.

Statistical analysis of aircraft crash data for GB found no significant evidence of a change in the background rate of crashes (between 1985 and 2006, expressed per km^2) nor a change in the rate of aerodrome-related crashes (between 1979 and 2006, expressed per movement) for small and large transport aircraft. However, a statistically significant increase in the accident rate for light aircraft of 4.4% per annum and for helicopters of 4.7% was found.

Based upon accidents between 1985 and 2006 the estimated background crash rate was greatest for England. For light aircraft, the annual crash rate for England is $2.93 \times 10^{-5} km^{-2}$ (95% C.I. [2.34, $3.63 \times 10^{-5} km^{-2}$]); for helicopters is $1.39 \times 10^{-5} km^{-2}$ (95% C.I. [1.00, $1.90 \times 10^{-5} km^{-2}$]); for small transport aircraft is $0.31 \times 10^{-5} km^{-2}\ y^{-1}$ (95% C.I. [0.14, $0.60 \times 10^{-5} km^{-2}\ y^{-1}$]); and for large transport aircraft is $0.04 \times 10^{-5} km^{-2}$ (95% C.I. [0.00, $0.19 \times 10^{-5} km^{-2}$]).

Based upon accidents between 1979 and 2006 the estimated aerodrome-related crash rates were similar across England, Scotland and Wales, hence the use of GB rates seems justified. The crash rate per million movements for light aircraft is 1.61 (95% C.I. [1.36, 1.90]); for helicopters is 2.12 (95% C.I. [1.43, 3.03]); for small transport aircraft is 3.14 (95% C.I. [2.18, 4.39]); and for large transport aircraft is 0.14 (95% C.I. [0.05, 0.32]). Adjusting the rate for light aircraft by the estimated trend of +4.4% per annum gives a considerably higher crash rate for 2014 of 3.89 per million movements. Similarly, adjusting the rate for helicopters by the estimated trend of +4.7% per annum gives a crash rate for 2014 of 5.16 per million movements.

An analysis by the International Atomic Energy Authority (IAEA, 2008) found a reduction in world-wide crashes involving Western jet aircraft with MCTOM of 2,250 kg to 27,000 kg, and >27,000 kg, over the period 1995 to 2004. However, trends by region were not reported thus it is uncertain whether this trend has been observed in Europe, or whether it has been driven by declines in countries where aviation safety has generally been poorer than the US and the JAA (The European Joint Aviation Authority) regions. The crash rate for North America was comparable to that of the JAA region. This analysis was based upon data on accidents involving Western built turbine powered aircrafts over 25 tonnes MCTOM collated by the UK based organisation Airclaims and supplied to the IAEA by the UK Civil Aviation Authority. An attempt should be made obtain these data to allow further investigation of changes in aircraft accident rates and inter-country differences.

The quantification of uncertainty in the models was considered to be essential and this was not contained within the Byrne model. Based upon the width of the confidence intervals for the accident rates derived in this report from crashes in GB, data relating to GB are considered adequate for determining average crash rates for the light aircraft, helicopter and small transport categories. There were few large transport category accidents over GB, therefore the uncertainty in the calculated rate was relatively large (95% CI [0.11, 0.36] $km^{-2}10^{-5}$ for annual background crashes and [0.05, 0.31] per million movements for aerodrome-related crashes); data from North America or Europe should be considered to supplement GB data for this category. In addition, the use of all reliable historical data will allow investigation of the changes in reliability over time. Using only the last 10 or so years is arbitrary and risks unnecessarily increasing the uncertainty in the estimated crash frequency; the use of larger data sets as well as a greater understanding of actual flight routes and flight frequencies would be required to build a more accurate model.

An analysis of crash location data supplied by Loughborough University was undertaken with a number of distributions investigated. Although a gamma distribution was judged the best fitting, other distributions including the Weibull and generalised extreme value distributions provided reasonable approximations to the data. The differences in the probability of a crash between these distributions were considerable, particularly with increasing distances from the runway. For landing undershoots at distances of up to 20 km from the runway threshold, there is great uncertainty in the cumulative probability and thus great uncertainty in the probability that a crash will occur at >20 km from the runway threshold. For the gamma distribution, the 95% C.I. ranges from approximately 1% to 6%; for the Weibull distribution, the 95% C.I. ranges from approximately 1% to 8%. These crash location distributions are not considered representative of light aircraft under 2,700 kg MCTOM.

Correlations between lateral and longitudinal crash distances were determined and the bivariate distribution of these distances modelled using a Gaussian copula. The strength of correlation varies according to the type of crash being strongest for crashes after take-off after the runway end and landing undershoots before the runway threshold. The influence of this correlation on the crash probability therefore varies according the location being considered. For landing undershoots, ignoring correlation led to greater estimated crash probabilities along the runway threshold but lower estimates at greater lateral and longitudinal distances from the runway threshold and centreline. These differences, being up to two orders of magnitude, were substantial. Around the vicinity of Dungeness B however, the estimated crash probabilities were similar.

The revised crash rates and location distributions determined in this study were used to estimate the probability of an accidental aircraft crash at a location in the vicinity of Lydd airport. Separate calculations were made per take-off and landing movement for light transport aircraft only. The calculated uncertainty was substantial with approximately a three-fold difference between the lower and upper 95% confidence limits for the risk posed by landings and a six-fold difference for the risk posed by take-offs. Application of the existing Byrne and Wong models gave landing and take-off crash probabilities outside of these ranges. The annual aerodrome-related crash frequencies using the Byrne model and an assumed number of take-off movements on Runway 21 and landing movements on Runway 03 were similar to those calculated using the HSL method. Hence although the landing and take-off probabilities under the Byrne model were lower than and greater than the HSL landing and take-off probabilities respectively, these differences cancel each other out when landing and take-off crash frequencies are combined.

As in the Byrne methodology, the background accident rates presented in this report have been expressed per km^2. The Byrne methodology derived both background crash rates and airways related crash rates. However, since the original development of the Byrne methodology, flight patterns in the

United Kingdom have changed considerably with air traffic control permitting many more direct routes that straighten the paths between ground based navigation aids. A preferable approach would be to remove the distinction between background and airways crashes and recalculate the background crash rates per km flown to be used in conjunction with location specific information on flight movements. This would much better capture the variation in background crash risks between locations and reflect the local operating conditions above and in the vicinity of a licensed nuclear site.

To implement such an approach flight information would be required both nationally, in order to calculate a background crash frequency per km flown, and locally to calculate the crash probability at a particular location i.e. a licensed nuclear site. Whilst in principle such information is available from National Air Traffic Services (radar) and EuroControl (based upon submitted flight plans), the availability and format of such data is unclear. In addition, aircraft under 2,000 kg MCTOM are neither required to submit flight plans or carry a transponder. The requirement at the national scale is for the total number of km flown per aircraft category per annum to use as the denominators in the proposed alternative derivation of background crash frequencies. Estimates may be possible based upon the (known) number of movements, average flight durations and average velocities. As well as NATS and EuroControl, local flight movements in the vicinity of a nuclear site could be obtained through Licensees undertaking their own monitoring.

For aerodrome-related crashes a three stage assessment is advocated: estimation of an average crash frequency; adjustment of the average crash frequency for local factors, if possible; and application of a crash location distribution. Whilst the Wong and ACRP 3 (Hall et. al, 2008) models provide some useful information for assessing inter-aerodrome variation in crash frequencies, several of the estimated risk factors may not be applicable to GB. For instance, very few UK aerodromes would meet the Federal Aviation Authority's criteria for being a hub airport or have 'significant terrain' within six miles of the airport. Similarly whilst the analysis of US data suggested that flights with foreign origins or destinations ran a greater risk of take-off overruns, it is not clear how this might translate to the UK. The risk factors relating to meteorological conditions, particularly rain, crosswinds, ceiling height and visibility, are considered the most reliable for application to GB. A useful sensitivity analysis would be to use the risk multipliers for meteorological factors to predict the variation in accident rates between a small number of geographically diverse aerodromes in GB. This would provide a lower bound to the extent of variation between aerodromes.

The calculation of crash frequency distributions in the vicinity of an aerodrome using the Byrne model was not necessarily representative of the anticipated crash rates that may be calculated using a third generation model that took curvilinear flightpaths into account. Whilst this would be a significant improvement, further work would be necessary to examine cross-track lateral accident locations for all phases of flight as no significant work appeared to have been done to validate any of the models, or the models used very few data points. Additional work to include normalisation, the use of normal operations data, accounting for aerodrome design factors and aircraft performance factors to move to a fourth generation model would be desirable in the longer term to improve accuracy.

A model could be developed based on an accident probability distribution along the whole length of its specific flightpath. The point probability in the vicinity of a licensed nuclear site, in combination with knowledge of the frequency with which aircraft passed and the lateral crash distribution would then enable a more accurate model to be built. Forecasts of future aircraft movements could be used to predict the aircraft accident frequency onto a licensed nuclear site.

As in the Byrne, Wong and ACRP models, the analysis of crash locations and subsequent application of the derived distributions assumes arriving and departing aircraft follow the extended runway centre line with no account made for offset approaches and departures that turn after reaching a minimum height above the runway. ESR Technology (2009) discusses the empirical modelling approach for curved flight paths developed by DNVT and NLR. These approaches to modelling curved flight paths should be investigated further to determine their suitability for use with the location distributions presented in this report, or to aid development of alternative methods for addressing curved flight paths. In addition, an attempt should be made to recalculate the crash locations in the US database along the actual flight paths flown, if flight path data exist. The longitudinal and lateral location distributions may then be refitted, providing distributions based on the location of crashes relative to the actual flight path, rather than on the assumed flight path on the extended centreline. In assessments of the crash risk at particular aerodromes, the generic crash location distribution should then be adjusted to account for the local flight paths.

The crash data from aircraft operations over GB is relatively sparse because, despite the high frequency of commercial flights, the accident probability per flight is low. Some hazardous scenarios may not have appeared in recent times, such as mid-air collision between airliners, although the accident probability at certain locations may have been relatively high. Therefore, any safety argument must include consideration of the probability of different hazardous scenarios. Whilst it is recognised that the operator of a licensed nuclear site is only concerned with the frequency of crashes onto the site and not prevention of their causes, the calculation of the total frequency should be based on the summation of the contribution from each hazardous scenario. In order to address the limited data issue it may be necessary to extend the geographic boundaries of the accident data set. It may also be necessary to consider an aviation specific hazard identification exercise to ensure that all relevant hazardous scenarios have been captured.

Some hazardous scenarios, such as the "beyond design case" accident may have occurred elsewhere in the world but not in United Kingdom's airspace or to an aircraft registered in the United Kingdom. The "beyond design case" hazardous scenario, whilst of relatively low frequency (at least historically for unintentional accidents) may be worthy of special consideration by the whole industry and national defence organizations as additional controls could be put into place relatively easily, given the magnitude of the consequences. This hazardous scenario is not addressed by any of the models.

If relatively low mass aircraft are significant in terms of the post-impact consequence analysis, then the Philips model adopted for general aviation activities was only first generation and may be relatively inaccurate as it may not reflect local conditions. It may be more appropriate to consider using the ACRAM model with adjustments for accident rates between data representing the United States and GB. This would act as a short term measure prior to the development of a more appropriate model to take account of curvilinear flightpaths and local conditions in the next generation of general aviation accident model. In terms of a general aviation background crash rate, there may be an adequate number of accidents to justify a more cluster based model, possibly based on the product kernel method used within ACRAM. This would address the concerns about peak areas of accident frequencies not being identified when applying Byrne/Philips across GB.

The grouping of aircraft into different mass and kinetic energy groups within the Byrne model did not appear to be consistent. There may be a case to consider former military jets now operated by private civilians within their former category. The classification of fast and slow traffic for en-route calculations was not consistent with the mass groupings as large turboprop airliners spanned the mass boundary. The continued transfer of government operations to civilian contractors leads to a classification issue at the boundary of civilian and military operations. Military flight training, search and rescue, coastguard, oil pollution control, military transport and air-to-air refuelling tasks have seen a significant amount of contracting out. Classifying these flights appropriately will have to be carried out.

The Byrne model classified military fast-jet accidents into three separate probability areas. These areas moved in subsequent analyses and were considered to be retrospective rather than predictive of the future crash frequency. The prediction of future military aviation losses, based on extrapolation from historic data may lead to an inaccurate result when considering a site specific accident rate. Aircraft types have changed over time. It was not possible to carry out any significant projection of the relevance of historic military accident rates to the likely future military accident rates within the timescales of this project. The forecasting of military flight accident frequency and locations may have to be carried out in association with the Military Aviation Authority. If cooperation cannot be established then it may be necessary to use data from previous generations of aircraft or similar aircraft types in order to determine accident rates. The future development of unmanned aerial vehicles poses a significant issue in the prediction of crash frequency and location for operators of licensed nuclear sites.

Military training areas have moved and the frequency of flights has changed. The local application of generic crash rates will suffer in terms of accuracy if the flight frequencies in the vicinity of the licensed nuclear site cannot be established in partnership with the military.

11 RECOMMENDATIONS

The project team suggested the following recommendations for consideration by the TAP:

1. All operators of licensed nuclear sites should undertake a site-specific hazard identification exercise in relation to the aviation-specific external threats to ensure that their safety arguments were complete and had not omitted any hazardous scenarios from consideration.
2. The geographic spread and time space of aircraft accident data should be expanded because of the sparse nature of accident data for crashes onto GB.
3. The operators of licensed nuclear sites, and other government agencies, should consider special measures to protect against “beyond design case” events from aviation-related activities.
4. The operators of licensed nuclear sites should be responsible for conducting local flight surveys to ensure that the number and type of flights operating in the vicinity of the licensed nuclear site is compatible with the assumptions used in the calculation of aircraft accident frequency.
5. The operators of licensed nuclear sites should ensure that local operating conditions that may modify the probability of a flight suffering an accident significantly are taken into account.
6. The significant number of general aviation accidents away from the aerodrome of departure and intended arrival may allow for a more site-specific model to be derived rather than the current generalised Byrne distribution.
7. The significant number of general aviation accidents in the vicinity of the aerodrome of departure or intended arrival may allow for a more site-specific model to be derived rather than the Philips model in current use. The use of the DOE standard as an improved method prior to the development of a new model should be considered.
8. The Byrne model should be improved for the calculation of crash frequency distributions in the vicinity of an aerodrome. The use of a third generation model, such as NLR, should be considered as a short term replacement until a model that is available includes normalisation, use of normal operations data, consideration of aerodrome design factors and consideration of aircraft performance factors.
9. The cross-track lateral accident location for all phases of flight would benefit from additional research to validate, or otherwise, the current assumptions within crash location models.
10. The grouping of aircraft into different mass and kinetic energy groups should be reconsidered with the objective of removing the inconsistencies present within the Byrne model. Operations by ex-military aircraft could be considered for grouping with current military aircraft. Operation of civilian aircraft but on military and state activities could be considered for grouping with current military aircraft.
11. The modelling of military aircraft accidents could be improved and associated with actual flight paths intended to be flown as well as forecast loss rates for new aircraft types.
12. The Byrne model could be improved through the local application of a hazard analysis to consider the licensed nuclear site acting as an obstacle to an otherwise safe flight.
13. The Byrne model could be improved by updating the assumptions relating to aircraft impact models, skidding friction factors, projectile bounce factors and projectiles dropping from aircraft.
14. The Byrne model should be extended, if required to comply with consequence analyses implications, to include the hovering phase of helicopter operations, the operation of gyrocopters, gliders, airships, gas-lifting balloons and hot-air balloons. The use of the DOE standard as a substitute would be an acceptable intermediate step until a more specific GB model could be developed.

15. Operations by unmanned aerial vehicles should be considered in greater detail in time.
16. Any future model developed for use in the vicinity of an aerodrome should consider the correlation between lateral and longitudinal crash distances; the use of a gamma distribution; the normalisation of the data including aircraft performance factors and flight performance factors and the use of normal operations data. The significance of the variation in weather conditions experienced across GB could be tested in a sample analysis in order to determine if such factors had to be considered at all locations of licensed nuclear sites.
17. If any model is to be developed beyond the Byrne model for use in GB then the usability could be improved by changing to look-up tables such as published in the DOE standard model or through a risk map being published for the whole of GB.
18. Any modelling of aircraft accident frequencies at a specific location should include the consideration of confidence intervals and the 95% confidence interval upper bound should be used in safety arguments to demonstrate that a licensed nuclear site does not suffer from excessive risk associated with aviation-related hazards.

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ABBREVIATIONS, ACRONYMS, INITIALISATIONS AND SYMBOLS

AAIB	Air Accidents Investigation Branch (United Kingdom)
ACRAM	Aircraft Crash Risk Analysis Methodology
ACRP	Airport Cooperative Research Program
ALARP	As Low As Reasonably Practicable
ASDA	Accelerate-Stop Distance Available
ASDR	Accelerate-Stop Distance Required
ATSB	Australian Transportation Safety Bureau
CAA	Civil Aviation Authority (the United Kingdom's aviation safety regulator)
CAST	Commercial Aviation Safety Team
DfT	Department for Transport
DNV	Det Norske Veritas (also DNV Technica, now GL DNV)
DOE	Department of Energy (United States)
EASA	European Aviation Safety Agency
ENAC	Ente Nazionale per l'Aviazione Civile (Italian Civil Aviation Authority)
FAA	Federal Aviation Administration (United States)
GfL	Gesellschaft fur Luftverkehrsforschung
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
IAEA	International Atomic Energy Agency
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
JAA	The European Joint Aviation Authorities (precursor to EASA)
LDA	Landing Distance Available
LLNL	Lawrence Livermore National Laboratory
MCTOM	Maximum certified take-off mass
NATO	North Atlantic Treaty Organization
NATS	National Air Traffic Services (also NATS Limited)
NLR	Nationaal Lucht en Ruimtevaartlaboratorium (Dutch)
NRC	Nuclear Regulation Commission (United States)
NTSB	National Transportation Safety Board (United States)
NUREG	Nuclear Regulation
OGP	Association of Oil and Gas Producers
ONR	Office of Nuclear Regulation
s	Longitudinal distance along a curvilinear flightpath
SI	Statutory Instrument
t	Cross track lateral distance on a curvilinear flight path
TAP	Technical Advisory Panel
TODA	Take-Off Distance Available
TODR	Take-Off Distance Required
TORA	Take-Off Run Available
TORR	Take-Off Run Required
TRB	Transportation Research Board
TSB	Transportation Safety Board (Canada)
UK	United Kingdom
US	United States
USA	United States of America

VHF	Very High Frequency
x	lateral displacement perpendicular to a runway's extended centre line
y	longitudinal displacement along a runway's extended centre line

APPENDIX A - AIRCRAFT CRASH DATA

Table A1 Light aircraft background crashes (1985-2006)

Year (number of crashes)	England	Scotland	Wales
1985 (6)	27.04.85 Streatley 15.05.85 Ringwood, Hants 23.05.85 4nm SE of Brize Norton 03.06.85 Otby, near Market Rasen 09.08.85 Welford, Northants 08.09.85 Zelstone, near Poole		
1986 (5)	14.06.86 Bincombe, near Dorchester 11.09.86 Chandlers Ford 29.09.86 3 nm N of Thirsk 03.10.86 Bethersden, Kent 13.12.86 Walthamstow		
1987 (10)	29.03.87 Brandesburton 17.05.87 Brunton, Northumberland 23.05.87 Pencarrow Head, near St Austell 12.06.87 Effingham, Surrey 14.07.87 Exeter 20.07.87 Chipping Norton 31.07.87 Brome, Suffolk 02.08.87 Shingay, near Royston 25.09.87 Tollesbury, Essex 29.11.87 Ambleside		
1988 (5)	15.01.88 Dawlish 02.03.88 Southport Beach 16.06.88 Detling Hill 18.07.88 Tewksbury	21.10.88 Dromochter	
1989 (3)	07.08.89 Scofton 23.03.89 Basingstoke	16.06.89 Ardnamurchan	
1990 (5)	24.03.90 3 m E of Mere 03.05.90 Chadlington 19.05.90 M25, Reigate 19.05.90 M25, Reigate	20.11.90 Dunbar Common, near Edinburgh	
1991 (5)	18.04.91 Stanmore Common 19.05.91 Aldermaston 20.05.91 Near Lancaster 17.08.91 Ashampstead		15.05.91 Llangollen
1992 (7)	13.02.92 Skiddaw 15.02.92 M25/A13 nr Thorrock 07.04.92 Consett 15.07.92 Forest of Bowland 09.12.92 8 m W of Luton	03.04.92 Loch Muick 22.08.92 Isle of Jura	
1993 (4)	21.03.93 Near Shrivenham 20.07.93 Shadoxhurst	18.03.92 3 m SW of Maybole 15.09.93 SW of Sanquhar	
1994 (6)	08.01.94 Wrekin 17.01.94 Thirlmere 20.01.94 Near Bloxwich 20.03.94 Near Wellesbourne Mountford 09.10.94 5 m SW of Binbrook 20.11.94 3 m N of Worthing		
1995 (3)	04.03.95 Near Malden, Essex 21.03.95 Knottingkey, Yorks 13.10.95 Sileay Ruy, Isle of Man*		
1996 (7)	05.05.96 Near Westcott 06.06.96 Pebworth, near Evesham	16.10.96 18 nm NW of Perth	

	15.06.96 Buxton 22.07.96 Tockington Park Farm, near Almondsbury, Bristol 25.09.96 2 nm W of Southport Pier 26.10.96 Dover VOR		
1997 (3)	27.11.97 1.8 miles NW of Shobdon Airport, Herefordshire	06.05.97 3 nm N of Cumbernauld Aerodrome 21.12.97 Near Ben House, Gatehouse of Fleet, Galloway	
1998 (3)	26.07.98 Bentworth, Hampshire 20.10.98 Mow Cop House, Staffordshire		23.05.98 Tryfan, North Wales
1999 (7)	21.01.99 300m from western edge of Mattersey, Nottinghamshire 29.04.99 Near Selby, Yorkshire 04.07.99 Near Easingwold, Yorkshire	09.05.99 2km S of Cromarty, Black Isle, Highlands	12.02.99 Berwyn Mountain, mid Wales 02.08.99 Moel Hebog mountain, near Beddlegert, North Wales 29.08.99 Sarn, near Newtown, Powys
2000 (5)	15.05.00 Hambledon Hill, 15 miles N of Leeds Bradford Airport 16.07.00 Near Upper Cumberworth, West Yorkshire	30.11.00 Fortingall, Perthshire 13.12.00 en route Inverness to Benbecula	11.09.00 20 miles N of Swansea
2001 (6)	24.02.01 Near Sharpthorne, West Sussex 12.05.01 Osea Island, Essex 23.06.01 Nash, Shropshire 22.07.01 Near Lichfield, Hampshire 15.08.01 Halesworth, Suffolk	25.01.01 10 nm South of Braemar, Grampian	
2002 (4)	27.02.02 Hannington, Hampshire 25.08.02 Devils Chair, Stiperstones, Shropshire		01.04.02 2 miles W of Cwmbran 18.05.02 12 nm west of Brecon VOR
2003 (2)	05.01.03 2 MILES NE of Towcester, Northamptonshire 13.04.03 Clitheroe, Lancashire		
2004 (4)	13.03.04 Hotham, South Cave, Humberside 27.06.04 Beacon Village, near Honiton, Devon 04.07.04 offshore, in Liverpool Bay, 2 nm N of Wallasey	22.10.04 37 miles NW of Inverness	
2005 (7)	25.05.05 Near Pottersbury, 6 miles NW of Milton Keynes 15.06.05 Near Wolton-under-Edge, Gloucestershire 18.08.05 Remenham (Berkshire) 17.11.05 near Bugbrooke, Northamptonshire 18.12.05 Moreton in Marsh, Gloucestershire	19.05.05 Approx. 20 miles N of Dundee	04.09.05 Irish Sea, 5 nm NW of Stumble Head, Pembrokeshire
2006 (3)	16.07.06 Hoxne, Suffolk 25.08.06 Near Bramley, South Yorkshire		11.09.06 Near Bethesda, Gwynedd
Total (110)	**84**	**16**	**10**
*Isle of Man has been included as a British Crown Dependency			

Table A2 Helicopter background crashes, 1985-2006 (military crashes in brackets)

Year (number of crashes)	England	Scotland	Wales
1985 (1)		(21.06.85 Near Dundee)	
1986 (1)	08.04.86 Swalcliffe		
1987 (1)	(16.10.87 Trewavas Head, Cornwall)		
1988 (1)	(30.08.88 Flamborough Head)		
1989 (6)	22.06.89 Pershore 16.11.89 Portmadog Beach 06.12.89 3 m S of Carlisle 18.12.89 Cudham, 2 nm SE of Biggin (04.03.89 Stanford)	(28.01.89 Lochan A Choire)	
1990 (3)	28.03.90 1 m W of Chinnor	24.01.90 Giffnock	(12.02.90 10 km NW of Valley)
1991 (1)	08.09.91 Welford-on-Avon		
1992 (4)	23.02.92 Royton 28.03.92 Coalport 29.05.93 Near Latimer 14.08.92 Crowthorne		
1993 (5)	23.06.93 Near Kendal 11.12.93 Near Wimborne (20.07.93 Stanford Training Area)		20.11.93 Near Brecon (12.08.93 Llyn Padarn Lake)
1994 (3)		07.12.94 Ballachulish (02.06.94 Mull of Kintyre)	22.05.94 Colwyn Bay
1995 (2)	(07.04.95 Yarcombe, Somerset) (05.10.95 Wye Valley, Chepstow)		
1996 (3)	23.04.96 1 nm S Portesham, Dorset 19.10.96 Near Cauldron Lowe, Staffs 22.10.96 Middlewich, Cheshire		
1997 (3)	16.03.97 Gravesend near Albury, Heartfordshire 11.08.97 Adjacent to M6 motorway at Nether Kellet, nr Lancaster 14.11.97 Cocking, near Chichester		
1998 (3)	19.04.88 900 m SW of Gumley 26.07.88 Near Rochester Airport 01.08.88 Near Six Mile Bottom, Cambridgeshire		
1999 (1)	(18.05.99 Tilton-on-Hill, E of Leicester)		
2000 (6)	01.02.00 2nm E of Chorley, Lancashire 08.03.00 Near Twyford, Berkshire 21.08.00 Dartford Marshes, Kent 23.08.00 Streatley, Berkshire	(27.10.00 Inner sound between Island of Rona and Applecross)	21.04.00 Coryton Drive, Cardiff
2001 (1)	(16.11.01 Brunton)		
2002 (3)	13.07.02 Hampton Magna, Warwickshire 19.10.02 Wooferton, Shropshire	17.02.02 Near Muirkirk, East Ayrshire	
2003 (4)	17.01.03 Cudham, Kent 10.04.03 Brightling, Sussex 02.12.03 Hurstbourne Tarrant, near Andover	30.07.03 Carlenrig, Teviothead, near Hawick	
2004 (1)	11.11.04 Cophams Hill Farm, Bishopton, Warwickshire		
2005 (1)	(23.02.05 Salisbury Plain Training)		
2006 (0)			
Total (54)	**32 (41)**	**4 (8)**	**3 (5)**

Table A3 Small transport background crashes (1985-2006); only years with crashes shown

Year (number of crashes)	England	Scotland	Wales
1993 (3)	13.01.93 Sellafield 11.06.93 Peak District, Broomhead Moor 15.08.93 Near Guildford, Surrey		
1995 (1)	24.05.95 6 miles NE of Leeds/Bradford Int. Airport		
1998 (2)	28.11.88* Owlacombe Cross, Near Bickington, Devon (foreign registered) 24.12.88 1 nm from the coast near Bradwell-on-Sea		
1999 (1)	01.88.99 Woolaston, Gloucestershire		
2000 (2)	18.08.00 Eastbourne, East Sussex 09.12.00 4 nm NW Louth, Lincolnshire		
2003 (1)			01.06.03 Borth, North Wales
Total (10)	**9**	**0**	**1**
Note: It is known that five of the six crashes that occurred between 1998 and 2003 involved privately owned ex-military jets (Hawker Hunter, two Jet Provosts, a Strikemaster and an Aero Vodochody Delfin).			

Table A4 Large transport background crashes (1988-2007); only years with crashes shown

Year (number of crashes)	England	Scotland	Wales
1988		22.12.88 Lockerbie (foreign-registered)	
1990		30.04.90 30 ft below summit of Maodel, Isle of Harris	
1993		27.05.93 8 nm NW Blair Atholl	
1994	25.02.94 Near Uttoxeter		
Total (4)	**1**	**3**	**0**

Table A5 Civil light aircraft aerodrome-related crashes (1979-2006)

Year	England	Scotland	Wales
1979 (2)	13.01.79 Biggin Hill Airport 12.12.79 Wycombe Air Park, Bucks		
1980 (6)	12.02.80 Nr Goodwood, Sussex 12.04.80 Woodplumpton, Preston 14.06.80 Shanklin Golf Course, Isle of Wight 29.06.80 0.5m N of Wybombe Air Park, Bucks 02.07.80 Near Ashford, Kent 24.08.80 Highwoodhall Farm, Pimlico, Herts		
1981 (1)	14.07.81 Nr Epping, Essex		
1982 (3)	09.05.82 Lasham Aerodrome, Hants 17.07.82 Old Warden Aerodrome, Beds 30.07.82 Brunton Aerodrome, Northumberland		
1983 (3)	27.02.83 Bromsgrove, Worcs 16.04.83 Markyate, nr Luton 04.11.83 1.25nm E of Biggin Hill Airport		
1984 (3)	21.08.84 Dunstable Aerodrome, Beds	16.06.84 Isle of Barra, Outer Hebrides 25.10.84 Portmoak Aerodrome, Kinross	
1985 (3)	25.04.85 Nr Fairoaks Aerodrome, Surrey 01.10.85 Leicester Aerodrome	08.11.85 Drumlanrig Castle, Dumfries	

1986 (6)	29.04.86 Stapleford 13.06.86 Barnstaple 03.07.86 Denham 04.08.86 Fenland 11.10.86 Barton, Manchester		15.06.86 Crofty, Glamorgan
1987 (9)	18.01.87 Honiton 25.02.87 Cranfield 23.07.87 Luton 06.09.87 Whitfield 22.09.87 Husbands, Bosworth, S Leicestershire	23.01.87 Perth 04.06.87 Glasgow 06.09.87 Perth	10.05.87 Trefgraig
1988 (1)	18.09.88 Horsham		
1989 (1)	29.07.89 Woodford		
1990* (5)	18.03.90 Rattlesdon 07.07.90 Cranfield 20.10.90 Near East Midlands	05.04.90 Campsie Fell, nr Glasgow Airport 27.05.90 Stoneykirk	
1991 (5)	10.03.91 Nr Chilgrove, W Sussex 31.03.91 Coventry, W Midlands 11.04.91 North Weald 06.07.91 Winterbourne, Nr Bristol 16.12.91 Chichester, W Sussex		
1992 (3)	12.07.92 Oxford Airport 04.10.92 Sheepwash, Devon 06.12.92 Nr Wycombe, Bucks		
1993 (2)	03.10.93 Br Bridport, Decon 15.11.93 Nr Biggin Hill, Kent		
1994 (2)	01.08.94 Parham, Suffolk 26.12.94 Nr Stapleford, Essex		
1995 (4)	16.06.95 Dunkeswell Airfield, Nr Honiton, Devon 09.07.95 Bakers Farm, Nr Corby, Northants 20.07.95 Stourhead Gardens, Mere, Wilts	05.05.95 Newmill Farm, Dolphinton, Lanarks	
1996 (8)	02.03.96 Shoreham Airport 04.05.96 Old Warden Airfield, Bedfordshire 31.05.96 Lydd Airport 31.07.96 Canterbury Airfield 26.08.96 Nr Barton Airfield, Manchester 21.11.96 Nr Compton Abbas Airfield, Dorset 23.11.96 Denham, Middlesex		30.10.96 Cardiff
1997 (7)	06.03.97 3.5 miles NE of Southend Airport 09.03.97 1 mile NE of Biggin Hill Airfield, Kent 25.07.97 Meppershall Airfield, Bedfordshire 03.08.97 Nr Shobdon Airfield, Herefordshire 08.08.97 Brunton Airfield, Northumberland 29.09.97 North Weald Airfield, Essex		20.08.97 Cardiff Airport
1998 (3)	17.05.98 Andrewsfield, Essex 09.08.98 Swanton Morley Airfield, Norfolk 15.08.98 Woburn Abbey, Bedfordshire		
1999 (10)	04.02.99 Turweston Aerodrome, Northamptonshire 28.03.99 Newnham, Hertfordshire 03.07.99 Bembridge Airport, Isle of Wight 17.07.99 East Mersea, Colchester 29.08.99 Husbands Bosworth Airfield, Leicestershire 18.09.99 Luton Airport 26.09.99 Charity Farm Airstrip, Baxterley, Warwickshire 06.06.99 Nr Moneweden, Suffolk 14.11.99 Belle Vue, Barnstaple 18.12.99 Bournemouth International Airport		
2000 (8)	04.03.00 RAF Cosford, Shropshire 24.03.00 Upwood Airfield, Cambridgeshire		

	19.04.00 2 nm north of North Weald Airfield 19.04.00 2 nm north of North Weald Airfield 12.05.00 Dunstable Downs Airfield, Bedfordshire 01.06.00 Rowley Mile Course, Newmarket, Suffolk 03.12.00 Warren Farm, Lambourne, Berkshire 30.12.00 Compton Abbas Airfield, Wiltshire		
2001 (11)	14.02.01 Davidstow Airfield 27.04.01 Sherburn Airfield, Yorkshire 11.05.01 Full Sutton Airfield, Pocklington 12.05.01 Leicester Airport 18.05.01 Withybush Airfield, Haverfordwest 19.06.01 Near Southampton Airport 23.06.01 RAF St Mawgan, Cornwall 11.08.01 1 nm N of Compton Abbas Airfield 02.09.01 Near Popham Aiirfield, Hampshire 14.09.01 Aston Down Airfield 28.12.01 Goodwood Aerodrome, West Sussex		
2002 (5)	16.07.02 White Waltham Airfield, Berkshire 21.07.02 White Waltham Airfield, Berkshire 22.08.02 Otherton Airfield, Staffordshire 03.11.02 Withycombe Farm	05.05.02 Strathallan Airfield, Perthshire	
2003 (7)	15.02.03 Bowland Forest Gliding Club, near Preston, Lancashire 29.03.03 Humberside International Airport 07.04.03 In a field close to Sandtoft Airfield, Humberside 31.05.03 Coventry Airfield 01.08.03 Horton Wood near Marlow, Bucks 06.12.03 180m west of Runway 01 threshold at Oxford (Kidlington) Airport		01.08.03 2 miles south west of Hawarden Airport, Clwyd
2004 (8)	01.02.04 Crowland Airfield, Lincolnshire 29.02.04 West Chiltington, West Sussex 30.03.04 Near Laneshaw Bridge, Colne 02.05.04 Bridge Farm, Acle, Norfolk 25.05.04 Popham Airfield, Hampshire 04.07.04 Lundy Island, Bristol Channel 28.08.04 Bournemouth International Airport 14.10.04 Wadswick Airstrip, near Cordsham, Wiltshire 16.10.04 Jersey Airport*		
2005 (10)	08.02.05 Near Horsmonden, Kent 25.03.05 Kinderton Lodge Farm, Middlewich 25.03.05 Kemble Airfield, Gloucestershire 30.04.05 Naish Farm, Clapton in Gordano, Bristol 02.05.05 Private airstrip near Keal Cotes, Lincolnshire 08.07.05 White Waltham Airfield, nr Maidenhead 09.07.05 Milfield Airfield, Northumberland 07.08.05 Bracklesham Bay, West Sussex 22.10.05 Near Biggin Hill Airport, Kent		30.08.05 Rhigos, South Wales
2006 (7)	29.06.06 Near Thirkleby Hall, North Yorks 19.07.06 Eastwood Park, Southend on Sea 22.07.06 Bournemouth Airport 30.07.06 Popham Airfield, Hampshire 05.08.06 Denham Green, Hampshire 06.08.06 On the edge of North Coates Airfield 25.09.06 Delamere, near Chester		
Total (144)	**128**	**10**	**6**
Note: The AEA report (1992) report lists 7 aircraft crashes (2 in England) whereas the ESR Technology report (2008) lists just 5 of those 7, for reasons unknown. Only these 5 have been included in the above table. *Jersey has been included as a British Crown Dependency			

Table A6 Civil helicopter airfield-related crashes (1979-2006); only years with crashes shown

Year	England	Scotland	Wales
1979 (2)			25.10.79 Gwynedd, Anglesey 13.11.79 Gwynedd, Anglesey
1981 (1)	01.08.81 Near Menthorpe, Selby		
1982 (1)		10.10.82 Aberdeen/Dyce Airport	
1984 (2)	13.05.84 Parwich, Near Ashbourne 13.09.84 Ledbury, Worcs		
1986 (1)	27.11.86 Dunkeswell		
1989 (1)	24.06.89 Thetford		
1990 (3)	27.06.90 Near Rochester, Staffs 13.07.90 Stanley, Co. Durham 31.08.90 Felsted, Essex		
1991 (1)	10.03.91 Halifax, W Yorkshire		
1996 (1)	16.12.96 Ledbury		
1997 (2)	16.01.97 Near Redhill	13.07.97 Glamis Castle, Near Forfar	
1998 (4)	28.01.98 1 nm W of Souldern Manor, near Bicester 09.03.98 Amport, Andover 26.07.98 Near Rochester Airport 10.10.98 Sulby, Near Welford		
2000 (2)	16.04.00 Carlisle Airport 02.12.00 Biggin, North Yorkshire		
2002 (1)		24.05.02 Brough of Birsay, Isle of Orkney	
2003 (2)	29.06.03 Shipdham Airfield, near Dereham, Norfolk 19.07.03 Cudham Lane South, Knockholt, Sevenoaks		
2004 (2)	03.03.04 1 mile east of Bournemouth (Hurn) Airport	19.09.04 Kentallen near Oban	
2005 (3)	08.05.05 Ockington Farm Strip, near Dymock, Gloucestershire	15.03.05 7.7 nm west-north-west of Campbeltown Airport, Argyll 21.12.05 3 nm NE of Caupor Angus, Tayside	
2006 (1)	01.06.06 West of Simon's Stone, Colliford Lake, Bodmin Moor, Cornwall		

Table A7 Civil small transport aerodrome-related crashes (1979-2006); only years with crashes shown

Year	England	Scotland	Wales
1979 (2)		31.07.79 Sumburgh Airport 01.10.79 Near Loch Leven, Tayside	
1980 (1)	23.03.80 1.5nm NW of Leeds/Bradford Airport		
1983 (1)	09.07.83 Shoreham Aerodrome		
1985 (1)	20.11.85 Rochester Aerodrome		
1986 (2)	13.03.86 Southend	12.06.86 Islay	
1987 (4)	07.04.87 Warlingham 26.04.87 Blackbushe 19.10.87 Leeds 20.10.87 Stanstead		
1991 (2)	19.05.91 Brimpton Airfield, near Aldermaston 30.06.91 Audley End, Essex		
1992 (2)	27.06.92 Woodford, Manchester 06.10.92 Prestwick		
1995 (3)	13.03.95 Near Andover, Hants 24.05.95 Near Leeds Bradford Airport 11.08.95 Fyfield, near Andover		
1996 (4)	14.07.96 Duxford Airfield 21.07.96 Near Barton Airfield, Manchester 01.09.96 Crosland Moor Airfield, Huddersfield	19.05.96 Griesta, near Lerwick	
1998 (1)	05.06.98 Dunsfold Airfield, Surrey		
1999 (1)		03.09.99 Field near Linwood, 0.5mile NW of Glasgow Airport	
2000 (3)	08.04.00 Goodwood Airfield, Chichester 14.06.00 In the Mersey Estuary west of Runway 09 threshold at Liverpool Airport 23.12.00 1nm NE of Blackbushe Airport, Surrey		
2001 (3)	02.06.01 Biggin Hill Airfield, Kent 03.06.01 Biggin Hill Airfield, Kent 06.06.01 About 1 nm east of Isle of Man Airport*		
2002 (3)	04.01.02 Birmingham International Airport 02.06.02 Duxford Airfield, Cambridgeshire	24.12.02 Aberdeen Airport	
2006 (1)	06.09.06 Duxford Aerodrome, Cambridgeshire		
Total (34)	28	6	0
*Isle of Man has been included as a British Crown Dependency			

Table A8 Civil large transport background crashes (1979-2008); only years with crashes shown.

Year	
1985	22.08.85 Manchester International Airport
1989	08.01.89 East Midlands
1994	21.12.94 Coventry
1999	22.12.99 Near Stanstead
2008	17.01.08 Heathrow

APPENDIX B – CRASH FREQUENCY CALCULATIONS

Byrne model

Crash frequency per landing and take-off movement

The ESR Technology report (Kingscott, 2002) presented an aerodrome-related crash frequency of **2.4 per million movements** (landings and take-offs were considered together) that was used in the Byrne model for deriving crash frequencies.

Location probability distributions

The probability density functions for landing and take-off accidents as used in the Byrne model were presented in section 7.2 For landing accidents, x locations before the runway threshold are represented as positive values; locations beyond the threshold are represented as negative values. The location centred at 2.5 km before the runway threshold and 3.8 km from the centreline is thus represented by x=2.5, y=3.8 using the Byrne coordinate system for landings. Substituting in x=2.5 and y=3.8 into equation (5) gives a probability (within a 1 km^2 area) of **1.74e-04 for landings.**

For take-off accidents, x locations beyond the TODA are represented as positive values. The location centred at 2.5 km after the TODA and 3.8 km from the centreline is thus represented by x=2.5, y=3.8 using the Byrne coordinate system for take-offs. Substituting in x=2.5 and y=3.8 into equation (6) gives a probability (within a 1 km^2 area) of **3.05e-04 for take-offs.**

Crash frequencies

The landing-related and take-off related crash frequencies under the Byrne model can be obtained by multiplying the aerodrome-related crash frequency by the landing and take-off probabilities of a crash at location x=2.5, y=3.8:

CL_{Byrne} = 2.4 x 1.74e-4 = 4.2e-04 per million landing movements

CT_{Byrne} = 2.4 x 3.05e-4 = 7.3e-04 per million take-off movements

Wong model

Crash frequency per landing movement

The Wong model assumes that the crash frequency is dependent on several factors such as the phase of flight (take-off or landing), the type of accident (overruns, undershoots, crash after take-off), local environment, meteorological conditions and type of aircraft. As such, it is not possible to derive a single probability that applies to all flight movements. Nevertheless, reference probabilities that apply to medium aircraft have been calculated based on the reference categories for the model variables. These reference values for LDUS and LDOR are **0.223** and **0.205 per million landing movements** respectively. These appear much lower than the Byrne frequency of 2.4 per million, however it must be stressed that these Wong reference frequencies are based on flight movements in the absence of snow, rain, strong winds, fog, etc. and are likely to underestimate the true frequency in typical everyday conditions.

Crash frequency per take-off movement

Reference probabilities that apply to medium aircraft have been calculated based on the reference categories for the model variables. These reference values for TOOR and TOC are **0.287** and **0.097 per million take-off movements** respectively. As explained for landings, it must be stressed that these Wong reference frequencies are based on flight movements in the absence of snow, rain, strong winds, fog, etc. and are likely to underestimate the true frequency in typical everyday conditions in Great Britain.

Location probability distributions

The location distributions used in the Wong model (Wong, 2007) are Weibull distributions. Separate distributions were fitted to the x and y locations for each of the different types of accidents. The complementary x and y cumulative probability distributions (CCPD) for landing undershoots, take-off overruns and crashes after take-off for the x and y locations, **expressed in feet,** are:

Landing undershoots given that the critical distance is before runway threshold: $e^{-0.01308x^{0.491355}}$ and $e^{-0.03y^{0.468}}$

Take-off overruns given that the critical distance is beyond runway end: $e^{-0.000132x^{1.342743}}$ and $e^{-0.008y^{0.840}}$

Crash after take-off given that the critical distance is beyond runway end: $e^{-0.000663x^{0.860267}}$ and $e^{-0.008y^{0.687}}$

The location centred at 2.5 km before the runway threshold and 3.8 km from the centreline is represented by x=8202, y=12467 using the Wong coordinate system for landing undershoots with critical x distance before the runway threshold (noting that 1 km is equivalent to approximately 3280.8 feet). For take-offs, the location is also represented by x=8202 and y=12467 using the coordinate system for take-off overruns and crashes after take-off with critical x beyond the runway end.

The CCPD equations may be used to derive the crash probabilities within a 1 km^2 area by taking the difference in the x cumulative probabilities at the area's x boundaries, and the difference in the y cumulative probabilities at the y boundaries. For landing undershoots, the probability of an accident between 2 and 3 km from the runway threshold (x distance) given that the critical location lies before the runway threshold is therefore

$$dX = e^{-0.01308{x_1}^{0.491355}} - e^{-0.01308{x_2}^{0.491355}}$$

Where x_1 = 2x3280.8 and x_2 = 3x3280.8.

i.e. dX = 0.0729.

Similarly the probability of an accident between 3.3 and 4.3 km from the centreline (y distance) given that the critical location lies before the runway threshold is

$$dY = e^{-0.03{y_1}^{0.468}} - e^{-0.03{y_2}^{0.468}}$$

Where $y_1 = 3.3 \times 3280.8$ and $y_2 = 4.3 \times 3280.8$,

i.e. dY = 0.0259.

The probability of a landing undershoot resulting in a final critical distance before the runway threshold is 0.743.

Therefore the probability of a landing undershoot having critical distance at a 1 km^2 area around the point x=2.5, y=3.8 (and considering symmetry about the line y=0) is: $(0.743 \times dX \times dY)/2 = 7.02e\text{-}4$. Similar calculations can be applied to derive the take-off overrun and crash after take-off probabilities at locations beyond the runway threshold.

Probability of a landing undershoot around a 1 km^2 area around x=2.5, y=3.8 is 7.02e-4

Probability of a take-off overrun around a 1 km^2 area around x=2.5, y=3.8 is 3.45e-17

Probability of a crash after take-off around a 1 km^2 area around x=2.5, y=3.8 is 3.11e-04

__Crash frequencies__

The landing-related and take-off related crash frequencies under the Wong model can be obtained by multiplying the aerodrome-related crash frequency by the landing and take-off probabilities of a crash at location x=2.5, y=3.8:

$CLDUS_{Wong}$ = 0.223 x 7.02e-4 = 1.57e-04 per million landing movements

$CTOOR_{Wong}$ = 0.287 x 3.45e-17 = 9.99e-18 per million take-off movements

$CTOC_{Wong}$ = 0.097 x 3.11e-4 = 3.02e-05 per million take-off movements

APPENDIX C - THE LICENSEE'S SAFETY CASE AND REVIEW CRITERIA FOR ONR INSPECTORS

The operator of a licensed nuclear site must be able to satisfy ONR that they understand the external threat associated with aircraft operations. In order to achieve this there need to be review criteria so that the inspectors can make rational judgements as to the acceptability of the operator's safety case for each specific licence application, renewal or transfer.

The following section has been developed by Loughborough University as guidance to the Inspectors when reviewing an individual safety case. This is not policy but for discussion and development by ONR. It is for ONR to determine if any operator's aviation-related external threat safety case should be the subject of an independent peer review prior to examination by ONR.

Reference is made in this section to the use by a licensee of the Byrne model (taken to include its updates) (Byrne, 1997), (Kingscott, 2002) (ESR Technology, 2008). The model is described here as "an average aircraft crash location and frequency model". This generalisation has been made because for several significant elements of aircraft accident location and frequency modelling, it takes an average crash rate frequency and then divides this by the mainland Britain land area. The model does not take into account several significant elements of local flight operational variations around Great Britain. The model is described in detail within Section 6.11 of this report.

Requirement One: *The licensee shall undertake a data gathering exercise to demonstrate that they understand the nature of flight operations in the vicinity of the relevant site.*

The likelihood of an aviation accident onto a licensed nuclear site is related to various location specific factors (such as the frequency of aircraft flights in the vicinity of the site) and probabilistic factors for each flight (such as the type of aircraft, the weather conditions and the phase of flight being carried out).

The documentation of the data gathering exercise shall include a description of relevant flightpaths in the vicinity of the plant associated with local airports, aerodromes, helipads etc. These shall include visual and instrument departure routes from local airports; local airport visual circuit patterns; visual and instrument arrival routes to local airports, including segregation of instrument arrivals into precision approaches and non-precision approaches with further sub-division into straight-in approaches, offset approaches and circling approaches; airport holding patterns and go-around flight tracks to be followed as part of a missed approach procedure.

The description shall include reference to en-route cruising routes as well as climb and initial descent routes in the vicinity of the site. General aviation activity in the vicinity of the site, including local flying training areas shall be described.

Military activity in the vicinity of the site shall be described and include, as a minimum, reference to low-level flying routes and training areas, weapon ranges and test/evaluation ranges as well as the general activities already described above.

Low-level flight activity by civilian aircraft, including search and rescue, coastguard, pipeline inspection, crop spraying, aerobatics and airshows in the vicinity of the site shall be described. Parachuting sites and activity near to the site shall also be identified and described. Local operations by police and ambulance fixed-wing aircraft and helicopters shall be described.

The local flying activities shall include descriptions of flights by fixed-wing aircraft, helicopters, gyrocopters, gliders, hot-air balloons and gas balloons. Operations by unmanned aerial vehicles in the vicinity of the site shall be described.

Some licensed nuclear sites allow aviation activities on-site and these shall be described including visiting civilian helicopter operations and military training flights.

The description of the local airspace around the site shall include airspace restrictions granted by Safety Regulation Group, Civil Aviation Authority and the Provost Marshall, Royal Air Force as well as any exemptions to those prohibited airspace restrictions.

The licensee would be expected to include a section relating to the time-based or aviation operational change-based review criteria for this section of the safety argument. For example, a time-based review may be carried out every five years provided that the statistics for flight operations in the vicinity of the plant have been considered at the predicted expansion rate for that period of time. This would fit in with the general review cycle of accident data that the operators appear to commission. An example of an aviation operational change may be when the local planning department consult with the licensee over a land-use planning application to open an aerodrome in the vicinity of the site. The licensee would be expected to define a management plan to keep abreast of aviation developments that may be triggers for the aviation operational review.

Requirement Two: *The licensee shall undertake an aviation specific hazard identification exercise to demonstrate that they understand the nature of the hazardous scenarios posed by flight operations in the vicinity of the relevant site.*

The hazard identification exercise shall be documented and carried out using appropriately qualified and experienced staff.

It is expected that the results of the hazard identification exercise shall include a full aircraft crash onto the site; a crash onto the site of parts of an aircraft as the consequence of an in-flight structural break-up; the skidding of an aircraft into the site following an off-site crash; the collision of parts of the aircraft having broken-up following an off-site crash but then continuing airborne to the site; and the site itself acting as an obstacle to a low-flying aircraft leading to a collision.

The requirement to identify in-flight break-up as a separate category may be necessary to ensure that the appropriate probability per flight and debris scatter areas are considered for this type of accident. The post-accident skidding of aircraft into the site shall be identified as one specific collision mechanism and the classifications of aircraft accident that imply this collision mechanism may be possible shall be identified. This is required to ensure that the appropriate probability per flight is allocated to this type of accident.

The identification of the possibility that an aircraft accident could occur off-site and then airborne parts continue a considerable distance (Ministry of Defence, 1988) into the site is required. Whilst this may be a relatively rare occurrence it will show that the hazard identification has been comprehensive. It is also required because the parts most likely to travel a considerable distance beyond the main wreckage field are engines with their associated high relative density, speed and rotational energy.

The shielding angles that may be claimed by the licensee for protection of some parts of the site against different types of accident shall be documented in the hazard identification process. This is necessary to ensure that the flight path of the aircraft considered in the analysis can be justified. The use of a single flight path angle for collisions with the site may be optimistic as different types of aircraft accident have different average descent angles and different ranges of descent angles associated with them.

It may be appropriate for the hazard identification to include comments on the collision energy that may be released and have to be absorbed by the site (linear kinetic energy, rotational energy and combustive fuel energy) as well as toxins that may be released by the aircraft (such as the use of depleted uranium and carbon fibre in the aircraft's structure) so that these may be considered in the consequence analyses following later in the risk analysis process.

The hazard identification shall document how the site may act as a vertical obstacle to safe flight, thereby inducing an aviation accident. This shall include documentation of the background conspicuity of the site in various different light and cloud cover conditions; the aviation hazard lights and other general lights displayed on-site; as well as the provision of protected airspace and arrangements for local flights including helicopters visiting the site. It should be noted that the ability to see-and-avoid will depend upon the site's conspicuity against the local terrain. The marking and lighting of the structures may assist in the prevention of a collision. This assumption would be challenged for operations taking place at night or in conditions of low cloud and/or poor visibility. It is not known what lighting strategies have been adopted by the site operators. The strategy could vary from making the plant obvious (with the disadvantage of increasing the ability of terrorist attack by air) to camouflage (with the disadvantage of decreasing the ability of the forced landing see-and-avoid manoeuvre). Compliance with the UK lighting regulations (CAA, 2011a and 2013) does not ensure that see-and-avoid will work in conditions of reduced visibility during daylight hours. There is no requirement to have obstacles lit under these conditions. Intuitively, this type of accident may be considered to be a low probability occurrence. However, it cannot be discounted as such until the licensee demonstrates the acceptability of this hazardous scenario, particularly in the light of one recent accident (AAIB, 2013). In the event of an engine failure or other minor mechanical failure, it may be possible for flight crew to avoid a licensed nuclear site prior to impact, provided that they are aware of the site and the aircraft is controllable. The documentation of this hazardous scenario should include an element of data selection and justification as to why a ratio between successful forced landings and fatal forced landings has been chosen.

The licensed site may have external interfaces for safety-related services, such as grid power and tertiary cooling water. An aviation accident may affect these services across the boundary of the site. The hazard identification shall include consideration of these interfaces.

Whilst it is recognised that the loss of these services is taken into account within other parts of a licensee's safety case, the Inspectors shall take note that the probability, frequency and continuity of service factors associated with an aviation accident as the initiating event for loss of service have been taken into account in the relevant part of the overall site safety case. For example, the collision between a hot-air balloon and the external grid power lines in the vicinity of the plant may result in the power lines being switched off for several hours during a rescue operation.

The hazard identification exercise shall also include a section reviewing the design basis and structural standards for protection against aircraft impact and the types of accident that do not need to be considered. Specific reference shall be made to the aircraft accidents that are "beyond design case" as some aircraft operations within the airspace above Great Britain have been identified in this project as falling into that category.

Requirement Three: *If the licensee wishes to argue that certain classifications of aircraft operation do not need to be considered because their mass, density, speed, rotational energy, fuel and weapon loads do not pose a post-accident consequential threat to the site then these types of flying machine shall be clearly identified and the analyses referenced, including consideration of each specific factor.*

The licensee may wish to exclude some types of aircraft from accident modelling because the safety-critical areas of the plant have been hardened against such impacts and post-impact effects. For example, gyrocopters may have: a very low frequency of flight in the vicinity of the plant; sufficiently low mass and density that their linear ballistic properties are within the design basis; sufficiently low rotational energy within the rotors and engine that their rotational ballistic properties are within the design basis; sufficiently low fuel mass and type of combustion properties that any post-impact ignition will not breach the thermal hardening protection of the safety-critical areas of the plant; and that reasonable measures have been taken to ensure that gyrocopters do not overfly the plant and avoid it by a significant distance laterally.

Requirement Four: *The licensee shall not use the provision of prohibited airspace granted by civil and military authorities as a demonstration that unintentional aircraft accidents onto the site may be discounted from further consideration.*

The rationale for this requirement is discussed in section 3.4 of this report.

Requirement Five: *If the licensee wishes to use an average aircraft crash location and frequency model, such as the Byrne model, then the licensee shall demonstrate that the flight operations in the vicinity of the site are at or below the average frequency for each specific aircraft class of concern assumed in the model selected.*

The use of an average crash distribution model is reasonable for sites that can demonstrate that flight operations in the vicinity of the plant are at or below the average frequency of flight and probability of accident per flight. This will require that the licensee identifies the average conditions assumed in the model and then demonstrates that operations in the vicinity of the site are at or below the average level. This requires consideration of the frequency of flights in the vicinity and the probability of an accident per flight to determine the average likelihood.

There is great variation in the frequency of flights within the vicinity of a site as well as the probability of an accident per flight. As an outline example only, the Dounreay licensed sites on the North coast of Scotland may have considerably fewer overflights by civilian airliners in the vicinity of the site when compared the Imperial College of Science and Technology licensed site near Ascot.

However, the Dounreay sites may have a significantly higher rate of military fast-jet traffic in low-level training routes and using the Cape Wrath bombing range for live bombing exercises.

Requirement Six: *If the licensee cannot demonstrate that an average crash location and frequency model, such as the Byrne model, can be used then more specific crash modelling of aircraft types, energies, location distribution and frequencies shall be carried out for types that pose a post-accident consequential threat to the site.*

The licensee shall use a reasonable model for the determination of aircraft crash distributions in the vicinity of the site. These models shall account for all of the types of operation mentioned unless they have been excluded under Requirement Three. The reason for selection, or development, of a particular model shall be justified.

The licensee shall use a reasonable model for the determination of aircraft crash frequency to be applied with the location model. The selection of data sets shall be justified and include appropriate allowances for relatively high probability types of accident within each class. The rate of accidents shall include justification of the flight frequencies involved as well as the probabilities.

The licensee shall include an analysis of confidence levels in the calculated crash rates onto/into the site and justify the statistical methods used to determine those confidence levels.

Requirement Seven: *The operator shall determine what portion of its safety budget shall be allocated to the aviation threat and what factor should be allocated to the unintentional crash budget.*

This is a standard risk management requirement. Further discussion is beyond the scope of this report.

Requirement Eight: *The operator shall demonstrate that the unintentional aviation-related crash risk exposure is at or below the relevant target level of safety.*

This is a standard risk management requirement. Further discussion is beyond the scope of this report.

Requirement Nine: *The operator shall demonstrate that the unintentional aviation-related crash risk exposure has been managed in accordance with relevant principles of risk management, including ALARP.*

This is a standard risk management requirement. Further discussion is beyond the scope of this report.