SANDIA REPORT
SAND2010-6721
Unlimited Release
October 2010

Assessment of Methodologies for Analysis of the Dungeness B Accidental Aircraft Crash Risk

Clifford W. Hansen and Jeffrey L. LaChance

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2010-6721
Unlimited Release
October 2010

Assessment of Methodologies for Analysis of the Dungeness B Accidental Aircraft Crash Risk

Clifford W. Hansen
Systems Engineering and Integration Department

Jeffrey LaChance
Risk and Reliability Analysis Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185

Abstract

The Health and Safety Executive (HSE) has requested Sandia National Laboratories (SNL) to review the aircraft crash methodology for nuclear facilities that are being used in the United Kingdom (UK). The scope of the work included a review of one method utilized in the UK for assessing the potential for accidental airplane crashes into nuclear facilities (Task 1) and a comparison of the UK methodology against similar International Atomic Energy Agency (IAEA), United States (US) Department of Energy (DOE), and the US Nuclear Regulatory Commission (NRC) methods (Task 2). Based on the conclusions from Tasks 1 and 2, an additional Task 3 would provide an assessment of a site-specific crash frequency for the Dungeness B facility using one of the other methodologies.

This report documents the results of Task 2. The comparison of the different methods was performed for the three primary contributors to aircraft crash risk at the Dungeness B site: airfield related crashes, crashes below airways, and background crashes. The methods and data specified in each methodology were compared for each of these risk contributors, differences in the methodologies were identified, and the importance of these differences was qualitatively and quantitatively assessed. The bases for each of the methods and the data used were considered in this assessment process. A comparison of the treatment of the consequences of the aircraft crashes was not included in this assessment because the frequency of crashes into critical structures is currently low based on the existing Dungeness B assessment. Although the comparison found substantial differences between the UK and the three alternative methodologies (IAEA, NRC, and DOE) this assessment concludes that use of any of these alternative methodologies would not change the conclusions reached for the Dungeness B site. Performance of Task 3 is thus not recommended.

CONTENTS

FIGURES

TABLES

NOMENCLATURE

AEA	Atomic Energy Authority
ARTCC	Air Route Traffic Control Center
CONUS	Continental Unites States
DOE	Department of Energy
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
MSL	Mean Sea Level
MTWA	Maximum Take-off Weight Authorized
NATS	National Air Traffic Services
NRC	Nuclear Regulatory Commission
SNL	Sandia National Laboratories
SPL	screening probability level
SRP	Standard Review Plan
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
US	United States
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy

1. INTRODUCTION

This report compares the United Kingdom Atomic Energy Authority (UKAEA) methodology for assessing the accidental aircraft crash hazard for nuclear facilities [1] to methods and standards for similar analyses issued by the International Atomic Energy Agency (IAEA) [2], United States (US) Department of Energy (DOE) [3], and the US Nuclear Regulatory Commission (NRC) [4]. Each methodology provides guidelines for quantifying the frequency of aircraft crashes for various types of aircraft and for different aviation activities. An additional methodology available in the United Kingdom (UK) developed by the National Air Traffic Services (NATS) [5] was excluded from this assessment due to the unavailability of the methodology document.

This comparison was requested by the United Kingdoms' Health and Safety Executive (HSE) Nuclear Safety Directorate in the course of their consideration of the Dungeness B nuclear power plant aircraft crash risk assessment. The Dungeness B aircraft crash risk assessment examines the external hazard posed by accidental aircraft crashes to the Dungeness B site in light of proposed expansion of the nearby Lydd Airport. The Dungeness B assessment was carried out using methods developed by UKAEA for assessing the accidental aircraft crash risk at nuclear facilities in the UK. Similar assessments are done for nuclear power facilities in the US and in other countries using different analysis methods. The comparison requested by HSE seeks to examine the extent to which the Dungeness B risk assessment's conclusions would differ if the assessment were conducted using methods employed outside the UK.

The Dungeness B aircraft crash risk assessment was previously reviewed by ESR Technology. The original review was carried out in July of 2007 [6] to address the impact of the proposed Lydd airport runway extension that would allow operation of larger aircraft at the airport. The assessment was updated in February of 2009 [7] to address the effects of updated aircraft crash rates for the UK [8]. The results of this review are confidential (UK Restricted) but address the guidance provided in the HSE Technical Assessment Guide [9]. Specific issues identified in Reference 9 include the limitations of both the UKAEA and NATS methodologies to model non-linear flight paths and the small amount of aircraft crash data on which the models have been based. To the extent possible, this report addresses whether the IAEA, NRC, or DOE methods are better suited to address these limitations.

Our comparison comprises qualitative descriptions of each methodology, supplemented by quantitative comparisons where elements of the several methodologies can be equated. We also examine whether the IAEA, NRC, or DOE methodology could be applied to an assessment of aircraft crash hazard for the Dungeness B site. Differences in the IAEA, NRC, and DOE methodologies and specified approaches related to the following items were identified and their potential effect on the conclusions of the analysis evaluated:

- categorization of aircraft and of aviation operations;
- definitions of an aircraft crash;
- the aircraft crash frequencies that are utilized and the potential effect on analysis conclusions if non-UK data were used;
- the treatment of airfield related crashes;

- the crash location models for both airfield and airway related crashes;
- the ability of the airfield crash models to reflect the Lydd Airport/Dungeness B situation; and
- the definition of effective site area including treatment of skid and shadow area.

2. COMPARISON OF METHODS

The comparison of methods for assessing the accidental aircraft crash hazard for nuclear facilities is based on the following documents:

UK1	Technical Assessment Guide: External hazards, T/AST/013 Issue 3, HSE, 2009 [9].
UK2	The calculation of aircraft crash risk in the UK, Contract Report 150/1997, prepared by AEA Technology, 1997 [1].
UK3	Background Aircraft Crash Rates for the United Kingdom, 1991-2000, IMC Report EE/GNSR/5044, prepared by AEA Technology (AEA/RAIR/LD76042/R/01 Iss. 2), May 2002 [10].
UK4	Review of Aircraft Crash Rates for the UK up to 2006, CE/GNSR/6016, prepared by ESR Technology, May 30, 2008 [8].
IAEA	External Human Induced Events in Site Evaluation for Nuclear Power Plants, IAEA Safety Guide No NS-G-3.1, IAEA, May 2002 [2].
NRC	Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition, NUREG-0800, Section 3.5.1.6 (Revision 4), U.S. NRC, March 2010 [4].
DOE	Accident Analysis for Aircraft Crash into Hazardous Facilities, DOE-STD-3014-2006, U.S. Department of Energy, May 2006 [3].

Both the HSE Technical assessment Guide (UK1) and NRC Standard Review Plan (SRP) provide guidance for reviewing aircraft crash assessments submitted for nuclear power plants. The UK1 document identifies the UKAEA methodology provided in UK2 as an acceptable approach. The NRC SRP includes an acceptable method and data within the document. The IAEA Safety Guide only provides general guidance for performing an aircraft crash assessment and does not provide specific methods. In contrast, the DOE document is a standard that includes specific methods and data for performing an aircraft crash risk assessment. All of the documents convey an expectation that the analyses are adapted to site-specific circumstances. In general, all of these methodologies share a similar analytic structure: using probability to characterize annual crash rates for different types of aircraft and different categories of aviation activity. However, the number of aircraft types and categories of aviation activity vary between the methodologies. The methodologies also differ in the level of detail provided, with more detailed guidance provided in the UKAEA and DOE methods than is found in the NRC method. Similarities and differences in analytic methods presented in the various standards are summarized here.

The UKAEA, NRC, and DOE methodologies quantify the probability of an aircraft crash using an annual crash rate. Each of these methods and the IAEA safety guide acknowledges a screening approach to hazard analysis, where the risk from aircraft crash may be deemed acceptable if the probability of aircraft crash is shown to be sufficiently low. When the probability is not sufficiently low then further analysis of the consequences of aircraft crashes are warranted. The UKAEA methodology does not specify a threshold probability value for consideration. In contrast, the NRC methodology allows for a qualitative demonstration of low probability (i.e., less than an order of magnitude of 10^{-7} per yr) of an accident resulting in radiological consequences greater than the exposure guidelines by examining the proximity of the site under consideration to airports, airways or military training areas. The DOE standard includes a screening value (10^{-6} per yr) for aircraft crash frequency below which detailed analysis of the consequences of a crash is not requested. The IAEA safety guide allows for a screening probability level (SPL) but makes no comment on a value for this quantity.

The UKAEA, NRC and DOE methodologies model aircraft crashes as a Poisson (or Bernoulli) process characterized by constant annual crash rates (or crashes per aircraft movement) per unit area. In the UKAEA methodology, this method is presented as an explicit assumption. In the IAEA, NRC and DOE documents, a similar assumption is implicit in the suggested methods for estimating the annual crash rate.

Each document distinguishes aircraft crashes by aircraft type (e.g., large aircraft, general aviation, military) and by the type of aviation activity involved (e.g., airfield-related operations and transit of airways) although the standards vary in the number of aircraft types and activity categories as summarized in Table 1. The documents also differ in their representation of different aviation activities, and in their characterization of crash location relative to runways and/or airways. Each document provides flexibility to adapt these categories and activities for the analysis of the site under consideration.

The UKAEA methodology suggests modeling crashes from aviation activities other than airfield- and airway-related activities with a background crash rate. The background rate is uniformly distributed spatially within separate regions of low and high crash concentration (e.g., military training areas). For other aviation activities, the UKAEA methodology outlines methods that account for crash location relative to runways and/or airways. The NRC SRP categorizes aviation activities as airfield-related, airway- or holding-pattern related, or resulting from general use of the designated airspace containing the site of interest. The NRC SRP assumes that crashes related to aviation activities are uniformly distributed within a defined region proximal to the runway, airway or airspace, or within the designated airspace. The DOE standard categorizes aviation activities as either airport-related or non-airport related, provides probability distributions for the location of an airport-related crash relative to the runway, and assumes that non-airport related crashes are uniformly distributed. The IAEA safety guide implicitly assumes that crash locations are uniformly distributed.

Each methodology also offers guidance on calculating the effective area of the nuclear facility. Because crash rates are given per unit area in all of the methodologies, the effective area is multiplied by the crash rate to obtain the annual frequency of crashes at the site. Guidance for determining effective area is generally consistent between the UKAEA, NRC, and DOE methodologies.

The UKAEA, NRC and DOE methodologies are supplemented by analyses that tabulate historical aircraft accidents to estimate crash rates. The IAEA safety guide does not reference similar analyses. The data provided in or referenced by each method result from analysis of historical aircraft crashes in the respective countries. With one exception, the data are for similar time periods, aircraft types and operating procedures, and thus the data should present comparable estimates of crash rates. The data in the NRC SRP for airfield related operations are taken from references dating to the 1970s, significantly predating the analyses conducted in the 1990s that support the UKAEA and DOE methodologies. The crash rate data are not normalized by the level of aviation activity in the region at the time which complicates comparison of historical crash rates between countries.

Table 1. Aircraft Types and Categories of Aviation Activities in Each Methodology

Document	Aircraft Type	Aviation Activities
UKAEA	Light civil aircraft (category 1) – fixed wing aircraft , both civil and military aircraft used for training, that are less than 2.3 tonne maximum take-off weight authorized (MTWA) Helicopters (category 2) – all civil and military helicopters Small transport (category 3) - fixed wing aircraft , both civil and military transport aircraft, that cover the MTWA range of 2.3 to 20 tonne Large transport (category 4) – any other fixed wing aircraft, civil or military, not covered in other categories Military combat and jet trainers (category 5) –all military fixed wing aircraft with MWTA up to 40-50 tonne capable of aerobatic flying	Airfield-related Airway-related Background (general and military air traffic)
IAEA	No categories defined	Airfield-related Airway-related Background (general air traffic)
NRC	Air carriers – both small and large commercial fixed wing aircraft General aviation - small fixed wing civil aircraft Military – US Navy (USN)/US Marine Corps (USMC) Military – US Air Force (USAF)	Airfield-related Airway-related Use of designated airspace Holding patterns
DOE	General aviation (civil) - Single engine reciprocating - Multiengine reciprocating - Turboprop - Turbojet Helicopters Commercial - air carriers (large commercial aircraft) - air taxis (small commercial aircraft less than 3.4 tonne (7500 lbs)) Military - large (bombers and cargo aircraft) - small (attack, fighter, and trainer aircraft)	Airfield-related Non-airfield related

In the remainder of this chapter, we first compare the categorization of aviation activities and the definitions for an aircraft crash that are used in each methodology. Next, we describe and quantitatively compare the calculation of crash rates for each method for the three categories of aviation activities used in the UKAEA methodology (airfield-related, airway-related, and background). In the quantitative comparisons, crash rates for the UK are taken from UK4 [7] and are generally consistent with the earlier values provided in UK3 [6]. We conclude by comparing the calculation of effective area of the facility between standards.

2.1. Categorization of Aircraft

In this report we organize the comparison between standards using the aircraft types and categories of aviation activities from the UKAEA methodology. Because the definitions of aircraft types and activity categories differ among the methods, here we outline how the types and categories are equated for comparison of the crash rates used in the different methodologies.

2.1.1 Light Civil Aircraft

We equate Light civil aircraft (UKAEA methodology) to General aviation (NRC and DOE) for this comparison. We note that the Light civil aircraft category in the UKAEA methodology includes some propeller-driven military training aircraft which are counted in the small Military category in the DOE standard. However, in the US these aircraft will be relatively few in number as compared to civilian aircraft and therefore we consider the General aviation category in the DOE standard to be comparable to the Light civil aircraft category in the UKAEA methodology. For comparison with the UKAEA methodology, crash rates for the four subcategories comprising general aviation in the DOE standard (single engine reciprocating, multiengine reciprocating, turboprop and turbojet) are averaged without weighting by the number of flights falling into each category.

2.1.2 Helicopters

The UKAEA methodology uses annual crash rates for helicopters per unit area for background aviation activity. The DOE standard reports annual crash rates for helicopters per overflight. Neither the NRC SRP nor the IAEA safety guide considers helicopters as a separate aircraft type. Because these quantities cannot be equated without knowledge of the number of helicopter flights, helicopter crashes are not compared between the various approaches.

2.1.3 Small Transport Aircraft

The Small transport aircraft type in the UKAEA methodology, defined in terms of maximum takeoff weight, generally equates to the Air taxi aircraft type in the DOE standard which is defined in terms of number of passengers or maximum payload weight. The NRC SRP has no comparable aircraft type; in the NRC SRP, the Commercial aircraft type includes both small and large transport aircraft.

2.1.4 Large Transport Aircraft

In the UKAEA methodology, Large transport aircraft refers to both commercial and military transport aircraft. In contrast, the Commercial aircraft type in the NRC SRP includes both large and small commercial aircraft, while in the DOE standard large transports are distinguished into commercial and military aircraft types. Thus, there are no aircraft types including large commercial transports that are directly equal between standards. For the purpose of comparison, we equate the UKAEA Large transport aircraft type to the NRC Commercial aircraft type, ignoring the difference in crash rates between large and small transport aircraft. We also equate the UKAEA Large transport aircraft type to the DOE commercial air carrier aircraft type, based on the fact that large military aircraft are not expected to operate from the Lydd airport.

2.1.5 Military Aircraft

The UKAEA methodology considers crash rates for military combat aircraft and jet trainers and includes with this type certain aircraft with similar size and mode of operations (e.g., the Tucano, a single-engine turboprop used as a military trainer). Crash rates for the UKAEA military aircraft type are equated here to those of the small military aircraft type in the DOE standard, and to the average crash rates for the two categories of military aircraft (USN/USMC and USAF) given in the NRC SRP, neglecting the difference in the number of sorties and flight operations inherent in the different crash rates. We are unable to determine whether the military aircraft categories in the NRC SRP include small fixed wing propeller-driven training aircraft, large military transports and helicopters as well as military combat aircraft and jet trainers, and assume here that military aircraft in the NRC SRP includes all of these aircraft. In the UKAEA methodology large military transport aircraft are counted in the Large transport category; some propeller-driven trainers are counted in the Light civil aircraft category; and helicopters are separated.

2.2 Categories of Aviation Operations

The UKAEA methodology groups aviation operations into three categories: airfield-related, airway-related, and background. The background aviation category includes low-level, point to point flight plans, aircraft in airport-related holding patterns, military flights and all helicopter flights. The operations categories in the IAEA safety guide mirror those in the UKAEA methodology. Both the NRC SRP and DOE standard include an airfield-related operations category. The NRC SRP includes an airway-related operations category as well as a category (use of designated airspace) roughly equivalent to the UKAEA background operations category, although in the NRC SRP, crash rates for this category are to be determined from analysis of operations within each area of designated airspace (rather than for the region or country as a whole). The NRC SRP also separates aircraft in holding patterns into a separate operations category. In contrast, the DOE standard groups all non-airport related operations into a single category (termed here non-airfield related). No general equalities are assumed here between these categories of operations. The comparison of crash rates and crash locations in the next section is organized using the categories found in the UKAEA methodology, and the comparable quantities from the other standards are discussed in turn.

2.3 Definition of an Aircraft Crash

The UK, NRC and DOE methodologies are supported by analyses of historical aircraft crashes that provide estimates of crash rates for different aircraft types and aviation activities. However the definition of an accident that is considered an accidental crash varies between these analyses. Criteria that were applied in the analyses of crashes are summarized in Table 2; additional detail is available in each referenced analysis. As demonstrated by the summary in Table 2, definitions of incidents considered as crashes vary substantially across the methodologies. As a consequence, caution should be used when comparing numerical values for crash rates between the various analyses. In this report we do not attempt to adjust the rates provided in the analyses to obtain crash rates meeting a common definition.

2.4. Airfield Related Crashes

2.4.1 Frequency of Crashes and Crash Location

The model for airfield related crashes in all standards is that of a Bernoulli process characterized by a constant crash rate per aircraft movement. The standards differ, however, in the characterization of the location of crashes relative to the runway.

The methods described in the UK standard for determining the frequency of airfield related crashes employ a model for probability that depends on location relative to the end of the runway. Using coordinates (x, y), where x (km) is oriented along a line extending the runway axis and y (km) is perpendicular to this line, the frequency of crashes g (crashes per year per unit area) at a given location (x, y) resulting from operations on a given runway is expressed as $g(x, y) = NRf(x, y)$ where N is the number of aircraft movements per year, R is the probability of an crash per movement, and $f(x, y)$ represents the conditional probability of a crash at location (x, y) given that a crash has occurred. The function $f(x, y)$ depends on the aircraft type and whether takeoff or landing is being considered; different functional forms for $f(x, y)$ are described in (UK1) for three groups of aircraft types: light civil aircraft; helicopters; and small transport, large transport and military aircraft. Parameters for each function are derived from studies of historical aircraft crashes. The frequency of crashes (crashes per year) at a given site is obtained by integrating $g(x, y)$ over the site area.

The methods described in the NRC SRP are somewhat simpler in form. The NRC SRP first permits the probability of airfield-related crashes to be assessed to be acceptably low if the distance from the site to the airport and the number of airport operations meets certain criteria. If these criteria are not met, the probability of airfield-related crashes is computed. Basically, the NRC SRP calculates the annual frequency of crashes g resulting from airfield operations as $g = NC$, where N is the number of aircraft movements and C is the probability per movement and per square mile that a crash affects the site in question. When several runways or airports may contribute to the annual crash frequency, the product NC is determined separately for each runway and summed to obtain an overall crash rate.

Table 2. Major Criteria Used to Determine Crash Rates Supporting Different Methodologies

Type of Crash	Major Criteria for Crash Analyses
UKAEA (from UK4)[a]	
Background crash rate	For civil aircraft: • Over UK mainland or within 2 miles (1.6 km) of coast • Involved fatalities or significant loss of aircraft control For military aircraft: • Accidents in damage category 4 (aircraft cannot be repaired in situ) or 5 (aircraft is total loss)
Airfield related crash rate	For civil aircraft: • Within 5 nautical miles (9.3 km) of runway threshold on approach or take-off phases • Resulted from significant loss of aircraft control • Involved fatalities or significant damage to aircraft For military aircraft: • Within 5 nautical miles (9.3 km) of runway threshold on approach or take-off phases • Accidents in damage category 4 (aircraft cannot be repaired in situ) or category 5 (aircraft is total loss)
Airway related crash rate [b]	Criteria are not clear from document UK3 [10]
NRC SRP	
Background crash rate	Crash rates not provided in standard
Airfield related crash rate	Occurred within 30° of runway centerline and 10 miles (17 km) of the end of the runway Involved fatalities
Airway related crash rate	Value based on assuming one major enroute failure per year
DOE Standard	
Airfield related crash rate	Crash occurred during takeoff, initial climb, runway approach, or landing phases Crash resulted in destruction of or major damage to airframe
Non airfield related crash rate	Crash occurred during climb-to-cruise, enroute, initial descent or airport approach phases Crash resulted in destruction of or major damage to airframe

a. Criteria in UK3 are somewhat narrower but result in similar estimates of crash rates.
b. Airway-related crash rates are not given in UK4.

The method outlined in the NRC SRP is supplemented by empirical distributions for C for several aircraft types (i.e., commercial air carriers, general aviation, and military (USN/USMC and USAF)). These distributions are given as functions of the distance between the location being considered and the end of the runway, and are more formally described here in terms of a polar coordinate system (r, θ) with origin at the end of the runway and $\theta = 0$ along the runway centerline. The frequency of crashes g (crashes per year per unit area) at a location (r, θ) resulting from operations on a given runway can then be expressed as $g(r, \theta) = NC = NC(r, \theta)$. Values for $C(r, \theta)$ are provided for $0 \le r \le 10$ miles (17 km) and $-60° \le \theta \le 60°$; the standard sets $C(r, \theta) = 0$ outside of this region. Similar to the UKAEA methodology, the frequency of crashes (crashes per year) at a given site is obtained by integrating $g(r, \theta)$ over the site area.

The DOE standard outlines an algorithm for determining the annual rate of crashes at a site due to airfield operations that is similar to that proposed in the UKAEA methodology. The rate F (crashes per year per unit area) is determined by $F(x, y) = NPf(x, y)$ where N is the number of aircraft movements per year (takeoff or landing), P is the probability of a crash per takeoff or landing, and $f(x, y)$ is the conditional probability of a crash at location (x, y) given that a crash has occurred. Different values for P and $f(x, y)$ are provided for each aircraft type and for takeoff and landing. The functions $f(x, y)$ are presented in tabular form to a greater degree of disaggregation than is found in the other methodologies. For example, different tables are presented giving values of $f(x, y)$ for small and large military aircraft, for takeoff or landing, and with and without a racetrack pattern to one side of the runway. The coordinate system (x, y) has its origin at the center of the runway, rather than at the end as in the other standard.

The IAEA safety guide generally leaves analysis of the frequency and location of airfield-related crashes to the discretion of the evaluating organization. However, the standard's guidance is broadly consistent with that provided in the DOE standard. First, at the screening stage (to determine if detailed evaluation is warranted) the IAEA safety guide suggests that airfield-related crashes may be ignored if the site is sufficiently far from airfields as quantified by a screening distance value (although no value for this quantity is suggested). If a detailed analysis is warranted, the standard remarks that crash location may be regarded to lie within a semicircle of 7.5 km in radius centered at the end of the runway, with crash locations more likely to lie within 3-4 km of the end of the runway and within 30° of the runway axis.

2.4.2 Comparison Between Standards

Based on the discussion above, the UKAEA methodology for airfield-related crash rates may be compared with the NRC and DOE methods. Our comparison considers both the probability of a crash per aircraft movement (takeoff and/or landing) as well as the probabilities of a crash at various locations given that a crash occurs.

Probability of a Crash Per Aircraft Movement

Table 3 compares the probabilities of an airfield-related crash per aircraft movement (takeoff and/or landing) for large and small transport, light aircraft (i.e., general aviation in the NRC and DOE methodologies), and military combat aircraft for the UKAEA, NRC and DOE approaches. The IAEA standard does not provide values for these probabilities. For large and small transport aircraft, a single value is provided for the NRC standard because this standard does not distinguish between the two categories of aircraft. For large transport aircraft, two values are provided for the DOE standard, corresponding to large commercial and military transports. Only the DOE standard provides separate values for takeoff and landing. The NRC standard does not explicitly provide the probability of an airfield-related crash per aircraft movement. Rather, the standard provides values for $f(r,\theta)$ that are the probabilities for a crash at location (r,θ) per aircraft movement. To obtain values for the probability of a crash per movement that can be compared with other standards, $f(r,\theta)$ was integrated over a 60º sector centered along the runway centerline (where $f(r,\theta)$ is nonzero) to obtain the results shown in Table 3.

Table 3. Probability of Crash ($\times 10^{-6}$) Per Aircraft Movement at Airfields

	UKAEA [8]	NRC [4]	DOE [3]	
			Takeoff	Landing
Large transport	0.14	0.24	0.19[a]	0.28[a]
Small transport	2.4		1.0	2.3
Light aircraft	1.9	1.0	11[b]	20[b]
Military combat	3.6	0.11	1.8	3.3

a. Commercial air carrier crash rates
b. General aviation, representative fixed wing crash rate

For large and small transport aircraft, the probabilities of a crash per aircraft movement at airfields are generally in agreement between the methodologies, differing by a factor of three or less. The order-of-magnitude difference between the UK and DOE Light aircraft crash rates likely results from differences in the definition of an event counted as a crash. The order-of-magnitude difference in the probability of military aircraft crashes between the NRC SRP and the other methods likely results from the different definitions for this category of aircraft. The UKAEA approach counts combat aircraft (i.e., small jets) and jet trainers in this category, placing large military transports in the Large transport category and some trainers in the Light aircraft category, and separating helicopters into their own category. The small military aircraft type in the DOE standard is broadly similar to the military combat aircraft type in the UKAEA methodology. In contrast, the NRC SRP appears to groups all military aircraft by military service (USN/USMC or USAF) and makes no distinction between combat, transport, and trainer aircraft, or between fixed and rotary wing aircraft.

Probability of Crash Location Conditional on Crash Occurrence

Figure 1 compares the distributions of crash location between the three methodologies. For each method, the probabilities of an airfield-related crash conditional on a crash occurrence are compared for Large transport aircraft (UKAEA) and commercial air carriers (NRC and DOE) for a site with an effective area of 500m × 500m centered at each of the indicated coordinates. The origin of the coordinate system is taken to be the end of the runway, which for the DOE standard is taken to be 4km in length. For the UKAEA and DOE methods the comparison uses the average of the separate probabilities for takeoff and landing accidents; the separate probabilities for takeoff and landing differ by less than a factor of 3. For the UKAEA and DOE approaches, probabilities are calculated by integrating the appropriate function $f(x, y)$ over the site area. The functions $f(x, y)$ are taken from the UKAEA and DOE methodology documents. For the NRC SRP, which does not specify probabilities of crash location conditional on crash occurrence, comparable probabilities are obtained by dividing the integrated value of $f(r, \theta)$ (i.e., probability of crash location within the boundaries of the site) by the appropriate probability of a crash per aircraft movement given in Table 3.

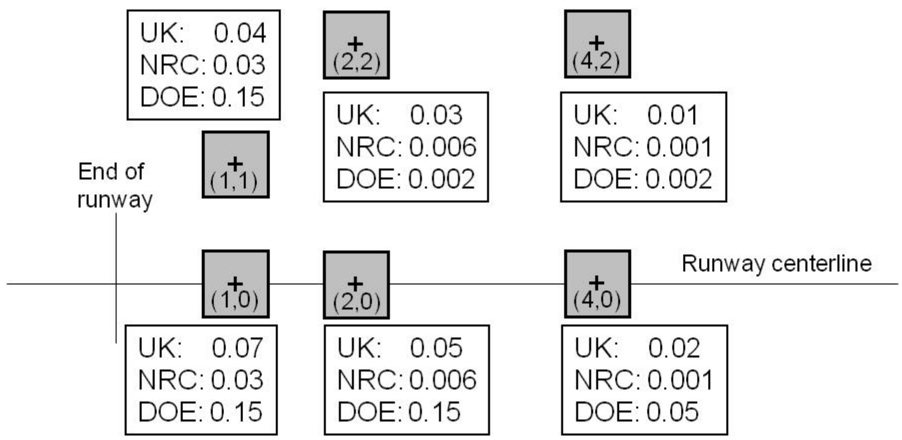

Figure 1. Probability of Crash Location Conditional on Crash Occurrence for Large Transport Aircraft.

Figure 1 shows that the DOE method considers crashes to be more likely along the extended runway centerline than in either the UKAEA or NRC method. Conversely the UKAEA method considers crashes more likely at locations offset from the runway than in the DOE or NRC methods. Comparison of crash location for other aircraft types obtains similar conclusions. We note that, except for military aircraft in the DOE standard, all three methods implicitly assume runway-aligned approaches or departures, and thus model the probability of crash location as symmetric with respect to the runway centerline. For military aircraft, the DOE standard considers near-airfield flight patterns involving racetracks that are offset from the runway and the resulting distributions for crash location are not symmetric with respect to the runway centerline. In the context of the Dungeness B aircraft crash risk assessment, this assumption is the subject of scrutiny and further investigation, and is discussed further in Section 3.4.

2.5 Crashes Related to Airways

2.5.1 Frequency of Crashes

The UKAEA approach includes a method for determining the frequency of airway-related crashes. The airway-related crash rate C_A (crashes per flight km per year) is given as

$C_A = N_A R_A \frac{afac}{alt}$ where N_A is the annual number of movements along the airway, R_A is the inflight reliability (i.e., probability of a crash per flight km along the airway), *afac* is a value obtained from a table in the UKAEA methodology document [1], and *alt* is the altitude (km) of the airway. Both N_A and R_A depend on aircraft type; values for R_A are provided in the UKAEA methodology document. The quantity *afac* assumes its greatest value when the site under consideration is under or nearly under the airway, and falls to zero when the distance from the airway centerline to the site is greater than three times the airway altitude, reflecting an assumption that crashes are normally distributed with respect to the airway centerline. Because values for C_A are anticipated to be small (e.g., on the order of 10^{-8} per year) and a Poisson model is used to describe the probability of a crash, C_A is essentially equivalent to the probability of an airway-related crash at the site under consideration.

However, the UKAEA methodology description concedes that:

1. Including both airway-related crashes and background crashes introduces some redundancy into the analysis;
2. Values for the reliability (crashes per flight km) are sufficiently low that airway-related crash rates are low compared to background crash rates.

Consequently, the discussion of airway-related crashes is included in the UKAEA methodology for completeness, and is acknowledged to be unnecessary for many sites.

In contrast, the NRC SRP requests estimates of the probability of airway-related crashes and of crashes related to aircraft operations in holding patterns. The NRC SRP uses the airway-related crash method to determine the probability of a crash from holding patterns. Airways and holding patterns are considered in the total probability of crashes only when the site under consideration is within 2 miles of the nearest edge of an airway or holding pattern.

The NRC SRP suggests determining the probability P_A of a crash from airways (and holding patterns) as $P_A = C \times N \times \frac{A}{w}$ where *C* is the inflight reliability per airway mile, *N* is the annual number of airway (or holding pattern) transits, *A* is the effective area of the plant (square miles), and *w* is the width of the airway (mile) plus twice the distance from the airway edge to the site. The UKAEA and NRC calculation methods are similar, differing somewhat in the dependence of the probability of a crash on site location relative to the airway.

The DOE method groups all aviation activities that are not airport-related into one category (non-airport related) and does not distinguish crashes related to airway transit from crashes resulting from other, non-airport related operations. Consequently, the DOE method for estimating the frequency of crashes resulting from non-airport related operations is discussed in Section 2.6.

The IAEA safety guide identifies air traffic in air corridors as a potential contributor to the probability of an aircraft crash and notes that the contribution is likely to be less than the screening probability level if the site is not coincident with a corridor. The IAEA suggests that airway-related crashes may be ignored if the site is sufficiently far from airways as quantified by a screening distance value, similar to the discussion of airfield-related crashes. No further guidance is provided regarding the calculation of the probability of a crash due to transits of air corridors.

2.5.3 Comparison Between Standards

Based on the discussion above, the UKAEA method for airway-related crash rates may be compared with the NRC method. Table 4 compares the probability of a crash per flight km along an airway, for large and small commercial transport aircraft (UKAEA categories 3 and 4), for sites with an effective area of 500m × 500m at various distances from the centerline of a 1 km wide airway at 9000m (approx. 30,000 ft) MSL (mean sea level). The UKAEA methodology document also provides values for light aircraft, helicopters and military combat aircraft. The NRC SRP provides only a value for commercial aircraft and does not distinguish between large and small transport aircraft.

Table 4. Probability of Crash ($\times 10^{-11}$) Per Aircraft Movement Along an Airway

Distance from Airway Centerline (km)	UKAEA	NRC
0	0.24	6.2
2	0.24	1.6
4	0.23	0.8
6	0.20	0.5
10	0.13	0.3

Values for the separate types of transport aircraft from the UKAEA methodology document are combined by weighting each crash rate by the number of flight kilometers estimated for the historical period from which the crash rates were obtained. An aggregate crash rate R_A for the UKAEA data is obtained as:

$$R_A = \frac{\left(3.9\times10^{-10}\ \text{crashes per km}\right)\left(1.0\times10^{9}\ \text{km}\right)+\left(4.7\times10^{-11}\ \text{crashes per km}\right)\left(4.8\times10^{9}\ \text{km}\right)}{1.0\times10^{9}\ \text{km}+4.8\times10^{9}\ \text{km}}$$
$$= 1.1\times10^{-10}\ \text{crashes per km.}$$

As indicated in Table 4, both the UKAEA and NRC methods predict a small probability of an airway crash on a 500m x 500m target area. The NRC method predicts a more rapid decrease in the crash probability as the distance between the airway and the target area increases than does the UKAEA methodology.

2.6 Background Crashes

2.6.1 Frequency of Crashes

The UKAEA methodology uses a background crash rate to represent the possibility of an aircraft crash that affects the site under consideration that does not result from airfield operations or transit of airways. Values for the background crash rates are given for different aircraft types in Reference 8. Except for military aircraft (UKAEA category 5), locations of crashes represented by the background crash rate are uniformly distributed spatially. For military aircraft, one rate is used for areas that are not within areas of high crash concentration (e.g., military training areas), a different rate is applied to areas of high crash concentration and a smoothing algorithm is suggested to continuously vary the crash rate in the transition zones between areas of high crash concentration and the surrounding areas.

The NRC SRP requests an analysis of all aviation operations in airspace in the vicinity of the site under consideration consistent with their designated uses (e.g., general aviation, military training). The analysis is to quantify the probability (per year) of a potentially damaging crash at the site resulting from aviation operations that are not associated with airfields or airways. No further guidance on the methods for this analysis is offered.

The DOE standard groups all aviation activities that are not airport-related into one category, non-airport related activities, and thus this grouping comprises both the airway-related and background crash rates described in the UKAEA methodology. The frequency of non-airport related crashes at a location (x, y) within the continental United States is determined by $F = NPf(x, y)A$ where the NP is the expected number of non-airport related crashes per year (conceptually, N is the number of aircraft operations and P is the probability of a crash per operation), $f(x, y)$ is the conditional probability of a crash per square mile at location (x, y) given that a crash has occurred, and A is the effective area (square miles) of the facility under consideration. Values for the product $NPf(x, y)$ are provided for several aircraft types and for a number of locations in the U.S. of interest, along with a value appropriate for the U.S. generally. Values for the individual factors in $NPf(x, y)$ are not given.

The IAEA safety guide acknowledges that general air traffic in the region contributes to the probability of an aircraft crash at the site under consideration. The IAEA states that, for the purpose of determining the probability of such an event, the site may be considered to be a circular area between 0.1 and 1 km^2 within a circular region of 100-200 km in radius. Presumably, the crash location is uniformly distributed throughout the region, and from this perspective the IAEA suggested approach is similar to the background crash rate for low crash concentration zones in the UKAEA methodology. The IAEA safety guide provides no guidance on determining the probability per unit area of a crash within the region.

The IAEA safety guide regards military aviation operations as occurring primarily within the defined airspace. Thus the IAEA approach would allow a judgment that the probability of a crash at the site under consideration resulting from military operations is acceptably low if the site is sufficiently far from military routes and airspace. However, the IAEA safety guide concedes that this judgment requires justification by an analysis of military aviation operations in the vicinity of the site and provides no specific guidance pertaining to the conduct of this analysis.

2.6.3 Comparison Between Standards

Based on the discussion above, only the DOE standard offers sufficient detail regarding background crash rates that quantitative comparison with the UKAEA methodology may be considered. However, direct comparison of background crash rates from the UK [8] with the non-airport-related crash rates from the DOE standard is problematic. Crash rates are not directly comparable between the UK and DOE documents, because the crash rates in both implicitly reflect the level of aviation activity in the geographic region. For example, the crash rates given in the DOE standard for the Sandia National Laboratory site in Albuquerque, New Mexico are derived from crash data and level of aviation activity in the Albuquerque Air Route Traffic Control Center (ARTCC) region (generally comprising the states of New Mexico and Arizona and part of the state of Texas). In contrast, the crash rates in Reference 8 are for the United Kingdom at large. Neither document attempts to normalize the crash rates by the level of aviation of activity (e.g., per flight mile or some other normalizing quantity). Obtaining crash rates from the DOE standard that can be equated to the background crash rates in the UK would require extensive reanalysis of data underlying the DOE standard to separate airway transits from other aviation activity and to normalize crash rates by the level of aviation activity in the region.

With these caveats, Table 5 compares the probability of a crash per year, per square kilometer, resulting from background aviation between the UKAEA and DOE methodologies. Values shown in Table 5 are the quantities $NPf(x,y)$ for the DOE standard. In the DOE standard, values are given for the continental United States (CONUS) generally as well as for two sites located within different regions: Sandia National Laboratories in Albuquerque, N.M. and Argonne National Laboratory in Argonne, IL. Sandia is located within the Albuquerque ARTCC region which handled approximately 11 million aircraft between 1975 and 1994 (the time period from which the crash rates are derived) and Argonne is located within the Chicago ARTCC which handled approximately twice as many aircraft during this period.

Table 5. Probability of Crash ($\times10^{-5}$) Per Year and Per Square Kilometer for Non-Airfield and Non-Airway Operations from the DOE Standard

Aircraft Category	UKAEA	DOE		
		CONUS	Sandia	Argonne
Light aircraft	2.04	7.7	38	116
Small Transport	0.26	0.039	0.01	0.15
Large Transport	0.11	0.015	0.008	0.03
Military Combat (Away From Military Areas)	0.41	0.15	0.19	0.03

Data for the UK standard are taken from UK4 [8]; results are similar to those presented in UK3 [10]. Data for the DOE standard are from Tables B-14 and B-15 of Reference 3. For the purpose of comparison across standards, background aviation is defined here to comprise aviation activities that are not associated with airfields and airways. The Large transport category in the UKAEA methodology is equated to the Commercial air category in the DOE standard. Crash rates for air taxis in the DOE standard are equated to crash rates for small transport aircraft in the UKAEA methodology. For the UKAEA methodology, results are shown for military combat aircraft for areas away from military operations areas. The UKAEA approach also provides background crash rates for areas of high military flight activity. The DOE standard does not provide military aircraft crash rates for areas of intensive military flight activity (e.g., low-level flight operations) although crash rates are provided for locations adjacent to such areas (e.g., the Nevada Test Site). The DOE standard provides crash rates for helicopters per overflight that are not comparable to the UK rates which are given per unit area.

2.7 Effective Area

The UKAEA, NRC, and DOE methodologies all compute crash rates per unit area. To determine the annual probability of an aircraft crash at a facility, the crash rate is multiplied by the effective area of the facility under consideration. The effective area is the ground area in which, should a crash occur, the crash could affect the facility's safety.

2.7.1 Calculation of Effective Area

Guidance for determining effective area is generally consistent between the three methodologies, although some of the methodologies provide more detail than others. All three methodologies enlarge a site's horizontal footprint by adding a shadow area around this footprint to account for the aircraft descent angle and the aircraft wingspan. Because descent angles and wingspans vary among aircraft types, the effective area in turn depends on aircraft type. Each methodology also acknowledges the possibility that the effective area could be increased by aircraft skidding into the facility after impact.

In the UKAEA methodology, the effective area (without skidding), A_E, is usually computed by $A_E = lw + \frac{2}{\pi} kh(w+l)$, where $l, w,$ and h are the length, width and height of a cuboid representing the facility of interest, k is a factor dependent on aircraft type, and the factor $\frac{2}{\pi}$ arises from averaging the effective area around all angles of the aircraft approach. The first term in the formula (lw) is the horizontal footprint of the cuboid; the second term ($\frac{2}{\pi} kh(w+l)$) is the average shadow area around the site. Facility length and width are each increased by twice the aircraft wingspan, where necessary for the purpose of the analysis. The factor k is obtained as the expected value of $\cot\theta$ where θ is a random variable for the aircraft descent angle. Historical data on aircraft crashes were analyzed to obtain empirical distributions for θ for three groups of aircraft: (i) light aircraft, small and large transports, and military combat aircraft when accidents initiate above 2000 ft; (ii) military combat aircraft when accidents initiate below 2000 ft; and (iii) helicopters. Values for the quantity $\frac{2}{\pi}k$ are provided in the UKAEA methodology document [1].

When descent angles are low, skidding may result in impacts onto a facility from a crash that does not directly impact the facility. A formula for skid distance S is provided as $S = V^2 / 2\mu g$, where V is the aircraft velocity on impact, μ is the coefficient of friction and g is the acceleration due to gravity. The skid distance is multiplied by a characteristic width to obtain an area. Because the standard does not specify a particular characteristic width to be used the analyst must determine an appropriate width for the facility under consideration. The UKAEA methodology acknowledges that this formula could yield unreasonably long skid distances. The UKAEA methodology encourages site-dependent analysis of nearby structures and terrain features such as berms that may reduce the likelihood of skidding impacts, as well as consideration that the effects of a skidding impact may be reduced compared to the effects of a direct impact.

The NRC SRP provides similar expectations for the determination of a site's effective area. The calculation of effective area involves adding the shadow area to the site's footprint to account for descent angle and considering aircraft skidding. However, no particular calculation approach is outlined and no formula or empirical data are provided to support the calculations.

The method outlined in the DOE standard is similar to that found in the UKAEA methodology. However, the DOE standard makes the simplifying conservative assumption that the direction of the aircraft is normal to the longest diagonal of a rectangle enclosing the facility (*R* in Figure 2, reproduced from Figure B-3 in Reference 3), instead of assuming that the direction of aircraft approach is random, as is done in the UKAEA methodology. In the DOE standard, the effective area A_E is computed as $A_E = A_f + A_S$, where A_f is the sum of the facility footprint and shadow area (fly-in area) and A_S is the area added to account for aircraft skidding after impact. These quantities are computed by

$$A_f = (WS + R)H\cot\phi + \frac{2L \times W \times WS}{R} + L \times W \tag{1}$$

and

$$A_S = (WS + R)S \tag{2}$$

where WS is the aircraft wingspan, R is the length of the longest diagonal, L, W, and H are the length, width and height, respectively, of a cuboid enclosing the facility, ϕ is the angle of descent, and S is the skid distance. Implicitly, the DOE standard defines the boundary of the effective area by the location of impact of the aircraft fuselage, whereas the UKAEA methodology considers the aircraft wingtips as defining the boundary of the effective area. Representative values for WS and mean values for $\cot\phi$ and S are provided for commercial aviation (i.e., small and large transports), general aviation (i.e., light aircraft), helicopters, and military aviation. For military aviation, no distinction is made in the DOE standard based on the altitude at which the crash initiates; however, separate values are provided for large and small military aircraft and for take-off and landing.

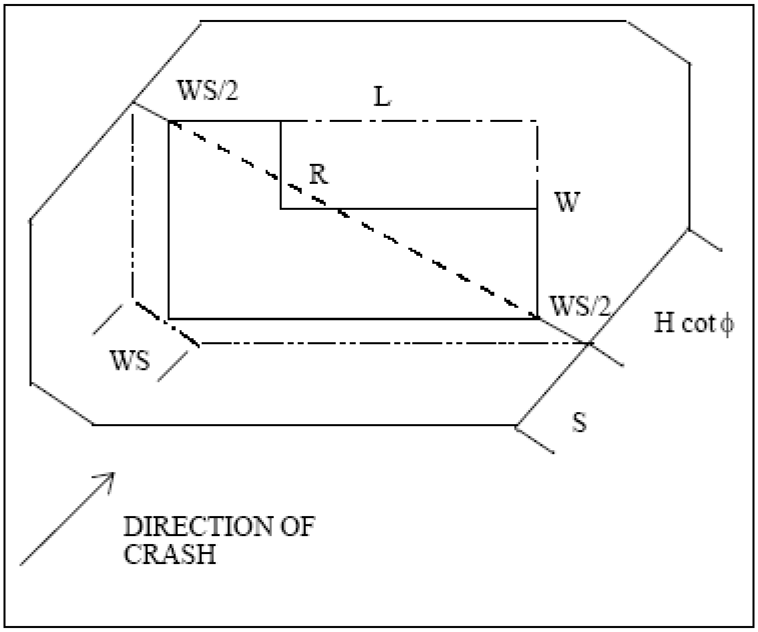

Figure 2. Effective Area Calculation in the DOE Standard.

The DOE standard cautions the analyst against relying on the calculation in Eq. (1) and Eq. (2) without considering additional features of the site. For example, the standard counsels that if a facility's critical areas (i.e., those areas which, if impacted by a crash, would compromise the facility's safety) are a small fraction of the facility's dimensions that this fact must be reflected in the analysis (presumably by reducing the effective area). Also, the area added to account for skidding may be reduced by the presence of nearby structures or features that may limit impacts from aircraft skidding or may constrain the impact angle such that a value other than the provided mean should be used.

The IAEA standard discusses the determination of effective area in qualitative terms that are broadly consistent with the other standards.

2.7.1 Comparison Between Standards

Effective areas for direct (not skidding) impacts resulting from the methods outlined in the UKAEA and DOE methodologies may be compared quantitatively. The additional area due to skidding is not compared here because the UKAEA guidance is somewhat ambiguous as to the determination of this area.

Assuming an unshielded facility with dimensions 100m × 50m × 10m and a commercial transport with wingspan of 30m, the UKAEA method obtains a value for the effective area of 19700 m^2 where the length and width of the facility have been increased by twice the wingspan.

For the same facility and aircraft, the DOE standard produces a value for the fly-in area A_f of 22000 m^2. For a small transport aircraft with wingspan of 18m, the UKAEA method yields an effective area of 13500 m^2, compared to a value of 19800 m^2 from the DOE method. The effect of wingspan is more pronounced in the UKAEA methodology as compared to the DOE standard because wingtip rather than fuselage location is used to determine the boundary of the effective area. However, the angle corresponding to the mean value for the cotangent of the descent angle is greater in the UKAEA method (38° for transport aircraft) than in the DOE standard (5.6°), resulting in greater values for $\cot\phi$ in the DOE standard than in the UKAEA approach. Regardless of these differences, both standards produce similar values for the effective area.

3. USE OF ALTERNATIVE STANDARDS

Here we consider whether an assessment of aircraft crash risk could be carried out for the Dungeness B site, using the methods set forth in the IAEA, NRC or DOE methodologies. Where an assessment appears to be feasible using one of these three methodologies, we comment on whether the assessment's conclusions would be substantially different than those obtained using the UKAEA method.

The Dungeness B site is offset from the extended centerline of the Lydd Airport by roughly 3 km downrange of the southern end of the Lydd runway and is offset from the runway centerline by approximately 4 km. The Dungeness B aircraft risk assessment concludes that the risk of radiological release from the aircraft crash hazard primarily results from the background crash rate, comprising roughly 90% of the total risk. The analysis concludes that the risk associated with operations at the Lydd airport comprises roughly 10% of the total, and that the contribution to risk from airway transits is negligible.

Our consideration of alternative methodologies focuses on the annual probability that a crash may occur that affects the site in question. This probability is generally obtained by multiplying annual crash rates per unit area by the site’s effective area. However, as discussed in Section 2.7, calculation of a site’s effective area is similar among the various methodologies. Consequently our discussion here focuses on the different annual crash rates that may be obtained using the different standards.

We conclude by discussing an issue of specific interest to the Dungeness B aircraft crash risk assessment: the assessment of aircraft crash risk from airfield-related operations in circumstances where approaches to the airfield are constrained by terrain and/or restrictions on airspace use.

3.1 IAEA Safety Guide

We find that the UKAEA methodology and the analysis methods outlined in its supporting documents are broadly consistent with the guidelines in the IAEA safety guide. Consequently, we conclude that an analysis for the Dungeness B site conducted using the IAEA safety guide *ab initio* would not reach substantially different conclusions.

3.2 NRC SRP

Only the airfield- and airway-related components of the risk at the Dungeness B site may be estimated using the NRC SRP, because this approach does not provide a method for estimating crash rates from background aviation activity. For airfield-related operations, the probabilities per movement of a crash are similar for large transport, small transport and light aircraft between the UK and NRC sources (see Table 3). Given that a crash occurs, the probability for the crash to be within a 500m × 500m location offset from the runway centerline by 3 km downrange and 4 km cross range (similar to the Lydd airport and Dungeness B site) is estimated to be 0.018 using the UKAEA method (average value of takeoff and landing probabilities) but is 0.001 when the NRC method is used. Consequently, if the contribution to risk from airfield-related operations were analyzed using the NRC method and data, the result would be less than is obtained with the UKAEA method and UK data. We reach this conclusion despite the age of the airfield-related crash data that supports the NRC SRP.

We are unable to quantitatively compare the contribution to risk from airway transits between the UKAEA and NRC methods. However, this contribution to risk was qualitatively assessed to be negligible in the Dungeness B aircraft crash risk assessment. The probability of a crash resulting from airway transits is higher in the NRC method by roughly one order of magnitude (Table 4) for sites that are close to the airway (i.e., within 4 km of the airway centerline) but much lower (effectively zero) for sites that are farther away. Thus, unless an airway is proximal to the Dungeness B site, the conclusion that airway-related operations present a negligible contribution to risk would also hold if the assessment were conducted with the NRC methodology.

3.3 DOE Standard

Only the airfield-related component of the risk at the Dungeness B site could be estimated using the DOE standard, because crash rates for non-airfield-related operations in the DOE standard rely on data representative of operations within regions of the United States that are not normalized to the level of aviation activity. For airfield-related operations, the probabilities per movement of a crash are similar for large transport, small transport and military aircraft between the UK and DOE sources (see Table 3). The probability of a crash per movement for light aircraft is an order of magnitude greater in the DOE standard than in the UK [8]. Given that a crash occurs, the probability for the crash to be within a 500m × 500m location offset from the runway centerline by 3 km downrange and 4 km cross range (similar to the Lydd airport and Dungeness site) is estimated to be 0.018 using the UKAEA methodology (average value of takeoff and landing probabilities) but is 0.0015 for commercial aircraft and 0.0033 for general aviation when the DOE standard is used (average of separate probabilities for takeoff and landing). Consequently, if the contribution to risk from airfield-related operations were analyzed using the DOE method and data, the result would be similar to that obtained with the UKAEA method and UK data. We reach this conclusion despite the differences between the light aviation category in the UKAEA methodology and the general aviation category in the DOE standard.

The methods for estimating the contribution to risk from background aviation (i.e., non-airfield and non-airway related) are conceptually similar between the UKAEA and DOE methodologies. Both methods estimate a crash rate for a geographic region by tabulating the number of crashes occurring during a period of time and assuming these crashes is randomly distributed throughout the region, thus obtaining a crash rate per unit area. However, the analyses of historical data referenced by the two methodologies produce crash rates that implicitly (and properly) reflect the level of aviation activity within the region. Thus, if the DOE standard were used to estimate the contribution to risk from background aviation, the analysis would necessarily employ crash rates derived from UK data rather than US data. Therefore, the contribution to risk from background aviation would be similar for either method.

3.4 Treatment of Constrained Approaches to Airfields

Reviews of the Dungeness B aircraft risk assessment indicate that considerable concern may be present regarding the appropriateness of the assumption of runway-aligned approaches and the effect of this assumption on estimates of the location of airfield-related crashes. At the Lydd airport, it is possible that runway-aligned approaches may not be possible at all times due to runway geometry and the presence of nearby restricted airspace. Reference 7 discusses two possible approaches to Lydd airport Runway 03 that would involve flight towards the Dungeness B facility: approach from the northeast, overflight of the runway, followed by anticlockwise turns to a Runway 03 aligned approach; and approach from the northwest followed by a left turn to align with Runway 03. If these approaches are in use, because the Lydd airport is offset from the extended runway centerline, it is possible that part of an aircraft's flight path may involve flight towards the Dungeness site. As described in Reference 7, the Dungeness B aircraft risk assessment is conducted in accordance with the UKAEA methodology, which implicitly assumes runway-aligned approaches.

We considered whether the NRC or DOE methodologies provide a means to better represent the particular circumstances for the Lydd-Dungeness situation than is provided by the UKAEA methodology. The methods outlined in the NRC SRP assume runway-aligned approaches and departures. Thus, the burden of adjusting the method to accommodate site-specific circumstances is transferred to the analyst. The NRC SRP requests analysis of the contribution to risk from aircraft in holding patterns which could serve as a model for the Lydd approach paths. However, the NRC SRP specifies estimating crash frequencies for aircraft in holding patterns by using the data provided for airway transits. Use of airway-related data is unlikely to be considered appropriate to estimate crash rates for aircraft that are descending to or ascending from an airfield. We conclude that the NRC SRP does not offer a better analysis methodology for the Lydd situation than is provided in the UKAEA methodology.

Except for military aircraft, the DOE standard also assumes that takeoff and landings are aligned with extended runway centerlines. For military aircraft, the DOE standard provides empirical distributions for crash locations when aircraft fly racetrack patterns near the airport. One leg of these racetrack patterns typically aligns with the runway centerline, with the other leg offset from and parallel to the runway. Upon entering the racetrack, aircraft overfly the runway along the runway centerline, execute a turn beyond the runway threshold, transit the offset leg, then make a final turn to align with the runway for landing.

The constrained approaches to the Lydd airport are somewhat similar to an offset racetrack, in that turns are made near the runway threshold to align with the runway. However, it is not apparent that the DOE standard's empirical distributions for crash location could be appropriately used in analysis of the Lydd airport situation.

The empirical distributions in the DOE standard (for military aircraft in racetrack patterns) count aircraft crashes as occurring during landing if the crash occurred at any point after the aircraft altitude is 'affected by its proximity from (sic) the approach runway to its departure from the runway under a controlled taxi.' Also, an aircraft that experiences trouble during takeoff, is retained under some degree of pilot control, but crashes during an attempt to return to the airfield is counted as a landing crash in the DOE standard. Consequently the distributions for crash location given in the DOE standard are derived from a set of crashes that includes a variety of flight phases not relevant to the constrained approaches to Lydd. Moreover, the distributions for crash location are not provided conditionally for specific parts of an aircraft flight path (e.g., transit of racetrack legs, turns), so there is no means of separating crashes that initiated during transit of those portions of the racetrack that are similar to the constrained approaches at Lydd. Finally, distributions of crash location for racetrack patterns are given only for military aircraft. Although large military aircraft (i.e., bombers and transports) are separated from military combat and training aircraft, application of the distributions for crash location would necessarily involve equating military aircraft types to the largely civilian aircraft anticipated to be operating at Lydd.

For these reasons, we conclude that the DOE standard does not offer a clearly better method to address concerns about the contribution to risk at the Dungeness B site arising from constrained approaches at the Lydd airport.

4. CONCLUSIONS

In this report we compare methodologies issued by UKAEA, the US NRC, the US DOE and the IAEA for assessing the hazard to nuclear facilities due to accidental aircraft crashes. We qualitatively compare the types of aircraft and categories of aviation activities considered in each standard and the definition of a crash that is used in analyses of historical aircraft crashes that support the various standards (Section 2.1). We also compare crash rates between the standards where quantitative comparisons may be made (Sections 2.4 – 2.6) and the calculation of the effective area of a facility (Section 2.7).

We found that the methodologies generally reflect similar approaches to analysis of aircraft crash hazard. Except for the IAEA safety guide, the reviewed methodologies are supported by analyses of historical aircraft crashes that quantify crash rates for each aircraft type and category of aviation activity. The methodologies differ, however, in the number of aircraft types and categories of aviation activities, in the definitions the types and categories, and in the definition of an aircraft crash that could potentially affect a nuclear site. The methodologies employ substantially different models for the location of a crash relative to a runway or airway. Moreover, the analyses use historical data that are specific to either the UK or the US and present crash rates that are not normalized by the level of flight activity in either country. Thus direct comparison of crash rates is problematic.

Despite the differences between the methodologies, in Section 3.0 we consider whether the hazard assessment for the Dungeness B site could be conducted using either the NRC or DOE methods rather than the UKAEA methodology. We conclude that the hazard assessment could be partially carried out using the NRC method, and if this assessment were done, the contributions to risk from airfield and airway related operations would not be substantially different. We also conclude that the hazard assessment could be more fully conducted using the DOE standard, and if done, the assessment would reach similar conclusions as are obtained using the UKAEA methodology. However, neither the NRC nor the DOE methods offer a clearly better method for the hazard assessment, and in particular, neither method appears to be better suited to address concerns about constrained approaches to the runway at the Lydd airport.

4. REFERENCES

1. HSE, *The calculation of aircraft crash risk in the UK*, Contract Research Report 150/1997, prepared by AEA Technology, (1997). ISBN 0 7176 1447 6.
2. IAEA, *External Human Induced Events in site Evaluation for Nuclear Power Plants*, NS-G-3.1, International Atomic Energy Agency, May 2002.
3. US DOE, *Accident Analysis for Aircraft Crash into Hazardous Facilities*, DOE-STD-3014-2006, U.S. Department of Energy, October 1996, Reaffirmation May, 2006.
4. US NRC, *Standard Review Plan, 3.5.1.6 Aircraft Hazards*, NUREG-0800, US Nuclear Regulatory Commission, Revision 3, March 2007.
5. *A Methodology for Calculating Individual Risk Due to Aircraft Accidents near Airports*, NATS R&D Report 0007, 2000.
6. ESR Technology, *Lydd Airport Planning Application: Review of Dungeness B Aircraft Impact Hazard Analysis*, ESRT/D0010905/001/Draft, 18 July 2007
7. ESR Technology, *Dungeness Aircraft Crash Risk: Updated Review of Assessment*, ESRT/D0010910/001/Draft 1, 23 Feb 2009
8. *.Review of Aircraft Crash Rates for the UK up to 2006*, CE/GNSR/6016, prepared by ESR Technology, May 30, 2008
9. HSE, *Technical Assessment Guide: External Hazards*, T/AST/13 – Issue 3 (2009).
10. *Background Aircraft Crash Rates for the United Kingdom, 1991-2000*, IMC Report EE/GNSR/5044, prepared by AEA Technology (AEA/RAIR/LD76042/R/01 Iss. 2), May 2002.

Sandia National Laboratories