Health and Safety
Executive

Failure Rate and Event Data for use within Land Use Planning Risk Assessments

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Failure Rate and Event Data for use within Land Use Planning Risk Assessments

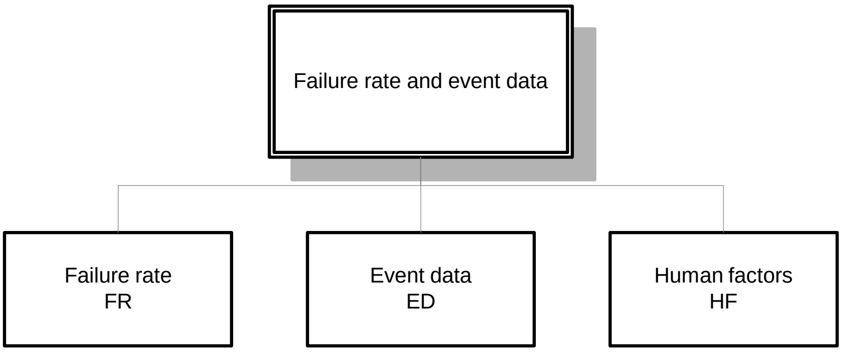
Introduction

1. HID CI5 has an established set of failure rates that have been in use for several years. This Chapter details those items and their failure rates. For items not within this set, or for which no values are currently available the inspector carrying out the assessment should estimate failure rate\s after discussions with Topic Specialists. The failure rates quoted within this document were derived and are intended for use on Land Use Planning cases. They were NOT originally intended for use in COMAH Safety Report Assessment because they do not necessarily take account of all factors that could be relevant and significant at particular installations. However, in the absence of site specific data, the values given here may serve as a starting point for safety reports.

2. Figure 1 shows the different types of information that are available in this chapter. For the full structure, see Figure 2.

3. Figure 2. This introductory section of PCAG also outlines a framework used in HID CI5 to keep references pertaining to failure rates and a system for recording the use of non-generic failure rates used in particular cases.

Figure 1 Information covered in Chapter 6K



4. The first section of this Planning Case Assessment Guide (PCAG) chapter covers failure rates. HID CI5 currently has established failure rates or has some information for most of the items. The items on the diagram in Figure 2 contain a failure rate value(s) and a brief derivation. For rates that have ranges the derivation also contains a brief guide on what factors may affect the value.

5. The second section contains information on event data. The derivation of the rates to be used and how to use them are described.

6. The third section covers human factors. This section will be added at a later date.

Generic Failure Rates

7. Many of the failure rates used in risk assessments within HID CI5 are based on values derived for RISKAT (RISK Assessment Tool) as detailed in the various parts of the Major Hazards Assessment Unit (MHAU) Handbook (now archived). These generic rates were derived in the early 1980’s when MHAU was first formed and have an established pedigree. They were originally derived in the context of assessing risks from chlorine plants. They have been added to and amended as needed in order to assess different types of plant and

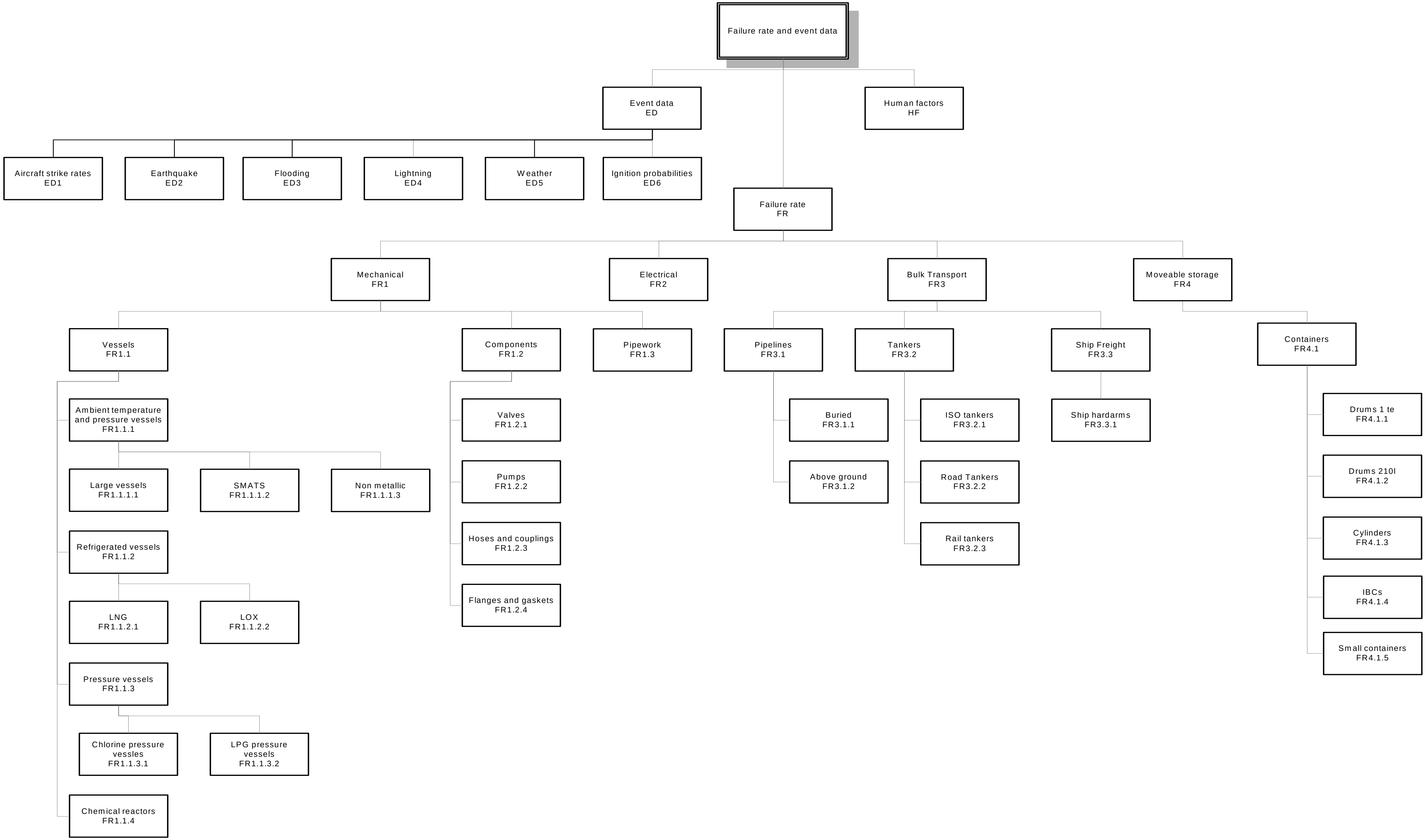
operations and Figure 2 has been extended accordingly. The value, type of release and derivation can be found in this chapter for the items shown in Figure 2. The assessor needs to decide whether or not the generic failure rates are appropriate for their assessment; if the generic failure rate is inappropriate then further work is required to derive a suitable specific failure rate.

Non Generic Failure Rates

8. The application of these generic failure rates to items being used for substances, processes and plant designs that might induce particularly arduous operating conditions or, alternatively, provide for increased reliability is a matter of judgement by the assessor. The greatest difficulty in assigning failure rates is the lack of appropriate industry failure rate data but, in the absence of failure rate data specific to particular plant, processes and substances, the generic values given in this section should be used as a starting point. These generic values can be modified to take account of site-specific factors. The specific failure rates are determined by expert judgement by the Topic Specialist, taking account of significant factors along with any specific data available. In this case, the Topic Specialist will record the recommended rates in a Failure Rate Advice (FR) note.

9. When non-generic values are used in HID CI5 assessments they should be justified and the reasoning behind their derivation recorded within an FR note. If the assessment case is panelled for peer review the relevant FR note should be presented with the case so that HID CI5 inspectors can endorse the value(s) used.

Figure 2 Overview of PCAG 6K structure



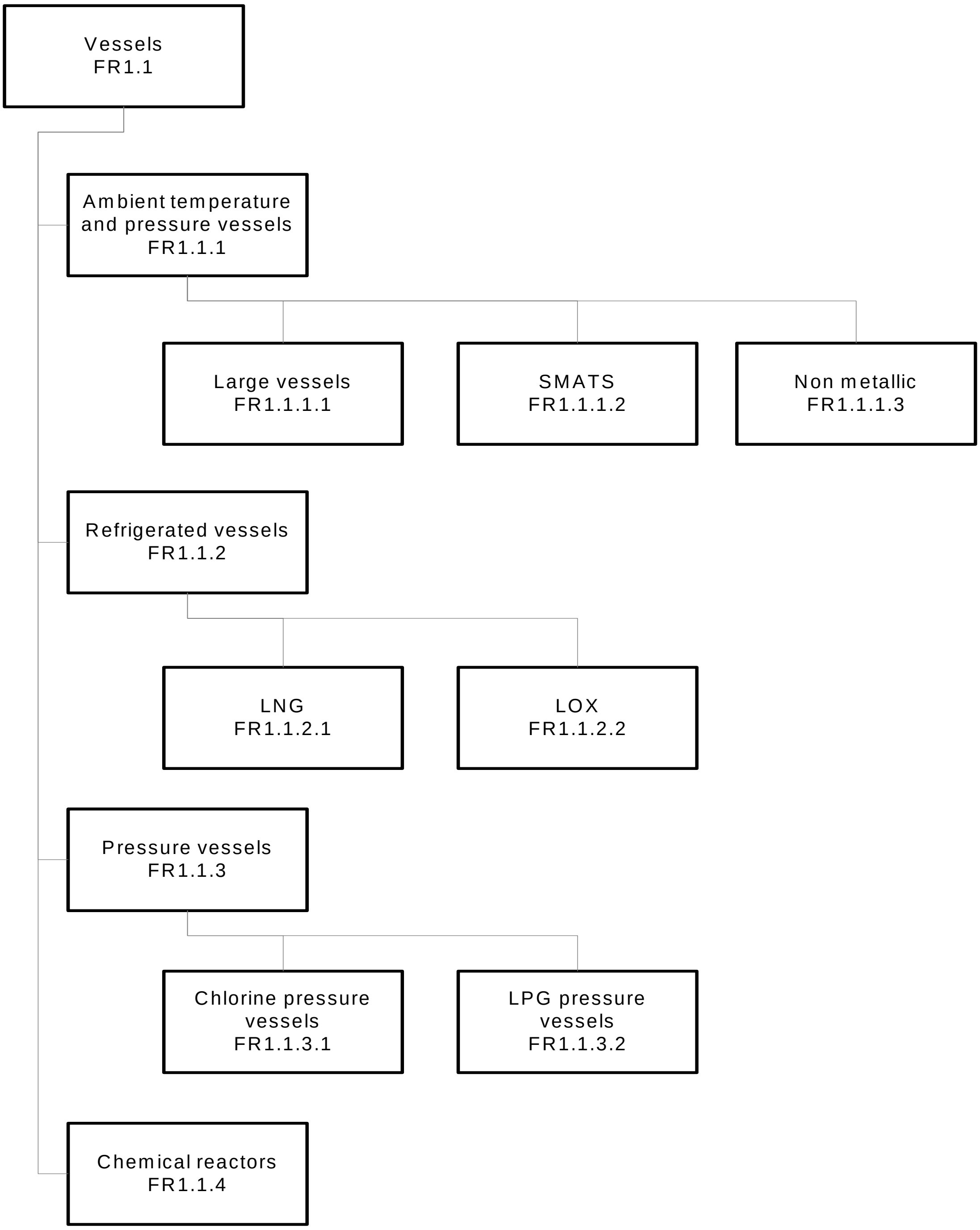
Item FR 1 Mechanical

10. Failure rates for equipment classified as mechanical are categorised as follows:

Item FR 1.1 Vessels

11. Failure rates for vessels are split into four categories that are further subdivided as shown in Figure 3 below. These vessels refer to fixed storage. Moveable storage (e.g. drums) are considered under Item FR 4.

Figure 3 Hierarchical Diagram for Vessels



Item FR 1.1.1 Ambient Temperature and Pressure Vessels

12. Ambient temperature and pressure vessels are divided as follows. Ambient pressure may be extended to cover vessels at slightly elevated pressure.

Item FR 1.1.1.1 Large Vessels

ITEM FAILURE RATES

Type of Release	Failure Rate (per vessel yr)	Notes
Catastrophic	5×10^{-6}	
Major	1×10^{-4}	
Minor	2.5×10^{-3}	
Roof	2×10^{-3}	

RELEASE SIZES

	Hole diameters for Tank volumes (m^3)		
Category	>12000	12000 – 4000	4000 - 450
Major	1000 mm	750 mm	500 mm
Minor	300 mm	225 mm	150 mm

Derivation

13. The failure rates apply to fixed position, single walled vessels with a capacity greater than $450m^3$, which operate at ambient temperature and pressure.

14. Roof failures includes all failures of the roof but does not include liquid pooling on the ground. For vessels that are storing flammable liquids, this could lead to a flammable atmosphere being formed and possible ignition and escalation. For tanks that store toxic chemicals a toxic cloud could be formed. Most atmospheric storage tanks are specifically designed so that the roof wall seam will preferentially fail hopefully mitigating the effects of an incident.

15. The above rates are derived from historical data in work carried out by Glossop (RAS/01/06). They are applicable to large flat-bottomed metal storage vessels where flammable liquids are stored at atmospheric temperature and pressure. These values are not directly applicable to vessels storing non-flammable liquids because a different set of failure modes is relevant. However, they may be used as a basis for such vessels – seek advice from the Topic Specialist.

References

Title	Author	Date	Comments
Failure Rates for Atmospheric Storage Tanks for Land Use Planning. HSL internal report RAS/01/06.	M Glossop	2001	

Failure Rate Advice (Confidential, not in the public domain)

16. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 1.1.1.2 Small and Medium Atmospheric Tanks

17. Small and Medium Atmospheric Tanks (SMATs) have a capacity of less than $450m^3$, made of steel or plastic.

ITEM FAILURE RATES

Type of Release	Non Flammable Contents (per vessel year)	Flammable Contents (per vessel year)
Catastrophic	8×10^{-6}	1.6×10^{-5}
Large	5×10^{-5}	1×10^{-4}
Small	5×10^{-4}	1×10^{-3}

18. Large releases are defined as a rapid loss of most or all contents e.g. large hole in a vessel leaking over several minutes.

19. Small releases are defined as smaller or much slower loss of contents e.g. through a small leak over 30 minutes.

20. FR117_2 defines hole sizes for tanks of unknown size (large holes are defined as 250 mm diameter and small holes as 75 mm diameter).

21. To calculate the hole sizes when the size of the tank is known, assume that a large hole would empty the tank in 5 minutes and a small hole would empty the tank in 30 minutes. What this equates to in terms of volumetric flow per second (tank volume/ time in seconds) can then be calculated and, from this, using the substance density, the mass flow in kg/s can be obtained. Using STREAM, it is then possible to determine what hole sizes would result in the calculated mass flow rates for small and large holes. The calculated hole sizes should be used unless they are larger than those specified in paragraph 18 (250/75mm), in which case the default 250mm and 75mm holes should be chosen.

Derivation

22. Failure rates are taken from RSU/08/14 by Brownless and Keeley. The rates were derived by fault tree analysis. The analysis suggested that the failure rates are sensitive to whether the substance stored is flammable or explosive and if so, whether the vessel has a weak roof seam (giving a preferential failure mode under pressure build up). The results also suggested that for catastrophic failures and large releases, corrosion is an important cause of failure, with spills (e.g. due to pipe or valve failure) and overpressure being important for smaller releases. Given the dominance of corrosion as a causal factor for catastrophic and large releases, consideration should be given to the applicability of the derived failure rates when considering vessels of plastic construction.

References

Title	Author	Date	Comments

Review of Failure Rates for Small Atmospheric Pressure Storage Tanks. HSL internal report RSU/08/14.	G Brownless and D Keeley	2008	

Failure Rate Advice (Confidential, not in the public domain)

23. See individual advice notes for specific details.

FR No	Application	Comments
117_2	SMATs, fixed tank up to 400-450m^3, plastic or metal and range of designs.	Revision to FR117. Catastrophic, large and small holes failure rates are provided for flammable and non-flammable contents.

Item FR 1.1.1.3 Non Metallic/Plastic

24. Currently there are no agreed HSE failure rates for this item. For small tanks, refer to Item FR 1.1.1.2 which also covers plastic tanks. Otherwise, see failure rate advice notes for specific failure rates, or refer to the Topic Specialist.

Failure Rate Advice (Confidential, not in the public domain)

25. See individual advice notes for specific details.

FR No	Application	Comments
101	HDPE spiral wound vertical atmospheric tank for HF acid.	Catastrophic, 50 mm and 13 mm diameter hole failure rates provided.
79	25te plastic wound, double skin vessels and half height containment.	Catastrophic, 50 mm, 25 mm, 13 mm and 6 mm diameter hole failure rates provided.
32	Allibert 5000 (PE) bunded polyethylene tank for HF acid.	Failure rates are provided for the catastrophic failure of the inner tank, and also for the inner tank and bund tank combined.

Item FR 1.1.2 Refrigerated Ambient Pressure Vessels

ITEM FAILURE RATES

Type of release	**Failure rate (per vessel year)**
Single walled vessels	
Catastrophic failure	4×10^{-5}
Major failure	1×10^{-4}
Minor failure	8×10^{-5}
Failure with a release of vapour only	2×10^{-4}
Double walled vessels	
Catastrophic failure	5×10^{-7}
Major failure	1×10^{-5}
Minor failure	3×10^{-5}
Failure with a release of vapour only	4×10^{-4}

RELEASE SIZES

	Hole diameters for Tank volumes (m^3)		
Category	>12000	12000 – 4000	4000 - 450
Major	1000 mm	750 mm	500 mm
Minor	300 mm	225 mm	150 mm

Derivation

26. All rates are based on the report by J.Gould, RAS/00/10. For the purposes of applying generic failure rates the various vessel designs have been placed into three categories:

1 Single wall tanks, where there is no outer containment designed to hold the cryogenic liquid or vapour.

2 Double walled tanks, where on failure of the inner wall the outer wall is designed to retain the liquid but not the vapour.

3 Full containment tanks, where the outer wall is designed to retain the liquid and the vapour.

27. A review of literature was performed to identify the failure rates for single walled vessels. The failure rates derived are based largely on experience from ammonia, LPG and LNG vessels of around 15000m^3. Event trees were produced using expert judgement to take into account the benefit of double walled tanks in containing releases from the inner tank. No credit should be given if the outer wall has not been designed to withstand the very low temperatures of the refrigerated contents.

28. The failure rates of the inner tank were not reduced to take account of any protection the outer wall and roof might provide, which could be significant for reinforced concrete outer containment. The review found no record of failures of LNG vessels so it is arguable that the generic figures should be reduced when applied to LNG facilities. Specific failure rates for double walled LNG tanks are derived in FR 1.1.2.1. The failure rates for double walled tanks should be used for full containment tanks, although the failure rate for the release of vapour only should be set to zero.

29. The rates quoted do not include failures due to overpressure as a result of the addition of a lower boiling point material to one stored at a higher temperature (e.g. the addition of propane to a butane storage tank). If this is considered a credible scenario the advice of the Topic Specialist should be sought. Failure rates for semi-refrigerated vessels will be based on those for pressure vessels and the advice of the Topic Specialist should be sought.

30. BS 7777 states that refrigerated storage vessels built up to the 1970's were predominantly single containment tanks. It is also still the practice that liquid oxygen, liquid nitrogen, and liquid argon are stored in single containment tanks. If a double wall is mentioned in regard to these vessels its function is generally to support the insulation and the roof, and not to contain the refrigerated liquid. Also, where other materials are stored refer to the Topic Specialist for advice on the applicability of these rates.

References

Title	Author	Date	Comments
New failure rates for land use planning QRA. HSL internal report RAS/00/10.	J Gould	May 2000	
BS 7777: Flat-bottomed, vertical, cylindrical storage tanks for low temperature service.	British Standards Institute	1993	

Failure Rate Advice (Confidential, not in the public domain)

31. See individual advice notes for specific details.

FR No	Application	Comments
19	Double skinned 66000 l liquid hydrogen vessels. Working pressure of inner tank is 12 barg although normal storage pressure is 4-5 barg.	Catastrophic, 50 mm, 25 mm, 13 mm and 6 mm diameter hole failure rates are provided.
84	Single skinned LPG tanks.	Catastrophic failure rate, 2000 mm, 1000 mm and 300 mm diameter holes and vapour release failure rates are provided.
89	Liquefied HCl.	Refrigerated pressure vessel. Catastrophic failure rate given.
105	Cryogenic ethylene (pressurised, semi-refrigerated), 20 te, temperature -53°C, pressure 12 barg.	Refrigerated pressure vessel. BLEVE frequency given.

Bibliography

32. These references represent other sources of information on the subject.

Title	Author	Date	Comments
Loss prevention in the process industries.	F P Lees	1980	1 x 10^{-5} failures/year, catastrophic failure based on Canvey data. Page 1018.
Bund overtopping – The consequences following catastrophic failure of large volume liquid storage vessels.	A Wilkinson	Oct 91	8.8 x 10^{-3} to 1 x 10^{-7} per tank per year, catastrophic failures of refrigerated and general purpose liquid vessels.
Gas terminal study. SRD review of Cremer and Warner failure rates. Confidential, not in the public domain.	P L Holden	Sep 81	

Title	Author	Date	Comments
Benchmark exercise on major hazard analysis, vol. 2, part 1.	S Contini (editor)	1992	Significant vapour release: 5.8 x 10^{-4} per vessel yr
Survey of catastrophic failure statistics for cryogenic storage tanks. Confidential, not in the public domain.	BOC	1989	Several values are quoted from the literature.
A method for estimating the off-site risk from bulk storage of liquid oxygen (LOX). Confidential, not in the public domain.	BCGA/HSE/SRD Working group	Not known	
An estimate of operating experience over the period 1954-1984 with low pressure, flat bottomed, metal tanks storing refrigerated and cryogenic liquids and the associated historical incidence frequencies. Confidential, not in the public domain.	J N Edmonson and P D Michell (AEA Technology)	1984	
An approach to hazard analysis of LNG spills.	D H Napier and D R Roopchand	1986	Catastrophic failure of inner tank leading to outer roof collapse: 0.8 – 2 x 10^{-6} per yr. Partial fracture of outer roof due to overpressurisation: 2 x 10^{-5} per yr. Catastrophic rupture of primary and secondary containment: 1 x 10^{-9} per yr. Serious leak from inner tank: 2 x 10^{-5} per yr,
Development of an improved LNG plant failure rate database.	D W Johnson & J R Welker	1981	Gives failure rates for major failures (for gas leaks) for a cryogenic storage vessel as 1.1 x 10^{-6} per hr For minor failures < 1.4 x 10^{-6} per hr

Item FR 1.1.2.1 LNG Refrigerated Vessels

ITEM FAILURE RATES

Type of Release	**Double wall (per vessel year)**
Catastrophic	5×10^{-8}
Major failure	1×10^{-6}
Minor failure	3×10^{-6}
Vapour release	4×10^{-5}

RELEASE SIZES

	Hole diameters for Tank volumes (m^3)		
Category	>12000	12000 – 4000	4000 - 450
Major	1000 mm	750 mm	500 mm
Minor	300 mm	225 mm	150 mm

Derivation

33. The failure rates above are taken from RAS/06/05 by Keeley.

34. RAS/06/05 reviews the basis for refrigerated vessel failure rates in general and considers their applicability to LNG storage. The report recommends that the double wall vessel failure rates for LNG tanks should be reduced from the generic values in FR 1.1.2.

35. The failure rates for single walled LNG tanks are unchanged and the generic values in FR 1.1.2 should be used. The failure rates for double walled tanks should be used for full containment tanks, although the failure rate for the release of vapour only should be set to zero.

References

Title	**Author**	**Date**	**Comments**
Review of LNG storage tank failure rates. HSL internal report RAS/06/05.	D Keeley	2006	

Failure Rate Advice (Confidential, not in the public domain)

36. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 1.1.2.2 Liquid Oxygen (LOX) Refrigerated Vessels

ITEM FAILURE RATES

Type of release	**Failure rate (per vessel year)**
Single walled vessels	
Catastrophic failure	2.2×10^{-5}
Major failure	1×10^{-4}
Minor failure	8×10^{-5}
Cluster tanks	
Simultaneous catastrophic failure of all tanks in cluster	1×10^{-6}
Catastrophic failure of single tank in cluster	1×10^{-6} x number of LOX tanks in cluster
Major failure	1×10^{-5}
Minor failure	5×10^{-5}

RELEASE SIZES

	Hole diameters for tank volumes (m^3)	
Category	4000 – 2000	200 – <2000
Major	400 mm	250 mm
Minor	120 mm	75 mm

Air separation units

Scenario	Failure rate (per vessel year)
Catastrophic failure	3×10^{-5}

37. Catastrophic failure is modelled as the instantaneous loss of vessel contents forming a vaporising pool.

38. A typical cluster tank usually consists of 5 or 7 smaller pressure vessels located inside a common large skin, which is used to contain the insulation material. The outer vessel is not designed to contain the vapour or liquid in the event of vessel failure.

Derivation

39. The partitioning between major and minor releases follows that for refrigerated ambient pressure vessels (Item FR 1.1.2). Scaling is applied to the tank size ranges used for refrigerated ambient pressure vessels to obtain the hole sizes and tank size ranges shown above. The values for single walled vessels for major and minor failures for refrigerated ambient pressure vessels are then used.

40. The cluster tank failure rates, excluding minor failures, are taken from FR 9.

41. The major failure rate for cluster tanks were obtained by summing the failure rates for the larger two hole sizes (50 mm and 25 mm) for pressure vessels (Item FR 1.1.3). Similarly, the minor failure rate for cluster tanks was calculated from the summation of the failure rates for the two smaller hole sizes (13 mm and 6 mm) from pressure vessels (Item FR 1.1.3).

References

Title	Author	Date	Comments
Revised LOX risk assessment methodology – HSE Panel Paper. Confidential, not in the public domain.	G Tickle, AEA Technology	14/01/03	Quotes the rates adopted by panel on 17 July 2001, which includes the single walled catastrophic failure rate.
LOX methodology modifications to address comments from 19th January 2004 MSDU Panel meeting – HSE Panel Paper. Confidential, not in the public domain.	G Tickle, AEA Technology	22/03/04	This introduces the release sizes, modifies the cluster tank minor failure rate and details its calculation along with that of major failures in cluster tanks. Major and minor failures for single walled vessels are also discussed.

Failure Rate Advice (Confidential, not in the public domain)

42. See individual advice notes for specific applications and reasoning.

FR No	Application	Comments
9	LOX cluster tanks and internal explosions.	LOX cluster tanks and internal explosions. Catastrophic and major failure rates are

		derived.
53	66te LOX vacuum insulated tanks.	Uses FR19 which derived catastrophic failure rates and rates for holes of size 50 mm, 25 mm, 13 mm and 6 mm.
55	Pressure vessels for LOX storage, 35te, operating pressure 17 bar. Vertical bullets with liquid off-take feeding an air warmed vaporiser delivering oxygen gas under pressure of around 10 bar.	Catastrophic, 50 mm and 25 mm diameter hole failure rates provided.

Item FR 1.1.3 Pressure Vessels

43. Failure rates for pressure vessels are further subdivided into those for LPG vessels, FR 1.1.3.1, and chlorine vessels, FR 1.1.3.2. For general pressure vessels the rates below, which are based on those for chlorine vessels, should be used as a starting point.

ITEM FAILURE RATES

Type of release	Failure rate (per vessel year)	Notes
Catastrophic	6×10^{-6}	Upper failures
Catastrophic	4×10^{-6}	Median
Catastrophic	2×10^{-6}	Lower
50 mm diameter hole	5×10^{-6}	
25 mm diameter hole	5×10^{-6}	
13 mm diameter hole	1×10^{-5}	
6 mm diameter hole	4×10^{-5}	

Derivation

44. The cold catastrophic and hole failure rates are taken from the MHAU handbook (now archived). These are derived in the Chlorine Siting Policy Colloquium and are applicable to chlorine pressure vessels in a typical water treatment plant. Although they are not applicable to all types of pressure vessels the values are a good starting point when trying to derive failure rates for vessels in other applications. The value chosen for catastrophic failure should normally be 2 chances per million (cpm), assuming that the vessel conforms to BS5500 or an equivalent standard and that there is good compliance with the HSW etc. act (1974), unless there are site-specific factors indicating that a higher rate is appropriate (e.g. semi refrigerated vessels [cryogenic pressure vessels]).

45. The values above take the effects of external hazards into account at a rate of 1×10^{-6} per vessel year for catastrophic failures. If site specific conditions are known to result in a higher external hazard rate then the overall failure rate used should be adjusted as necessary. Examples of external hazards are shown in Figure 4.

46. Domino effects on adjacent tanks are possible. Assuming a split along a longitudinal seam and that 50% of such splits are orientated such that the vessel is driven into an adjacent one, then the rate of impact on a second vessel following a catastrophic failure would be 10^{-6}. Not all of these impacts would cause catastrophic failure of the second vessel, however. If it is further assumed that 25% of the impacts cause catastrophic failure, this gives a total frequency of 1/8 of the catastrophic failure rate. This is very much an estimate and, if the scenario proves to be dominant in the risk assessment, further advice should be sought.

47. A review of pressure vessel failure rates was carried out in 2006. The outcome of the review was to recommend that HSE continue to use the current values within PCAG for pressure vessel failure rates unless new information suggests otherwise. This work is documented in a HSL report by Keeley and Prinja, RAS/06/04.

48. The HSE pressure vessel failure rates have also recently been reviewed by Nussey (2006). The review concluded that the HSE failure frequencies for pressure vessels continue to be soundly based and justified.

References

Title	Author	Date	Comments
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium
Pressure Vessel Failure Rates – A Summary Report. HSL internal report RAS/06/04.	D Keeley and A Prinja	2006	
Failure frequencies for major failures of high pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands.	C Nussey	2006	www.hse.gov.uk/comah/highpressure.pdf
FR 87. Confidential, not in the public domain.	S C Pointer	2005	Domino failures of adjacent tanks

Failure Rate Advice (Confidential, not in the public domain)

49. See individual advice notes for specific details.

FR No	Application	Comments
14	29.6 te fixed bromine tanks.	Catastrophic failure rate produced.
19	Double skinned 66000 l liquid hydrogen vessels.	Catastrophic failures, 50 mm, 25 mm, 13 mm and 6 mm holes. Working pressure of inner tank is 12 barg although normal storage pressure is 4-

		5 barg.
55	Pressure vessels for LOX storage, 35te, operating pressure 17 bar. Vertical bullets with liquid off-take feeding an air warmed vaporiser delivering oxygen gas under pressure of around 10 bar.	Catastrophic failures, 50 mm and 25 mm diameter hole failure rates produced.
63	High pressure gas bullets.	Cold and hot catastrophic, full manhole, 50 mm and 25 mm diameter hole failure rates produced.
87	Domino failures of adjacent tanks.	Single vessel and 2 vessel catastrophic failure rates produced.
89	Liquefied HCl, 13.5 bar g and temperature of -40°C.	Catastrophic failure rate produced.
105	Cryogenic ethylene (pressurised, semi-refrigerated), 20 te. Temperature -53°C, pressure 12 barg.	BLEVE frequency given.

Bibliography

50. These references represent other sources of information on the subject.

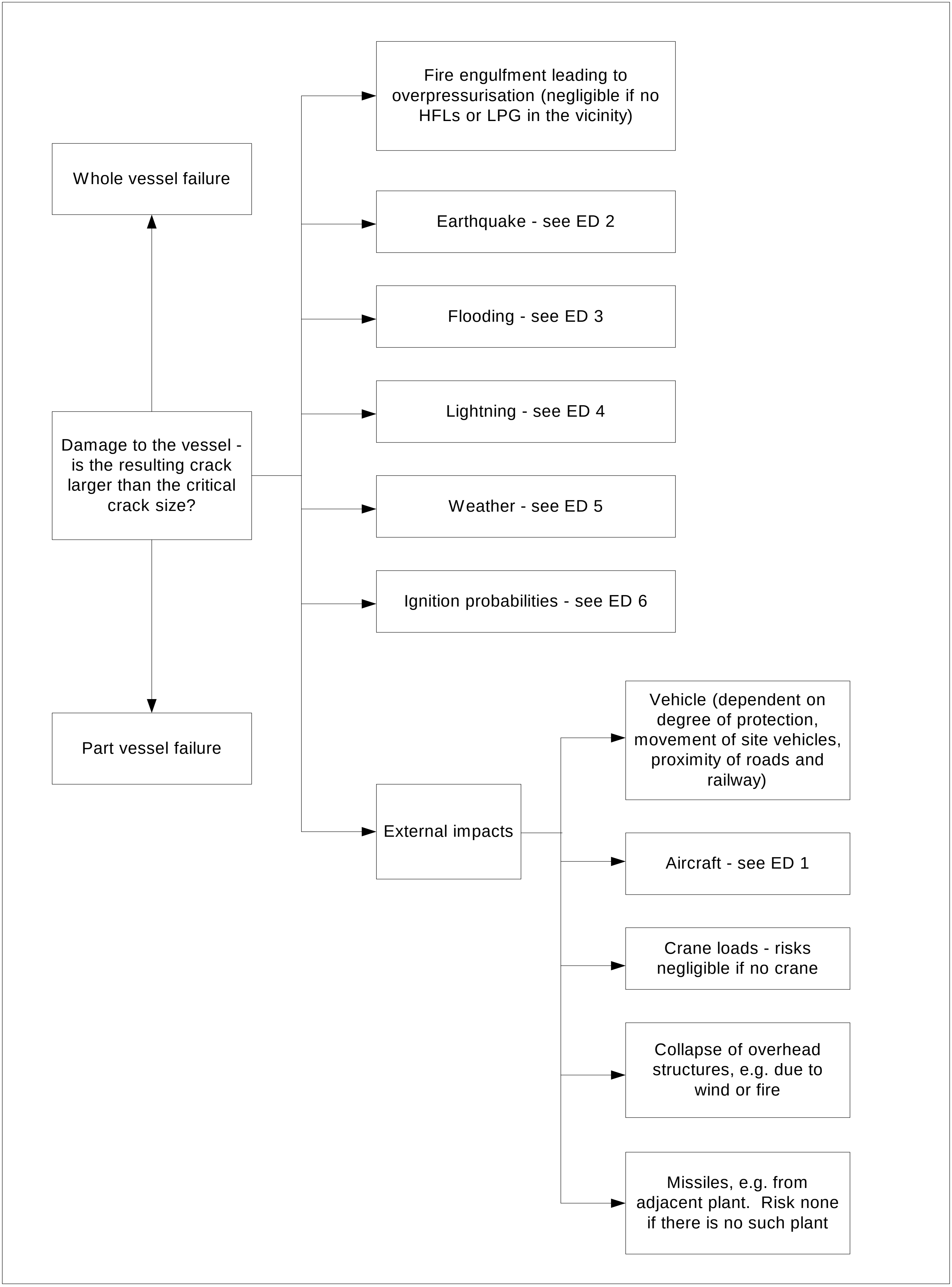
Title	**Author**	**Date**	**Comments**
A literature review of generic failure rates and comparison with the failure rates used in RISKAT. Confidential, not in the public domain.	R Hankin	Dec 91	
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	7.4×10^{-6}
Guidelines for process equipment reliability data.	American Institute of Chemical Engineers	1989	9.5×10^{-5}, catastrophic failure of pressure vessels page 205.
“Covo” report.	Rijnmond public authority	Nov 81	6×10^{-6}, catastrophic failures. Table IX.I.
Loss prevention in the process	F P Lees	1980	1×10^{-5} per yr, catastrophic failure

Title	Author	Date	Comments
industries.			based on Canvey data. Page 1018.
CIMAH safety case. Confidential, not in the public domain.	W S Atkins	Jun 94	
CIMAH safety case support. Confidential, not in the public domain.	Technica (USA)	May 1989	(Smith and Warwick data).
A survey of defects in pressure vessels in the UK during the period 1962-1978 and its relevance to nuclear primary circuits.	Smith and Warwick	Dec 81	4.2×10^{-5} per vessel yr, catastrophic data (includes boilers).
Reliability Technology.	Green & Bourne	1972	Two values are given for pressure vessels: General – 3.0×10^{-6} per hr High standard – 0.3×10^{-6} per hr
The predicted BLEVE frequency of a selected 2000 m^3 butane sphere on a refinery site.	M Selway	August 1988	Determines BLEVE frequency of an LPG tank to be 9×10^{-7} per yr (p 24).
An initial prediction of the BLEVE frequency of a 100 te butane storage vessel.	K W Blything & A B Reeves	1988	Uses fault tree analysis (FTA) to determine BLEVE frequency of a butane tank to be 10^{-8} to 10^{-6} per vessel yr.
Failure rates – LPG tanks. Confidential, not in the public domain.		1994	
A further survey of pressure vessel failures in the UK (1983 – 1988) – public domain version.	T J Davenport	1991	Value of 5.1×10^{-5} per yr derived for all pressure vessels. Also individual values derived for air receivers, steam receivers and boilers.

Title	Author	Date	Comments
Proposed gas terminal. Confidential, not in the public domain.	Technica	Aug 1991	
CIMAH safety report for gas terminal. Confidential, not in the public domain.	Technica	Jun 94	
Gas terminal study. SRD review of Cremer and Warner failure rates. Confidential, not in the public domain.	P L Holden	Sep 81	
QRA data. Confidential, not in the public domain.	Technica	May 89	
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	
Safety report R2000 reactor rupture fault tree analysis. Confidential, not in the public domain.	Not given	1994	
Safety report. Confidential, not in the public domain.	Technica	1994	Split into various causes.
Estimation of cold failure frequency of LPG tanks in Europe. Confidential, not in the public domain.	W Sooby & J M Tolchard	1994	
Calculation of release frequencies. Confidential, not in the public domain.	WS Atkins	Jul 95	
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	
Loss prevention in the process industries.	F P Lees	1986	General pressure vessel: 3 High standard: 0.3 (units of failures x10^{-6}

Title	Author	Date	Comments
			per yr)
SR module. Confidential, not in the public domain.	Unknown	1978	
Guidelines for the preparation and review of a report under the CIMAH regulations. Confidential, not in the public domain.	BP CIMAH Liaisons Group	May 93	
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	
Generic land use planning consultation zones - chlorine. Confidential, not in the public domain.	Not given	Oct 94	
Some data on the reliability of pressure equipment in the chemical plant environment.	D C Arulanantham & F P Lees	Oct 80	Various vessels; pressure vessels, boiler drums etc. (p 328).
Safety cases within the Control of Industrial Major Accident (CIMAH) Regulations 1984.	M L Ang & F P Lees	1989	Value given for chlorine pressure vessel.
The likelihood of accidental release events. Confidential, not in the public domain.	Rhône Poulenc Chemicals	Not dated	Various tank failures considered.
Quantified risk assessment. Confidential, not in the public domain.	AEA Technology	1996	
A method for estimating the off-site risk from bulk storage of liquid oxygen (LOX). Confidential, not in the public domain.	BCGA/HSE/SRD Working Group	Not given	
Risks associated with the storage of and use of chlorine at a water treatment plant (2nd draft). Confidential, not in the public domain.	SRD	Nov 81	This report derives a value for the failure rate for chlorine pressure vessels. Failure rates are thought to be over conservative.

Figure 4 External Hazards for Pressure Vessels



Item FR 1.1.3.1 Chlorine Pressure Vessels

ITEM FAILURE RATES

Type of release	Failure rate (per vessel year)	Notes
Catastrophic	4×10^{-6}	Use where site specific factors increase likelihood of failure
Catastrophic	2×10^{-6}	Normal value
50 mm diameter hole	5×10^{-6}	
25 mm diameter hole	5×10^{-6}	
13 mm diameter hole	1×10^{-5}	
6 mm diameter hole	4×10^{-5}	

Derivation

51. The cold catastrophic failure rates are taken from the MHAU handbook (now archived). These are derived in the Chlorine Siting Policy Colloquium and are applicable to chlorine pressure vessels. The above values have been adopted as the generic failure rates for pressure vessels for use within RISKAT.

52. The catastrophic failure rate should be taken as 2×10^{-6} per vessel yr unless site specific factors are known to increase that value.

53. The values above take the effects of external hazards into account at a rate of 1×10^{-6} per vessel year for catastrophic failures. If site specific conditions are known to result in a higher external hazard rate then the overall failure rate used should be adjusted as necessary. Examples of external hazards are shown in Figure 4.

54. A review of pressure vessel failure rates was carried out in 2006. The outcome of the review was to recommend that HSE continue to use the current values within PCAG for pressure vessel failure rates unless new information suggests otherwise. This work is documented in a HSL report by Keeley and Prinja, RAS/06/04.

55. The HSE pressure vessel failure rates have also recently been reviewed by Nussey (2006). The review concluded that the HSE failure frequencies for pressure vessels continue to be soundly based and justified.

References

Title	Author	Date	Comments
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium
Pressure Vessel Failure Rates – A Summary Report. HSL internal report RAS/06/04.	D Keeley and A Prinja	2006	
Failure frequencies for major failures of high pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands.	C Nussey	2006	www.hse.gov.uk/comah/highpressure.pdf

Failure Rate Advice (Confidential, not in the public domain)

56. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Bibliography

57. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A Literature Review of Generic Failure Rates and Comparison with the Failure Rates Used in RISKAT. Confidential, not in the public domain.	R Hankin	December 1991	
Guidelines for Process Equipment Reliability Data.	Centre for Chemical Process Safety of the American Institute of Chemical	1989	$9.5x10^{-5}$, catastrophic failure of pressure vessels page 205.

	Engineers		
Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, a Pilot Study.	Rijnmond Public Authority	November 1981	$6x10^{-6}$, catastrophic failures. Table IX.I.
Calculation of Release Events Frequencies. Confidential, not in the public domain.	W S Atkins	2 July 1995	
Chlorine Safety Report– The Likelihood of Accidental Chlorine Release Events. Confidential, not in the public domain.	W S Atkins	October 1995	
Safety Cases Within the Control of Industrial Major Accident Hazards (CIMAH) Regulations 1984.	M L Ang and F P Lees	1989	$2x10^{-6}$ per yr (instantaneous release).
Risks Associated with the Storage of and Use of Chlorine at a Water treatment Plant (2nd Draft). Confidential, not in the public domain.	SRD	November 1981	

Item FR 1.1.3.2 LPG Pressure Vessels

ITEM FAILURE RATES

Type of release	Failure rate (per vessel year)	Notes
Catastrophic	2×10^{-6}	Cold vessel failures
BLEVE	1×10^{-5}	
50 mm diameter hole	5×10^{-6}	
25 mm diameter hole	5×10^{-6}	
13 mm diameter hole	1×10^{-5}	

Derivation

58. The cold catastrophic and BLEVE failure rates are taken from the MHAU handbook (now archived). These are standard failure rates for use within RISKAT.

59. The value for catastrophic failure is based on a survey carried out in 1983 by the LPGTA (now renamed to UKLPG) on LPG releases and vessel populations in the UK. From calculations by E.M. Paper in the file MHAU/PR/6003/94 the survey gave 280,000 vessel years with no catastrophic failures. This gave a failure rate of $<2.5 \times 10^{-6}$ per vessel yr. This survey has been updated assuming no failures up to 1992, which gives a failure rate of 9.4×10^{-7} per vessel yr. This failure rate is derived from LPG tanks most of which (95%) are less than 1 te and larger vessels may have different failure rates. Taking this into account, and the generic failure rates used within HSE, the value of 2×10^{-6} continues to be used.

60. The cold catastrophic failure rate was reviewed by Nussey in 2006 and the conclusion was that the value of 2 cpm was still reasonable. The review also concluded that the HSE failure frequencies for pressure vessels continue to be soundly based and justified.

61. The mounding or burying of LPG tanks gives protection from fire engulfment and significantly reduces the possibility of a BLEVE. The mounding or burying also changes the likelihood of the possible causes of cold failure.

62. Where the LPG tank is fully mounded or completely buried, the BLEVE frequency can be taken as zero. Partially mounded tanks or other tanks that have part of the surface exposed are assigned the standard BLEVE frequency. In all cases the cold catastrophic failure frequency and the vessel hole rates remain unchanged unless demonstrated otherwise.

63. The values above take the effects of external hazards into account at a rate of 1 x 10-6 per vessel year for catastrophic failures. If site specific conditions are known to result in a higher external hazard rate then the overall failure rate used should be adjusted as necessary. Examples of external hazards are shown in Figure 4.

64. A review of pressure vessel failure rates was carried out in 2006. The outcome of the review was to recommend that HSE continue to use the current values within PCAG for pressure vessel failure rates unless new information suggests otherwise. This work is documented in a HSL report by Keeley and Prinja, RAS/06/04.

References

Title	Author	Date	Comments
Pressure Vessel Failure Rates – A Summary Report. HSL internal report RAS/06/04.	D Keeley and A Prinja	2006	
Failure frequencies for major failures of high pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands.	C Nussey	2006	www.hse.gov.uk/comah/highpressure.pdf

Failure Rate Advice (Confidential, not in the public domain)

65. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Bibliography

66. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A Literature Review of Generic Failure Rates and Comparison with the Failure Rates Used in RISKAT. Confidential, not in the public domain.	R Hankin	December 1991	
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	7.4×10^{-6}
Guidelines for process equipment reliability data.	American Institute of chemical	1989	9.5×10^{-5}, catastrophic failure of pressure vessels page 205.

	engineers		
“Covo” report.	Rijnmond public authority	Nov 81	6 x 10^{-6} per yr, catastrophic failures. Table IX.I.
Loss prevention in the process industries.	F P Lees	1980	1 x 10^{-5} per yr, catastrophic failure based on Canvey data. Page 1018.
CIMAH safety case support.	Technica (USA)	May 89	6.5 x 10^{-6} per yr, catastrophic data (Smith and Warwick data).
The predicted BLEVE frequency for a sphere.	M Selway	August 1988	The predicted BLEVE frequency of a selected 2000 m^3 butane sphere on a refinery site.
An initial prediction of the BLEVE frequency of a 100 te butane storage vessel.	K W Blything & A B Reeves	1988	Uses FTA to determine BLEVE frequency of a butane tank to be 10^{-8} to 10^{-6} per vessel year.
Failure rates – LPG tanks. Confidential, not in the public domain.		1994	
Estimation of cold failure frequency of LPG tanks in Europe. Confidential, not in the public domain.	W Sooby & J M Tolchard	1994	
Guidelines for the preparation and review of a report under the CIMAH regulations. Confidential, not in the public domain.	BP CIMAH Liaisons Group	May 93	

Item FR 1.1.4 Chemical Reactors

ITEM FAILURE RATES

General Reactors

Type of release	Failure rate (per reactor year)	Notes
Catastrophic	1×10^{-5}	The analysis suggests an uncertainty of plus or minus 5×10^{-6} per reactor year.
50 mm diameter hole	5×10^{-6}	
25 mm diameter hole	5×10^{-6}	
13 mm diameter hole	1×10^{-5}	
6 mm diameter hole	4×10^{-5}	

Reactors with Known Potential for Thermal Runaway

Type of release	Failure rate (per reactor year)	Notes
Catastrophic	5×10^{-5}	

Reactors known not to be Capable of Thermal Runaway

Type of release	Failure rate (per reactor year)	Notes
Catastrophic	3×10^{-6}	

Derivation

67. All of the rates are taken from the panel paper by P Betteridge (Panel Paper 1999-003). These values are for pressurised chemical reactors, and include both batch and continuous, but not non-metallic reactors or small lab-scale reactors. The main assumption is that both pressure vessels and reactor vessels will share a set of common failure modes and that the failure rate due to these will be the same for both types of vessel. Both types of vessel will also have a set of failure modes that are unique to that type of vessel.

68. The values proposed for less than catastrophic failure are those for chlorine storage vessels. To take into account the number of large flanges often found on reactors, each flange should be given a failure rate of 3×10^{-6} per year with a hole size equivalent to assuming a loss of a segment of gasket between two bolts. The value obtained should then be added to the

appropriate value from the table above to give the net failure rate. This would mean that for a reactor with four 8-bolt 200 mm flanges, the failure rate would be 1.2 x 10^{-5} per reactor year with an equivalent hole size of 13 mm for a 2 mm gasket.

69. The catastrophic failure rate for reactors with known runaway potential has been derived from the work originally carried out by P. Betteridge. In order to derive a value from the available data, simplifying assumptions were necessary and as a result the rate quoted should be regarded as a best estimate from the available data rather than an absolute value.

References

Title	Author	Date	Comments
HSE Panel Paper 1999-003. (Confidential, not in the public domain)	P. Betteridge	1999	

Failure Rate Advice (Confidential, not in the public domain)

70. See individual advice notes for specific details.

FR No	Application	Comments
43	Runaway reaction in chemical reactors. Design pressure of 4 barg.	Catastrophic failure and catastrophic failure + building failure rates provided.
44	Reactor failures due to water ingress. Glass lined agitated vessels up to 500 gallons fitted with a jacket for steam heating and water cooling duties.	Pilot plant. Overall failure rate from reactor and water ingress is provided.
72	Catastrophic failure for reactors, filters and centrifuges. Pressure rated to 5-7 barg, centrifuges restricted to 0.1 barg.	Catastrophic failure rates for reactors, centrifuges and filters are provided.

Item FR 1.2 Components

71. Failure rates for mechanical components are categorised as follows:

Spray Releases

72. Spray releases covers a specific type of leak that occurs at different kinds of plant and pipework. Spray releases are normally only considered when assessing risks from toxic substances that would otherwise have very small hazard ranges because of their low volatility.

73. A spray release is defined as a release where the spray from a hole is broken into droplets small enough to not rain out, i.e. it is atomised. It could occur in fixed pipework or in a flexible hose connection (say between a tanker and a storage vessel). Spray releases also arise from plant such as pumps and valves, particularly around shafts and drives. In order for a spray release to occur, two conditions are required:

- A very narrow breach in the containment boundary (< 50μm)
- A significant pressure (in excess of 1 barg)

74. Only crack-like holes, (i.e. with considerable length) need be considered, because point defects of 50 μm size will have negligible flow rate. Clearly, these small breaches with specific geometry are a small subset of the range of failures that could occur. No data is available directly from industry on spray frequencies. Frequencies were estimated by considering sprays as a subset of all small holes. Data for small holes in the type of plant that might give rise to sprays were obtained from a variety of sources. The judgements used in deriving the spray release figures were agreed in an MSDU Panel Paper of 4 February 2004, entitled ‘Spray Releases’ by P J Buckley (Confidential, not in the public domain). The paper was presented at a panel meeting on 16 February 2004.

75. Spray releases can occur under items 1.2.1-1.2.4.

Item FR 1.2.1 Valves

ITEM FAILURE RATES

Type of event	Failure rate (per demand)	Notes
Failure to close	1×10^{-4}	Manual valve (Exc. Human Error)
Failure to close	3×10^{-2}	ROSOV (Inc. Human Error)
Failure to close	1×10^{-2}	ASOV
Failure to operate	1.3×10^{-2}	XSFV

SPRAY RELEASE FREQUENCY

	Frequency	Effective length of crack
Valve	200×10^{-6} per valve per year	Shaft circumference

Derivation

76. All rates are taken from the MHAU handbook volume 3 (now archived). These values are derived in the Components Failure Rates paper, which is a comparison of 12 sources of failure rates derived elsewhere. The values are for chlorine duty although the review included LPG, petrochemical, steam/water, nuclear and other data.

77. The failure to close manual chlorine valves is given as 1×10^{-4} per demand not including human error. Manual valves are valves that have to be closed in an emergency by the operator taking suitable precautions, e.g. donning a SCBA (self-contained breathing apparatus).

78. A ROSOV is a remotely operated shut-off valve that allows rapid remote isolation of significant processes. The failure to close a ROSOV is given as 3×10^{-2} per demand.

79. An ASOV (Automatic shut-off valve) is a valve normally held open and is closed by detection equipment with no need for manual intervention. The failure to close for ASOVs is given as 1×10^{-2} per demand. The value may be higher if gas detection equipment is used as opposed to a pressure drop system.

80. Excess flow valves (XSFV) have a failure rate of 1.3×10^{-2} per demand if tested every year and an order of magnitude higher if tested every 10 years.

81. Where human error is likely to be a significant factor the advice of HID Human Factors Specialists should be sought. The advice of Control and Instrumentation Specialists should also be sought where there is a need for a site-specific assessment.

References

Title	Author	Date	Comments
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium

Failure Rate Advice (Confidential, not in the public domain)

82. See individual advice notes for specific details.

FR No	Application	Comments
49	Relief valve for natural gas.	Rate per year or per demand.

Bibliography

83. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A literature review of generic failure rates and comparison with the failure rates used in RISKAT. Confidential, not in the public domain.	R Hankin	Dec 91	Average values for failure rate data.
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	Gives the failure (per demand) for ASOV, ROSOV and EFV (Excess Flow Valve).
Major hazard aspects of the transport of dangerous substances.	Advisory Committee on Dangerous Substances	1991	LPG road tanker: various valve failures (p285-6) Chlorine tanker valves (p205 and 264) Ammonia tanker valve failures (p206)
Guidelines for process equipment reliability data.	American Institute of chemical engineers	1989	Sparsely populated database.

Title	Author	Date	Comments
“Covo” report.	Rijnmond public authority	Nov 81	Risk assessment and fault tree analysis. Table IX. I (FTO).
Loss prevention in the process industries.	F P Lees	1980	Probably originating from the “Covo” report. Page 1005.
CIMAH safety case. Confidential, not in the public domain.	W S Atkins	Jun 94	
Reliability Technology.	Green & Bourne	1972	Gives failure rates for hand operated, ball, solenoid, control and relief valves.
An initial prediction of the BLEVE frequency of a 100 te butane storage vessel.	K W Blything & A B Reeves	1988	Various values given for leaks, and failure to close, considers pressure relief valves, pressure control valve and EFV.
Proposed gas terminal. Confidential, not in the public domain.	Technica	Aug 1991	Leaks from valves are included in the pipework failure rate. Only failure on demand is given.
CIMAH safety report for gas terminal. Confidential, not in the public domain.	Technica	Jun 94	
CIMAH safety report. Confidential, not in the public domain.	WS Atkins	May 94	
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	Valve seal failure data.
Safety report. Confidential, not in the public domain.	Technica	1994	
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	
Loss prevention in the process industries.	F P Lees	1986	Values given in failures x 10^{-6} per hr

Title	Author	Date	Comments
			Control valves: 30 Ball valves: 0.5 Solenoid valves: 30 Hand operated: 15 Relief valve (leak): 2 Relief valve (blockage): 0.5
HF QRA. Confidential, not in the public domain.	Unknown	Jul 94	
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	ASO: FTO and leak NRV: FTO and leak Control valve: FTO and leak Manual shut off: leak Relief valve: FTO, leak
Transport of dangerous substances. Confidential, not in the public domain.	ACDS	Mar 90	
Fault tree illustrating the combination of events leading to a fire during LPG unloading. Confidential, not in the public domain.	British Gas	1995	Fault tree analysis, actual values not given.
Safety cases within the Control of Industrial Major Accident (CIMAH) Regulations 1984.	M L Ang & F P Lees	1989	Failure rate of tanker EFV, 0.01/ demand.
Failure data collection and analysis in the Federal Republic of Germany.	K Boesebeck and P Homke	Not given	Various shut off valves considered p. 18, MOV considered for leaks, FTO P. 19, FTO: (300 to 3000) x 10^{-6} per demand Leak: (6 to 25) x 10^{-6} per

Title	Author	Date	Comments
			demand
The likelihood of accidental release events. Confidential, not in the public domain.	Unknown	Not given	
Reliability and maintainability in perspective.	D Smith	1988	Ranges of failure rates quoted for FTO for the following valve types: ball, butterfly, diaphragm, gate, needle, non-return, plug, relief, globe, and solenoid. (p.249).
Quantified risk assessment. Confidential, not in the public domain.	AEA Technology	1996	
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	
Site specific assessment. Confidential, not in the public domain.	AD Little	Apr 94	
Risks associated with the storage of and use of chlorine at a water treatment plant (2nd draft). Confidential, not in the public domain.	SRD	Nov 81	
Valve and pump operating experience in French nuclear plants.	J R Aupied, A Le Coguiec, H Procaccia	1983	This reference gives a detailed treatment of valves and breaks down the data for gate, globe, check, plug and safety relief valves. There is also a breakdown of the medium handled by the valves. It is claimed that non-operation forms 20% of the failure and that leakage forms 30% of the failures.

Title	**Author**	**Date**	**Comments**
A review of instrument failure data.	F P Lees	1976	Failure of control valves and pressure relief valves to operate correctly. Control valve fail shut: 0.2 per yr Control valve fail open: 0.5 per yr Pressure relief valve fail shut: 0.001 per yr Also total fail to danger and fail safe are given, solenoid and hand valves are considered.
OREDA – Offshore reliability data handbook.	OREDA	1984	Contains a variety of data on valves of different types and considers a range of failure modes. Includes FTO and leakage.
Non-electric parts reliability data.	M J Rossi, Reliability Analysis Centre	1985	Failure rates are given for a range of different valves (ball, butterfly, check, diaphragm, gate etc.). It is not clear whether these failures refer to leaks or failure to operate.
Development of an improved LNG plant failure rate database.	D W Johnson & J R Welker	1981	Mean time between failures for cryogenic valves is 1,569,000 hrs for major failures, other values also given.
Interim reliability evaluation. Program procedures guide. Confidential, not in the public domain.	D D Carlson	Jan 93	Gives mean and median values for failure rates for a wide range of valves (motor operated, solenoid, check, manual, etc.). In many cases gives values for failure to operate and leakage. Mean values quoted for catastrophic leak.

Item FR 1.2.2 Pumps

ITEM FAILURE RATES

Type of event	Failure rate (per year per pump)	Notes
Failure of casing	3×10^{-5}	

SPRAY RELEASE FREQUENCY

	Frequency	Effective length of crack
Pump single seal	500×10^{-6} per pump per year	Shaft circumference
Pump double seal	50×10^{-6} per pump per year	Shaft circumference

Derivation

84. All rates are taken from the MHAU handbook volume 3 (now archived). The failure rate refers to the catastrophic failure of the pump casing giving a release rate equivalent to a full bore leak from the pipework.

References

Title	Author	Date	Comments
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium

Failure Rate Advice (Confidential, not in the public domain)

85. See individual advice notes for specific details.

FR No	Values	Application
	No specific advice	

Bibliography

86. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A literature review of generic failure rates and comparison with the failure rates used in RISKAT. Confidential, not in the public domain.	R Hankin	Dec 91	Average values for failure rate data.
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	Failure rate of 1 x 10^{-4} per yr given for guillotine failure (failure of the pump casing).
Guidelines for process equipment reliability data.	American Institute of chemical engineers	1989	Sparsely populated database.
“Covo” report.	Rijnmond public authority	Nov 81	Risk assessment and fault tree analysis. Table IX. I .
Loss prevention in the process industries.	F P Lees	1980	Probably originating from the “Covo” report. Page 1005.
CIMAH safety case support. Confidential, not in the public domain.	Technica (USA)	May 89	
An initial prediction of the BLEVE frequency of a 100 te butane storage vessel.	K W Blything & A B Reeves	1988	Frequency of a small leak (0.5” diameter.) 5.2 x 10^{-4} per yr. Other values also given (p. 32).
Proposed gas terminal. Confidential, not in the public domain.	Technica	Aug 1991	Pump failure rates are given for small, large and catastrophic failures.
CIMAH safety report for gas terminal. Confidential, not in the public domain.	Technica	Jun 94	As above.
QRA data. Confidential, not in the public domain.	Technica	May 89	Hole size distribution.
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	

Title	Author	Date	Comments
Loss prevention in the process industries.	F P Lees	1986	Failure to start 1 x 10^{-3} per demand
SR module. Confidential, not in the public domain.	Unknown	1978	
Guidelines for the preparation and review of a report under the CIMAH regulations. Confidential, not in the public domain.	BP CIMAH Liaisons Group	May 93	
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	Various events considered.
Failure data collection and analysis in the Federal Republic of Germany.	K Boesebeck and P Homke	Not given	No actual failure data is given but the distributions of the repair times are shown as graphs.
Reliability and maintainability in perspective.	D Smith	1988	Failure rates for: Centrifugal 10 – 100 x 10^{-6} per hr Boiler 100 – 700 x 10^{-6} per hr Fire water (p. 247).
Benchmark exercise on major hazard analysis, vol. 2 part 1.	S Contini (editor)	1992	A list of pumps and their failure rate is given in table 8.1 (p. 32).
Quantified risk assessment. Confidential, not in the public domain.	AEA Technology	1996	
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	
Site specific assessment. Confidential, not in the public domain.	AD Little	Apr 94	

Title	**Author**	**Date**	**Comments**
Valve and pump operating experience in French nuclear plants.	J R Aupied, A Le Coguiec, H Procaccia	1983	The mean feed water pump failure rate is found to be 5.6×10^{-4} per yr.
OREDA – Offshore reliability data handbook.	OREDA	1984	Values are given for centrifugal, diaphragm, and reciprocating pumps used for a range of applications.
Non-electric parts reliability data.	M J Rossi, Reliability Analysis Centre	1985	A wide range of pump types are considered (axial piston, boiler feed, centrifugal, electric motor driven, engine driven etc.). Various rates are quoted along with upper and lower intervals.
Development of an improved LNG plant failure rate database.	D W Johnson & J R Welker	1981	Mean time between failures for cryogenic pumps is 4,000 hrs for major failures. Other values also given.
Interim reliability evaluation. Program procedures guide. Confidential, not in the public domain.	D D Carlson	Jan 93	Mean and median values given for various pump types (motor driven, turbine driven, and diesel driven) for failure to start and failure to run given start.

Item FR 1.2.3 Hoses and Couplings

ITEM FAILURE RATES

	Failure rate per operation x 10^{-6}		
Facility	Guillotine failure	15 mm diameter hole	5 mm diameter hole
Basic facilities	40	1	13
Average facilities	4	0.4	6
Multi safety system facilities	0.2	0.4	6

SPRAY RELEASE FREQUENCY

	Frequency	**Effective length of crack**
Hose and coupling	0.12 x 10^{-6} per transfer	Hose diameter

Derivation

87. The hose and coupling failure rates apply to road tanker transfers. The guillotine failure rates are taken from the report by Gould and Glossop, RAS/00/10. An extension of this work by Keeley (RAS/04/03) derived the smaller hole failure rates. The work was carried out for chlorine transfer facilities but should be applicable to similar transfer operations. The safety systems applicable to the facilities are pullaway prevention (e.g. wheel chocks, interlock brakes, interlock barriers), pullaway mitigation that stops the flow in the event of pullaway (e.g. short airline, but only if it will separate and activate a shut off valve before the transfer system fails, movement detectors), and hose failure protection (pressure leak test, hose inspection). Facilities have been divided into three categories to typify the range of precautions that might be found in practice:

Basic	These have one pullaway prevention system such as wheel chocks, carry out inspection and pressure/leak tests to prevent transfer system leaks and bursts, but have no pullaway mitigation.
Average	Two pullaway prevention systems (one of which should be wheel chocks) as well as inspection and pressure/leak tests to prevent transfer system leaks and bursts but no effective pullaway mitigation.
Multi safety systems	Two pullaway prevention systems, and also an effective pullaway mitigation system and inspection and pressure/leak tests to prevent transfer system leaks and burst.

88. Fault trees were produced to reflect the three types of facilities. No additional credit should be given for duplicate non-redundant safety systems. Note that an emergency shutdown (ESD) system by itself does not affect the likelihood of a release. Only when used in conjunction with a movement detector or short airline will the probability be changed. The effect of an ESD system activated by gas detectors, pressure drop in the transfer system or the operator will be to change the duration of the releases used in estimating the risk.

89. The failure rates are not applicable to transfers over an extended time period (e.g. from tank containers to a process), nor do they include transfer by loading arms.

References

Title	Author	Date	Comments
New Failure Rates for Land Use Planning QRA. HSL internal report RAS/00/10.	J Gould and M Glossop	May 2000	
Hose and Coupling: Less than catastrophic failure rates – Milestone 2. HSL internal report RAS/04/03/1.	D Keeley and A Collins	2004	

Failure Rate Advice (Confidential, not in the public domain)

90. See individual advice notes for specific details.

FR No	Application	Comments
65	Tanker unloading drive away prevention for ethylene oxide or propylene oxide.	Driveaway failure rate provided.

Bibliography

91. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A literature review of generic failure rates and comparison with the failure rates used in RISKAT. Confidential, not in the public domain.	R Hankin	Dec 91	
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	Refinement on reference above.
Major hazard aspects of the transport of dangerous	Advisory Committee on	1991	5.5 to 11 x 10^{-5}, spills of motor spirit per delivery (p.

Title	Author	Date	Comments
substances.	Dangerous Substances		256) 1 to 9 x 10^{-7} spills of LPG per delivery (p. 258) 0.6 to 1 x 10^{-6}, leaks of ammonia per delivery (p. 260) 0.76 to 1.9 x 10^{-5}, ship transfer accident rates per delivery (p. 131).
Guidelines for process equipment reliability data.	American Institute of Chemical Engineers	1989	5.7 x 10^{-5} failure per hour for road loading hoses not including couplings.
“Covo” report.	Rijnmond public authority	Nov 81	4 to 40 x 10^{-6} failures per hour for lightly and heavily stressed hoses. Generic figure used in the risk assessment and fault tree analysis. Table IX.I.
Loss prevention in the process industries.	F P Lees	1980	4 to 40 x 10^{-6} failures per hour for lightly and heavily stressed hoses. Generic figure probably originating from Covo report (p. 1005).
CIMAH safety case. Confidential, not in the public domain.	WS Atkins	Jun 94	
Reliability Technology.	Green & Bourne	1972	Gives failure rates for heavily stressed and lightly stressed hoses as 40 x 10^{-6} and 4 x 10^{-6} per hr respectively.
An initial prediction of the BLEVE frequency of a 100 te butane storage vessel.	K W Blything & A B Reeves	1988	0.77 to 57 x 10^{-6} failures per use. Details on the likelihood of various types of failure p. 11 and 42-44.
Major hazard risk analysis of two proposed routes for the M56 – M62 relief road. Confidential, not	Technica	Jul 91	

Title	Author	Date	Comments
in the public domain.			
Safety report. Confidential, not in the public domain.	WS Atkins	May 94	Broken down into pullaway, coupling failure, hose failure and pipework failure.
Acrylonitrile safety report. Confidential, not in the public domain.	Technica	1994	Table giving values for a range of hole sizes for flexible hose leaks (Table IX.3).
Calculation of release event frequencies. Confidential, not in the public domain.	WS Atkins	Jul 95	
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	Connection/disconnection error, hose pullaway, coupling failure.
Loss prevention in the process industries.	F P Lees	1986	Coupling; 5.0, unions and junctions; 0.4 (units: failures x 10^{-6} per yr).
Risk assessment acrylonitrile. Confidential, not in the public domain.	Courtaulds Research	Aug 88	
SR module. Confidential, not in the public domain.	Unknown	1978	
HF QRA. Confidential, not in the public domain.	Unknown	Jul 94	
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	
Transport of dangerous substances. Confidential, not in the public domain.	ACDS	Mar 90	
Generic land-use planning consultation zones - chlorine. Confidential, not in the public domain.	Unknown	1994	

Title	**Author**	**Date**	**Comments**
Fault tree illustrating the combination of events leading to a fire during LPG unloading. Confidential, not in the public domain.	British Gas	1995	Fault tree analysis, actual values are not given.
The likelihood of accidental release events. Confidential, not in the public domain.	Rhône-Poulenc Chemicals	Not dated	
Survey of catastrophic failure statistics for cryogenic storage tanks. Confidential, not in the public domain.	BOC	1989	
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	
The hazard analysis of the chlorine and sulphur dioxide storage installation plant. Confidential, not in the public domain.	Cremer and Warner	Nov 77	
Non-electric parts reliability data.	M J Rossi, Reliability Analysis Centre	1985	Values quoted for hydraulic hoses: 0.2×10^{-6} per hr and 33×10^{-6} per hr. Values quoted for couplings: 5.3×10^{-6} per hr and 1.4×10^{-6} per hr.

Item FR 1.2.4 Flanges and Gaskets

ITEM FAILURE RATES

Type of event	Failure rate (per year per joint)	Notes
Failure of one segment of a gasket.	5×10^{-6}	The hole size is calculated as the distance between two bolts and the gasket thickness.
Failure of Spiral Wound Gasket	1×10^{-7}	Hole size calculated as gasket thickness multiplied by pipe circumference.

SPRAY RELEASE FREQUENCY

	Frequency	Effective length of crack
Fixed pipe flange	5×10^{-6} per flange per year	Pipe diameter (max 150mm crack length)

Derivation

92. All rates are taken from the MHAU handbook volume 3 (now archived). The 5×10^{-6} value is derived in the Components Failure Rates paper, which is a comparison of 9 sources of joint failure rates derived elsewhere. The values were derived for chlorine duty although the review included LPG, petrochemical, steam/water, nuclear and other data. Assuming a fibre or ring type gasket in a 25 mm pipe, four bolt flange and a 3.2 mm gasket the gasket failure will produce an equivalent hole of 13 mm diameter.

References

Title	Author	Date	Comments
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium

Failure Rate Advice (Confidential, not in the public domain)

93. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice.	

Bibliography

94. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A literature review of generic failure rates and comparison with the failure rates used in RISKAT. Confidential, not in the public domain.	R Hankin	Dec 91	
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	5 x 10^{-6} per yr for significant leak of a fibre and ring type gasket (assumed to only be the loss of a section of gasket between two adjacent bolts).
Major hazard aspects of the transport of dangerous substances.	Advisory Committee on Dangerous Substances	1991	LPG rail wagon (p207): Flange gasket 1.4 x 10^{-12} per journey Manhole gasket 6.4 x 10^{-9} per journey Ammonia transfer 6.4 x 10^{-10} per gasket per transfer (p259) Chlorine road tanker 1.3 x 10^{-9} per journey (p264) LPG tanker p285-6.
Guidelines for process equipment reliability data.	American Institute of Chemical Engineers	1989	Types of failure not given.
Loss prevention in the process industries.	F P Lees	1980	0.1 to 100 x 10^{-6} per hr, page 1008.
CIMAH safety case. Confidential, not in the public domain.	WS Atkins	Jun 94	
CIMAH safety case support. Confidential, not in the public	Technica (USA)	May 89	

Title	Author	Date	Comments
domain.			
Reliability Technology.	Green & Bourne	1972	Failure rate for gaskets is 0.5×10^{-6} per hr
An initial prediction of the BLEVE frequency of a 100 te butane storage vessel.	K W Blything & A B Reeves	1988	Small (0.5”) leak: 4.7×10^{-6} per yr Medium (1”) leak: 3.5×10^{-7} per yr (p. 28)
Proposed gas terminal. Confidential, not in the public domain.	Technica	Aug 1991	Failure rate taken as filter failure rate.
Safety report. Confidential, not in the public domain.	WS Atkins	May 94	
QRA data. Confidential, not in the public domain.	Technica	May 89	Range of values quoted for different pipe diameters and hole sizes.
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	
Acrylonitrile safety report. Confidential, not in the public domain.	Technica	1994	
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	
Loss prevention in the process industries.	F P Lees	1986	0.5 failures $\times 10^{-6}$ per hr.
SR module. Confidential, not in the public domain.	Unknown	1978	
Safety cases within the Control of Industrial Major Accident Hazard (CIMAH) regs.	M L Ang & F P Lees	1989	3×10^{-6} per yr for 0.6 mm thick 5×10^{-6} per yr for 3 mm thick.

Title	**Author**	**Date**	**Comments**
Reliability and maintainability in perspective.	D Smith	1988	0.05 – 3 failures x 10^{-6} per hr, gasket type not specified.
Quantified risk assessment. Confidential, not in the public domain.	AEA Technology	1996	
A method for estimating the off-site risk from bulk storage of liquid oxygen (LOX). Confidential, not in the public domain.	BCGA/ HSE/ SRD Working Group	Not given	
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	
Non-electric parts reliability data.	M J Rossi, Reliability Analysis Centre	1985	Failure rate quoted for: RFI gasket: 0.4 x 10^{-6} per hr Rubber gasket: 0.5 x 10^{-6} per hr

Item FR 1.3 Pipework

ITEM FAILURE RATES

Failure rates (per m per y) for pipework diameter (mm)					
Hole size	0 - 49	50 - 149	150 - 299	300 - 499	500 - 1000
3 mm diameter	1×10^{-5}	2×10^{-6}			
4 mm diameter			1×10^{-6}	8×10^{-7}	7×10^{-7}
25 mm diameter	5×10^{-6}	1×10^{-6}	7×10^{-7}	5×10^{-7}	4×10^{-7}
1/3 pipework diameter			4×10^{-7}	2×10^{-7}	1×10^{-7}
Guillotine	1×10^{-6}	5×10^{-7}	2×10^{-7}	7×10^{-8}	4×10^{-8}

SPRAY RELEASE FREQUENCY

	Frequency	Effective length of crack
Fixed pipework	1×10^{-6} per metre per year	Pipe diameter (max 150mm crack length)

Derivation

95. The original values for pipework diameter < 150 mm were set out in the MHAU handbook volume 3 (now archived). They were derived in the Components Failure Rates paper, which is a comparison of 22 sources of pipework failure rates derived elsewhere. The values were derived for chlorine pipework although the review included LPG, petrochemical, steam/water, nuclear and other data. This information has been updated and augmented in an MHAU Panel discussion and Paper presented by the MHAU Topic Specialist on failure rates. The information presented in the table above is applicable to all process pipework.

96. The comparison of failure rates from the various sources is made difficult by:

- The various definitions of failures, leak, splits, rupture, etc.;
- The units used to describe the failure rates, per metre, per length, per connection, etc.;
- The difficulty in defining pipework and pipelines;
- The commonality of data source of the various reviewed failure rates; and

97. Different populations; the data comes from a wide range of populations including varying fluids, chlorine, LPG and nuclear materials as well as a wide range of countries. The

validity of assuming that a generic failure rate, derived from such a wide range, will be applicable to a UK installation might be questioned.

98. For severe leaks and guillotine failures, the analysis of worldwide chlorine pipework failures must be significant. This indicates a failure rate of 4.4×10^{-5} per vessel year, which becomes approximately 2×10^{-6} per m per yr if 20 metres of pipework per vessel is assumed. The SRS (Systems Reliability Service) work (SRD/037/WP1) indicates a corresponding failure rate of 2×10^{-5} per m per yr dependent on the assumed proportion of severe leaks to failures. Technica (Technica Safeti Package) used a failure rate of around 1×10^{-6} per m per yr for pipework of 50 mm diameter and above.

99. For lesser failures, the leakage failure rate implied by F17's (obsolete HSE accident reporting form) records of 1×10^{-4} per m per yr is supported by the SRS work, 10 to 100% of 4×10^{-4} per m.yr, and to some extent by ICI (Hillhouse report), pinholes 3×10^{-4} per m.yr to significant leaks 3×10^{-6} per m.yr. For significant leaks rather than those that are just detectable, several sources suggest that failure rates of around 1×10^{-5} per m.yr, including ICI (ICI 78/3) and Cremer and Warner (Rijnmond and Canvey reports).

100. The failure rate is assumed to decrease with increasing pipework size by ICI (Hillhouse ICI), Technica (Technica Safeti Package), Cremer and Warner (Canvey Report and SRD PD104), Wash (WASH 1400) and Kletz (1980). This relationship is only questioned by SRS where the converse relationship is suggested. There are possible reasons for more frequent failures of larger pipework, including lesser likelihood of impact glancing off larger pipework, its greater weight making supports more important, its greater diameter creating more possibility of a build-up of a corrosive residue. However, the CHEMRAWN (J L Hawksley, ICI) figure further confirms that the general view is that failure rates decrease with larger pipework sizes, by about half an order of magnitude between 50 and 150 mm diameter.

101. Failure rates for pipework with a diameter greater than 150 mm are derived in Gould (1997) – Large bore pipework failure rates which considers data from 9 other references. The majority of these data are from DNV Technica. It is suggested that the frequency of a guillotine failure decreases with increasing pipework diameter, therefore a single failure rate for large bore pipework failures would either overestimate the failure rate for the larger pipework or underestimate the failure rate for smaller pipework. To reduce the effect of this, large bore pipework is divided into 3 categories: 150 – 299 mm, 300 – 499 mm, 500 – 1000 mm. For pipework with diameter greater than 1000mm discussion with the Topic Specialist is required. The guillotine failure rate was found by plotting the values from these eight sources and applying expert judgement to define an 'average' value.

102. In addition to guillotine failure, three other failure scenarios are considered for each of the large bore pipework sizes. These are: leakage (4mm), split (25 mm) and major failure (1/3 pipework diameter). In order to calculate the frequency of these events, the following equation is used:

Frequency (per year) = $(4.7 \times 10^{-7})L/D$

where L is the length of the pipework and D is the diameter.

103. The failure rate derived represents the overall failure rate for pipework and represents both small and large failures. The distribution of the failure rate across the range of failure scenarios is shown below:

% of pipework cross sectional area	% Distribution
1	60
5	25
20	10
100	5

104. This was applied to the three categories (using the smallest diameter to represent the range), these points were plotted on a graph which was then used to estimate the frequencies of the required hole sizes.

References

Title	**Author**	**Date**	**Comments**
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium.
The reliability of pipework in UK process industry, SRD/037/WP1.	AG Cannon	1983	
Technica Safeti Package “Computer-based system for risk analysis of process plant”, Appendix IV.			
A study of some toxic gas emission hazards …, ICI 78/3.	J McQuaid et al		
Risk analysis of six potentially hazardous industrial objects in the Rijnmond area, a pilot study.	Cremer and Warner	1982	
Analysis of the Canvey Report.	Cremer and Warner		Report for the Oyez organisation.
ICI’s report on the HSE/ICI risk assessment study.	Hillhouse ICI		
Comments on reliability data used in the Cremer & Warner safety assessment of the proposed … gas	Cremer & Warner	1981	

Title	Author	Date	Comments
terminal and SNG plant, SRD PD104.			
An assessment of accident risks in US commercial nuclear power plants, USNRC, WASH 1400.	WASH		
Safety aspects of pressurised systems, fourth International Pressure Vessel Symposium.	T A Kletz	1980	
Some social, technical and economical aspects of the risks of large chemical plants, at CHEMRAWN III conference.	J L Hawksley, ICI	1984	
Large bore pipework failure rates. Confidential, not in the public domain.	J Gould	Sep 97	Suggests failure rates for a range of pipe sizes and failure scenarios.

Failure Rate Advice (Confidential, not in the public domain)

105. See individual advice notes for specific details.

FR No	Application	Comments
40	Solid pipework swivel jointed loading arm for liquid sulphur dioxide.	Catastrophic and leak failure rates given.
61	Failure of plastic lining of steel pipework.	Failure rate per unit given.
90	Blast furnace gas main, diameter between 1.8 m and 2.75 m.	Rates for 1000 mm pipe assumed.

Bibliography

106. These references represent other sources of information on the subject.

Title	Author	Date	Comments
A literature review of generic failure rates and comparison with the failure rates used in RISKAT. Confidential, not in the public	R Hankin	Dec 91	Average values for failure rate data.

Title	Author	Date	Comments
domain.			
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	Refinement on above reference.
Major hazard aspects of the transport of dangerous substances.	Advisory Committee on Dangerous Substances	1991	Pipework failures for chlorine, ammonia and LPD (p. 205-207).
Guidelines for process equipment reliability data.	American Institute of Chemical Engineers	1989	Gives failure rate of 0.0268 per 10^6 hrs (p. 183).
"Covo" report.	Rijnmond public authority	Nov 81	Risk assessment and fault tree analysis. Table IX.I.
Loss prevention in the process industries.	F P Lees	1980	Probably originating from Covo report. P 1005.
CIMAH safety case. Confidential, not in the public domain.	WS Atkins	Jun 94	
CIMAH safety case support. Confidential, not in the public domain.	Technica (USA)	May 89	Failure rates are given for a range of pipe diameters.
Reliability Technology.	Green & Bourne	1972	Failure rate for pipes given here is 0.2 x 10^{-6} per hr. Page 568.
IChemE, Major Hazard Assessment Panel, Draft Report reviewing historical incident data. Confidential, not in the public domain.	K W Blything & S T Parry	Aug 85	Historically derived failure rates.
Proposed gas terminal report. Confidential, not in the public domain.	Technica	Aug 91	Gives a hole size distribution and factors for different types of pipework.
Major hazard risk analysis of two proposed routes for the M56 – M62 relief road. Confidential, not in the	Technica	Jul 91	A detailed numerical analysis of the pipework failure by pipe size and hole size for process and

Title	Author	Date	Comments
public domain.			transport pipes is given.
Gas terminal CIMAH safety report.	Technica	Jun 1994	Appears to be ICI data.
Gas terminal study. SRD review of Cremer and Warner failure rates. Confidential, not in the public domain.	P L Holden (SRD)	Sep 81	
Safety report. Confidential, not in the public domain.	WS Atkins	May 94	From Covo report.
QRA. Confidential, not in the public domain.	Technica	Jan 89	Pipework and flange rate combined.
QRA data. Confidential, not in the public domain.	Technica	May 89	
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	
Acrylonitrile safety report. Confidential, not in the public domain.	Technica	1994	
Calculation of release event frequencies. Confidential, not in the public domain.	WS Atkins	Jul 95	Various failure rates are given for different sections of piping.
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	Rupture and leak considered for various sections of pipe.
Loss prevention in the process industries.	F P Lees	1986	≤ 3”: 1 x 10^{-9} per hr, > 3”: 1 x 10^{-10} per hr rates are for rupture (per section).
Risk assessment acrylonitrile. Confidential, not in the public domain.	Courtaulds Research	Aug 88	Rates are obtained from fault trees.

Title	Author	Date	Comments
SR module. Confidential, not in the public domain.	Unknown	1978	
HF QRA. Confidential, not in the public domain.	Unknown	Jul 94	
Guidelines for the preparation and review of a report under the CIMAH regulations. Confidential, not in the public domain.	BP CIMAH Liaisons Group	May 93	Pipework failure is collated and expressed as an equation.
Some social, technical and economical aspects of the risks of large chemical plants.	J L Hawksley	1984	Graph representing failure rate data for various pipe diameters.
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	
Generic land-use planning consultation zones - chlorine. Confidential, not in the public domain.	Unknown	1994	
Failure rates for pipework.	NW Hurst, et al.	Feb 94	Mean value for all the diameters considered is 4.6 x 10^{-7} per m per yr.
Safety cases within the Control of Industrial Major Accident Hazards (CIMAH) regs.	M L Ang & F P Lees	1989	Guillotine failure for 25 mm pipe given as 0.3 x 10^{-6} per m per yr.
Failure data collection and analysis in the Federal Republic of Germany.	K Boesebeck & P Homke	Not Given	Various values for different materials, table 2 p. 16.
The likelihood of accidental release events. Confidential, not in the public domain.	Unknown	Not given	
Piping failures in the United States nuclear power plants: 1961 – 1995.	HS Bush et al.	Jan 96	An examination of failure data by pipe size, failure type and failure mechanism.

Title	Author	Date	Comments
Pipe failures in US commercial nuclear power plants.	Electric power research institute	Jul 92	Historical failures used to derive failure rates for PWR and BWR for large, medium and small loss of containment accidents (p 5-11).
A review of reliability of piping on light water reactors. Confidential, not in the public domain.	Spencer H Bush	Not given	
Quantified risk assessment. Confidential, not in the public domain.	AEA Technology	1996	
A method for estimating the off-site risk from bulk storage of liquid oxygen (LOX). Confidential, not in the public domain.	BCGA/ HSE/ SRD Working Group	Not given	
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	
Site specific assessment. Confidential, not in the public domain.	AD Little	Apr 94	
The hazard analysis of the chlorine and sulphur dioxide storage installation plant. Confidential, not in the public domain.	Cremer and Warner	Nov 77	
Risks associated with the storage of and use of chlorine at a water treatment plant (2nd draft). Confidential, not in the public domain.	SRD	Nov 81	
Development of an improved LNG plant failure rate database.	D W Johnson & J R Welker	1981	Mean time between failures is given as: 582 x 10^6 ft-hrs (if time to repair is ignored this is approx. 45 x 10^{-6} per m per yr), this figure is for 'major' failures, other values

Title	Author	Date	Comments
			given.

Item FR 2 Electrical

107. Currently there are no agreed HSE failure rates for this item. The following references represent other sources of relevant information. A range of equipment will fall under this category, such as motors, contactors, relays and actuators such as solenoids. Much of the equipment will fall under IEC 61508 or IEC 61511. This data will be used for SIL (Safety Integrity Level) assessments and on Layers of Protection Analysis (LOPA).

Bibliography

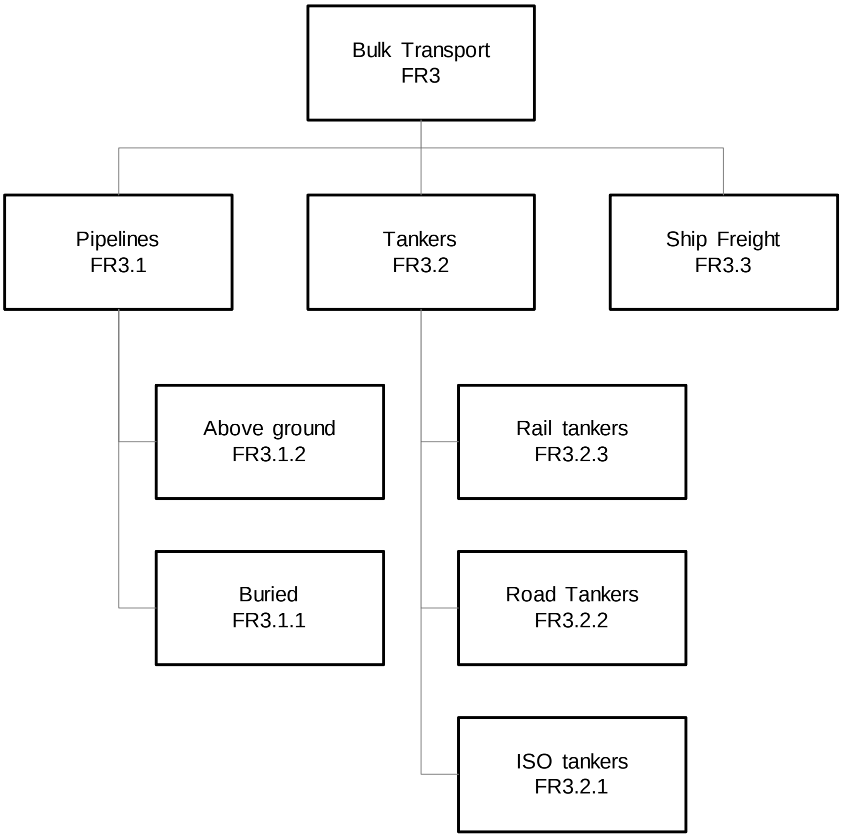
Title	Author	Date	Comments
IEEE Guide to the collection and presentation of electrical, electronic, sensing component and mechanical equipment reliability data for nuclear power generating stations	Institute of Electrical and Electronics Engineers Inc	1983	Covers a wide range of electrical components
Reliability Technology	Green and Bourne	1972	Average failure rates quoted for a wide range of electrical components in table A.7 (p.564)
Loss prevention in the process industries (V2)	F P Lees	1986	Variety of electrical components in table A9.2 and A9.3
Failure data collection and analysis in the Federal Republic of Germany	Boesebeck and Homke	Not dated	Table 7 gives failure rates for electrical devices
Reliability and maintainability in perspective (3rd Edition)	D J Smith	1988	Table 1 gives failure rates for a wide range of electrical and non-electrical equipment. Table 2 gives failure rates for micro-electric components
A review of instrument failure data	F P lees	1976	A range of instrumentation considered
OREDA – Offshore reliability data handbook	OREDA	1984, 1992, 1997, 2002	A variety of process control and electric equipment are included

Handbook of reliability data for electronic components used in communications systems, HRD5	British Telecommunications	1994	
Reliability data for safety instrumented systems, PDS data handbook	SINTEF	2006	
Safety equipment reliability handbook (3rd edition)	Exida.com LLC	2007	Part 1 Sensors, Part 2 Logic solvers and interface modules, part 3 Final elements
IEC 61508: Functional safety of electrical/ electronic/ programmable electronic safety-related systems.	International Electrotechnical Commission	2005	
IEC 61511: Functional safety – safety instrumented systems for the process industry sector.	International Electrotechnical Commission	2003	

Item FR 3   Bulk Transport

108. Failure rates for transport related items are categorised as shown in Figure 5.

Figure 5 Hierarchical diagram for bulk transport



Item FR 3.1 Pipelines

Introduction

109. Assessors carrying out Land Use Planning assessment may have cause to assess pipelines carrying a range of substances. The report by Howard and Chaplin, listed under FR 3.1.1, provides failure rates for a number of different substances. The failure frequencies available for gas pipelines fall into two categories, those for buried pipelines and those where the pipeline is above ground at a gas installation.

Item FR 3.1.1 Buried Pipelines

110. HID CI5’s PIPIN (PIPeline INtegrity) software package calculates failure frequencies for buried high pressure gas transmission pipelines, for use as inputs to the pipeline risk assessment program MISHAP, described in Chapter 6C. PIPIN can handle other pipelines but advice from the Topic Specialist should be sought before embarking on such work. The failure frequencies calculated by PIPIN may be input to MISHAP manually, or may be read by MISHAP from a PIPIN output file. The current version of PIPIN, Version 2.3, is more fully described in the PIPIN documents listed in the Bibliography.

PIPIN Description

111. PIPIN contains two principal models: -

- Operational Experience: using a generic approach derived from historical records of pipeline releases.
- Predictive: a predictive probabilistic approach using proprietary SYSREL code with fracture mechanics models to calculate failure frequencies due to third party damage for high pressure gas transmission pipelines.
- Current policy is to use a combination of both models: Operational Experience for Mechanical, Natural and Corrosion failures and Predictive for Third Party Failures. An option is available to enable this combination to be calculated automatically.

Current advice

112. The table illustrates which source of data should be used for each cause of damage. Gasoline, for example, uses CONCAWE data for mechanical and corrosion failures, UKOPA for natural failures and the PIPIN predictive model for TPA.

Cause	**Data set**			
	CONCAWE	**UKOPA**	**EGIG**	**PIPIN predictive**
Mechanical	Gasoline Spike crude oil Vinyl Chloride Carbon dioxide	Natural Gas Ethylene	LPG	
Natural		All commodity types		
Corrosion	Gasoline Spike crude oil	Natural Gas Ethylene	LPG	

	Vinyl Chloride Carbon dioxide			
TPA				All commodity types*

*May underestimate values for substances that lead to embrittlement of pipeline, for example, CO2.

References

Title	Author	Date	Comments
Update of pipeline failure rates for land use planning assessments. HSL report.	K Howard and Z Chaplin	2009	Currently a draft version.
Ethylene pipeline failure rates for Land Use Planning assessments. HSL report RSU/SR/08/03	Z Chaplin	2008	

Failure Rate Advice (Confidential, not in the public domain)

113. See individual advice notes for specific details

FR No	Application	Comments
116-2	Carbon dioxide pipeline	Cautious best estimate – assume rates for hazardous liquid pipelines
123	Methodology for use when PIPIN fails to converge	

Item FR 3.1.2 Above Ground Pipelines

ITEM FAILURE RATES

Failure Category	Failure Rate (per m per year)
Rupture (>1/3 diameter)	6.5×10^{-9}
Large Hole (1/3 diameter)	3.3×10^{-8}
Small Hole (5 mm – 25 mm diameter)	6.7×10^{-8}
Pin Hole (≤5 mm diameter)	1.6×10^{-7}

Applicability

114. The values above are applicable to general natural gas above ground installations subject to the following general limitations:

- Pipeline not to be more than 1.5 metres above ground level.
- Above ground section of pipeline under assessment to be entirely within a secure compound.
- Sites containing high speed rotating machines (e.g. compressor stations) should be referred to the Topic Specialist for advice.
- Sites where the presence of the pipeline is ancillary to the main activity (e.g. process plants) should be referred to the Topic Specialist for advice.
- The Topic Specialist should be informed on each occasion that these failure frequencies are used.

Derivation

115. The origin of the derivation is uncertain but the figures have been accepted by HID CI5 with the conditions specified in paragraph 113.

References

Title	Author	Date	Comments

Failure Rate Advice (Confidential, not in the public domain)

116. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 3.2 Tankers

117. Failure rates for this item are categorised as follows:

Item FR 3.2.1 Tank Containers (ISO Tankers)

ITEM FAILURE RATES

Type of event	Failure rate	Notes
Catastrophic failure	4 x 10^{-6} per vessel year	With no pressure relief system
Catastrophic failure	3 x 10^{-6} per vessel year	With a pressure relief system
50 mm diameter hole	3 x 10^{-5} per vessel year	This includes releases due to the valve being left open by the operator.
25 mm diameter hole	3 x 10^{-5} per vessel year	
13 mm diameter hole	6 x 10^{-5} per vessel year	
4 mm diameter hole	3 x 10^{-4} per vessel year	
Vapour release	5 x 10^{-4} per vessel year	50 mm diameter hole
50 mm diameter hole	6 x 10^{-7} per lift	Failures due to dropping of the tank < 5 metres.
Catastrophic failure	3 x 10^{-8} per lift	Failures due to dropping of the tank > 5 metres.
50 mm diameter hole	6 x 10^{-7} per lift	Failures due to dropping of the tank > 5 metres
50 mm diameter hole	9 x 10^{-11} per pass	Failures due to a container being dropped on to the tank.

Derivation

118. Failure rates are based on the report by J.Gould, RAS/00/10. Tank containers are tanks built within an ISO standard frame, 8 ft square and either 20 or 40 ft in length, allowing them to be fitted on several modes of transport and stacked. The failure rates apply to cold failures of pressure vessels not induced by fire engulfment or impingement. Empty tank containers are expected to contribute little to the off-site risk and should be excluded.

119. A literature search was performed to identify failure events of the tank containers and lifting equipment. It is assumed that tank containers dropped from up to about one ISO

container high (less than 5m) such as when stacking two-high will only produce a 50 mm hole. Tank containers dropped from a greater height such as when lifted above two-high stacks are assumed to suffer catastrophic failure 5% of the time, and a 50 mm hole for the remainder.

References

Title	**Author**	**Date**	**Comments**
New Failure Rates for Land Use Planning QRA. HSL internal report RAS/00/10.	J Gould	2000	

Failure Rate Advice (Confidential, not in the public domain)

120. See individual advice notes for specific details.

FR No	**Application**	**Comments**
	No specific advice issued.	

Bibliography

121. These references represent other sources of information on the subject.

Title	**Author**	**Date**	**Comments**
Tank container failures.	A B Harding	Mar 96	Various failure values given as per yr and per lift.
HF QRA. Confidential, not in the public domain.	Not given	Jul 94	

Item FR 3.2.2 Road Tankers

ITEM FAILURE RATES

Failure Category	Failure Rate (per km)
Serious accident rate	2.2 x 10^{-7}

Derivation

122. Failure rate is based on a report by Z. Chaplin, RSU/SR/2009/10. The rate was derived from MOD data for “serious” on-site accidents involving vehicles of over 4 tonnes in weight, for the period 1997 - 2008. A serious accident was defined as one for which the cost of repair was at least £10,000.

References

Title	Author	Date	Comments
Derivation of an on-site failure rate for road tankers. HSL internal report RSU/SR/2009/10.	Z Chaplin	2009	

Failure Rate Advice (Confidential, not in the public domain)

123. See individual advice notes for specific details.

FR No	Application	Comments
13	Road tanker unloading rates for chlorine and bromine tank containers	Catastrophic failure rate
66	Unloading Ethylene oxide from road tankers	Catastrophic failure rate
108	BLEVE of road tanker carrying 26 te LPG	

Bibliography

124. These references represent other sources of information on the subject.

Title	Author	Date	Comments
Major hazard aspects of the transport of dangerous substances.	Advisory Committee on Dangerous Substances	1991	Frequency of spills from various initiating events (p237). Frequencies for punctures

Title	Author	Date	Comments
			and small spills during stopovers (p252). Unloading event frequencies for LPG (p258). Gaskets, coupling and joint failures for ammonia (p259). Gasket and valves for chlorine (p264 and 285-6). Hose and coupling failure for ammonia unloading (p288).
CIMAH Safety Case. Confidential, not in the public domain.	W S Atkins	June 1994	
Calculation of Release Events Frequencies. Confidential, not in the public domain.	W S Atkins	2 July 1995	
Chlorine Safety Report – The Likelihood of Accidental Chlorine Release Events. Confidential, not in the public domain.	W S Atkins	October 1995	
Risk Assessment Acrylonitrile. Risk Assessment Butadiene. Confidential, not in the public domain.	Courtaulds Research	August 1988	
The Major Hazard Aspects of the Transport of Chlorine. Confidential, not in the public domain.	D Leeming and F Saccomanno	August 1993	
The Likelihood of Accidental Release Events. Confidential, not in the public domain.	Rhone-Poulenc Chemicals Ltd – Avonmouth Site	Not Given	
The Likelihood of Accidental Chlorine Release Events (Extract	W S Atkins	1994	

Title	Author	Date	Comments
From a CIMAH Safety Case). Confidential, not in the public domain.			
Risks Associated with the Storage of and Use of Chlorine at a Water treatment Plant (2nd Draft). Confidential, not in the public domain.	SRD	November 1981	

Item FR 3.2.3 Rail Tankers

125. Currently there are no agreed HSE failure rates for this item. The following references represent another source of information on the subject.

Bibliography

Title	Author	Date	Comments
Major hazard aspects of the transport of dangerous substances.	Advisory Committee on Dangerous Substances	1991	Frequency of spills from various initiating events (p237). Frequencies for punctures and small spills during stopovers (p252). Unloading event frequencies for LPG (p258). Gaskets, coupling and joint failures for ammonia (p259). Gasket and valves for chlorine (p264 and 285-6). Hose and coupling failure for ammonia unloading (p288).
The Major Hazard Aspects of the Transport of Chlorine. Confidential, not in the public domain.	D Leeming and F Saccomanno	August 1993	Compares different data sources for road and rail tanker accident rates and fault probability.

Item FR 3.3 Ship Freight

126. The transfer of substances via ship hardarms is covered in item FR 3.3.1.

Item FR 3.3.1 Ship Hardarms

127. The item failure rates are relevant to transfer operations via ship hardarms.

128. The first table is for the transfer of liquefied gases.

ITEM FAILURE RATES

	Failure frequencies per transfer operation		
Cause of failure (1)	Guillotine break	Hole = 0.1 cross sectional area of pipe	Simultaneous guillotine breaks (for multiple arms)
Connection failures (2)			
Arm	3.4x10^{-7}	3.1x10^{-6}	
Coupler (3)	5.1x10^{-6}	-	
Operator error (4)	5.4x10^{-7}	4.9x10^{-6}	
Sub-total per arm	6.0x10^{-6}	8.0x10^{-6}	
Ranging failures (5)			
Mooring fault	6x10^{-7}	-	
Passing ships (6)	2x10^{-7}	-	
Sub-total per system	0.8x10^{-6}		0.8x10^{-7} When multiple arms used (7)
Total failure rate when one arm used (8)	7x10^{-6}	8x10^{-6}	-
Total failure rate when 2 arms used (8)	13x10^{-6}	16x10^{-6}	1x10^{-7}
Total failure rate when 3 arms used (8)	19x10^{-6}	24x10^{-6}	1x10^{-7}

129. The second table is for the transfer of liquid cargo.

ITEM FAILURE RATES

	Failure frequencies per transfer operation for liquid cargo		
Cause of failure (1)	Guillotine break	Hole = 0.1 cross sectional area of pipe	Simultaneous guillotine breaks (for multiple arms)
Connection failures (2)			
Arm	3.2x10^{-6}	29.0x10^{-6}	
Coupler (3)	5.1x10^{-6}	-	
Operator error (4)	3.6x10^{-6}	3.6x10^{-6}	
Sub-total per arm	1.2x10^{-5}	3.3x10^{-5}	
Ranging failures (5)			
Mooring fault	19.2x10^{-6}	-	
Passing ships (6)	6.6x10^{-6}	-	
Sub-total per system	2.6x10^{-5}		2.6x10^{-6} When multiple arms used (7)
Total failure rates when one arm used (8)	3.8x10^{-5}	3.3x10^{-5}	-
Total failure rates when 2 arms used (8)	5.0x10^{-5}	6.6x10^{-5}	2.6x10^{-6}
Total failure rates when 3 arms used (8)	6.2x10^{-5}	9.9x10^{-5}	2.6x10^{-6}

130. Notes to both tables are as follows:

1) The table does not include failures on the ship itself e.g. pipes, pumps, valves, flanges. Incidents of overfilling of the ship during transfers to a ship are not included. Some of the failure frequencies are dependent on the length of transfer time and a 12-hour transfer time has been assumed.
2) Connection failures apply to every unloading arm that is used during the transfer operation. Failure may lead to flow from both ends of the disconnected arm.

3) It is assumed that all unloading arms handling liquified gases have emergency release couplings (ERC) designed to achieve a quick release with a minimum of spillage. The coupler failures specified here are events where the ERC parts without the valves in the coupling closing. Incidents where the coupling parts correctly will lead to minimal spillage.
4) This includes not making a connection correctly, opening the wrong valve or at the wrong time, or spilling cargo when disconnecting or venting.
5) Ranging failures are due to gross movement of the ship at the jetty. It is assumed that the unloading system is fitted with ranging alarms. (Absence of ranging alarms is assumed to increase the failure frequency due to Mooring faults by a factor of 5 and absence of ERC couplings would increase the Passing ships frequency by a factor of 5).
6) The failure frequency due to passing ships assumes 10 passing ships during offloading.
7) Ranging failures may simultaneously affect more than one connection where multiple hard arms are in use (i.e. the ship moves and more than one hard arm becomes disconnected). When ranging incidents occur where multiple hard arms are connected it is assumed that 10% of the failures will lead to flow from two of the connections.
8) The totals in the last three rows indicate how the data should be used. If there is only one arm then it is not possible to have two simultaneous guillotine breaks. If two are used then the probability of the connection failures is doubled, the ranging failures probability remains the same and there is now a probability that two simultaneous guillotine breaks can occur. If three hard arms are used then the probability of a connection failure is tripled, the probability of a ranging failure remains the same, and the probability of any two out of the three hard arms suffering a simultaneous guillotine break is assumed to be the same as when two hard arms are used.

Derivation

131. The failure rates presented here are based on the panel paper by P Buckley ‘Failures during ship transfers’ 8/11/04, 10/01/05 and 27/06/05 that reviewed a number of available reports and data sources. Failure Rate Advice note 124 summarises the derivation of the failure rates.

References

Title	Author	Date	Comments
Major hazard aspects of the transport of dangerous substances, HSC HMSO1991 ISBN 0-11-885676-6.	Advisory Committee on Dangerous Substance	1991	
Risk assessment of QEII dock, Eastham. 340/CD/1024/2001. Confidential, not in the public domain.	DNV	1992	
Failures during ship transfers, Panel Paper	P Buckley	08/11/04	
Panel minutes. Confidential, not in the public domain.		08/11/04	

Failures during ship transfers – Proposal for PCAG 6K, Panel Paper. Confidential, not in the public domain.	P Buckley	10/01/05	
Panel minutes. Confidential, not in the public domain.		10/01/05	
Failures during ship transfers – Proposal for PCAG 6K, Panel Paper. Confidential, not in the public domain.	P Buckley	27/06/05	
Panel minutes. Confidential, not in the public domain.		27/06/05	

Failure Rate Advice (Confidential, not in the public domain)

132. See individual advice notes for specific details.

FR No	**Application**	**Comments**
FR 124	Ship hardarms.	Guillotine and hole failure rates due to a number of causes.

Item FR 4 Moveable Storage

133. Moveable storage is further subdivided as follows:

134. For items 4.1.2 – 4.1.5 there are currently no agreed HSE failure rates but relevant advice notes have been included in each section.

Item FR 4.1.1 Drums 1 te

ITEM FAILURE RATES

Type of event	Failure rate	Notes
Spontaneous drum failure	2×10^{-6} per drum year	
Holes in drum (large)	1.2×10^{-6} per drum movement	
Holes in drum (small)	5×10^{-6} per drum movement	Rounded up from 4.8
Sheared liquid valve	4.5×10^{-6} per drum movement	Increased by a factor of 5 if valve points towards centre of room
Sheared vapour valve	4.5×10^{-6} per drum movement	
Coupling failure (guillotine)	10×10^{-6} per full drum used	
Coupling failure (leak)	90×10^{-6} per full drum used	
Operator failure (liquid)	1×10^{-6} per full drum used	x 10 for sites with automatic change over
Operator error (vapour)	1×10^{-6} per full drum used	
Pipework	3×10^{-6} per metre year	

Derivation

135. The original values were taken from the MHAU handbook volume 3 (now archived) for chlorine drums, and are applicable to other 1 te pressure vessel drums. Fault and event trees are used with a review of previous work and expert judgement to derive the failure rates. Drum failure is derived from static chlorine storage vessel failure rates, while those for holes and sheared valves are derived from a drum dropping frequency.

References

Title	Author	Date	Comments

Failure Rate Advice (Confidential, not in the public domain)

136. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Bibliography

137. These references represent other sources of information on the subject.

Title	Author	Date	Comments
Risk assessment of chlorine transport. Confidential, not in the public domain.	Technica	Jun 90	Historical data from Hong Kong and the US transport of drums
HF QRA. Confidential, not in the public domain.	Not given	Jul 94	
Generic land use planning consultation zones - chlorine. Confidential, not in the public domain.	Not given	Oct 94	

Item FR 4.1.2 Drums 210 litre

138. 200-220 litre drums. Currently there are no agreed HSE failure rates for this item. See failure rate advice notes for specific failure rates, or refer to Topic Specialist.

Failure Rate Advice (Confidential, not in the public domain)

139. See individual advice notes for specific details.

FR No	Application	Comments
34	210 l drums	Catastrophic (2 types of release), major and minor failure rates presented.
67	200 l and 5 l UN certified HF drums	Catastrophic (2 types of release), major and minor failure rates presented.
74	Moveable containers for HF, other acids and oleum	Catastrophic, major (50 mm) and minor (25 mm) failure rates presented.
106	220 l containers of strong aqueous HF, rated to 1.5 bar, 52 l containers, rated to 200 bar, of pressurised liquid WF6 and 8 l toxic containers, rated to 200 bar, of pressurised liquid Cl2	Catastrophic, major and minor failure rates for 220 l containers, catastrophic and 50 mm, 25 mm, 13 mm and 6 mm hole failure rates presented for 52 l and 8 l containers.

Item FR 4.1.3 Cylinders

140. Currently there are no agreed HSE failure rates for this item. See failure rate advice notes for specific failure rates, or refer to Topic Specialist.

Failure Rate Advice (Confidential, not in the public domain)

141. See individual advice notes for specific details

FR No	Application	Comments
119	Chlorine cylinders	Catastrophic and valve shear failure rates provided.

Item FR 4.1.4 IBCs

142. Currently there are no agreed HSE failure rates for this item. See failure rate advice notes for specific failure rates, or refer to Topic Specialist.

Failure Rate Advice (Confidential, not in the public domain)

143. See individual advice notes for specific details

FR No	Application	Comments
31	Stainless steel IBCs	Catastrophic, large (50 mm) and small (25 mm) hole failure rates provided.
33	HF acid non-UN IBCs	Catastrophic, large (50 mm) and small (25 mm) hole failure rates provided
39	UN IBCs	Catastrophic, large (50 mm) and small (25 mm) hole failure rates provided
74	Moveable containers for HF, other acids and oleum	Catastrophic, major (50 mm) and minor (25 mm) failure rates provided
114	HF $1m^3$	Catastrophic, major (50 mm) and minor (25 mm) failure rates provided

Item FR 4.1.5 Small Container

144. Currently there are no agreed HSE failure rates for the different types of small containers. See failure rate advice notes for specific failure rates, or refer to Topic Specialist.

Failure Rate Advice (Confidential, not in the public domain)

145. See individual advice notes for specific details

FR No	Application	Comments
20	HF acid carboys, delivered by lorry, removed to storage by fork-lift truck (FLT) and transported on wooden pallets with 9 carboys to a pallet.	Major (225l release) and minor (90l release) failure rates provided.
23	500kg PE containers, 0.8 m^3, transported by lorry on wooden pallets and transferred on site by FLT.	Catastrophic, major (90 mm) and minor (25 mm) failure rates provided.
50	Plastic containers for hydrogen peroxide transported by lorry on wooden pallets and transferred on site by FLT.	Catastrophic, major (90 mm) and minor (25 mm) failure rates provided.
57	25 l HF plastic carboys, delivered by lorry, removed to storage by FLT and transported on wooden pallets with 16 carboys to a pallet.	Catastrophic (2 release rates), major and minor failure rates provided.
67	200 l and 5 l UN-certified HF drums.	Catastrophic (2 types of release), major and minor failure rates provided.
81	1m^3 containers (IBCs or drums).	Catastrophic, major (50 mm) and minor (25 mm) failure rates provided.
98	Toxic atmospheric pressure storage tank and toxic moveable containers up to 1 m^3.	Catastrophic, major (50 mm) and minor (25 mm) failure rates provided (uses FR81).
106	220 l containers of strong aqueous HF, rated to 1.5 bar, 52 l containers, rated to 200 bar, of pressurised liquid WF6 and 8 l toxic containers`, rated to 200 bar, of pressurised liquid Cl2.	Catastrophic, major and minor failure rates provided for 220 l containers, catastrophic and 50 mm, 25 mm, 13 mm and 6 mm hole failure rates provided for 52 l and 8 l containers.

Event Data

146. Event data consists of external hazards that need to be taken into consideration when deriving an overall probability of failure for an item. The event data are split as follows:

Item ED 1	**Aircraft Strike Rates**	Page 94
Item ED 2	**Earthquake**	To be advised
Item ED 3	**Flooding**	Page 102
Item ED 4	**Lightning Strike Rates**	Page 103
Item ED 5	**Weather**	To be advised
Item ED 6	**Ignition Probabilities**	To be advised

Item ED 1 Aircraft Strike Rates

Introduction

147. The following is taken from Chaplin (RSU/SR/2009/06). The background crash rates quoted should be used for all sites whereas the remainder of the methodology need only be used when a site lies close to an airfield or beneath a flight path.

Background Crash Rate

148. The first stage in calculating the frequency of an aircraft striking an installation is to establish a background crash rate. The figures in Table 1 have been derived by Atkinson and Thompson (2008) as an update to the report by Byrne (1997).

Table 1 Aircraft crash rates calculated by Atkinson and Thompson

Aircraft Category	**Crash rate from Atkinson and Thompson (km^{-2} yr^{-1} x10^{-5})**
Light aircraft	2.04
Helicopters	1.05
Small transport aircraft	0.26
Large transport aircraft	0.11
Military combat aircraft	0.41
Total	3.87

149. The figure quoted for military combat aircraft (MCA) assumes that the site in question is not within an area of high crash concentration, which tends to correspond to areas where low-level flying occurs. There are two such areas in the UK; one in Northern England and the other around Lincolnshire. If the site falls within these zones then Atkinson and Thompson report a value of 5.81x10^{-5} km^{-2} yr^{-1}. If the site falls within a transition zone i.e. within 50 km of the boundary of a high MCA crash concentration zone, then the following equation has been derived to calculate the value for MCA:

$$f(x) = 5.81 \times 10^{-5} e^{-x/18} + 4.05 \times 10^{-6} \quad (1)$$

where x is the distance from the boundary of the high crash concentration zone and is less than 50 km, and $f(x)$ is the crash rate.

150. The high crash concentration zones are illustrated in Figure 6, which is taken from Atkinson and Thompson for the years 1996-2006. The high crash concentration zones are the inner shaded boxes on the map whilst the transition zones are shown by the outer shaded areas.

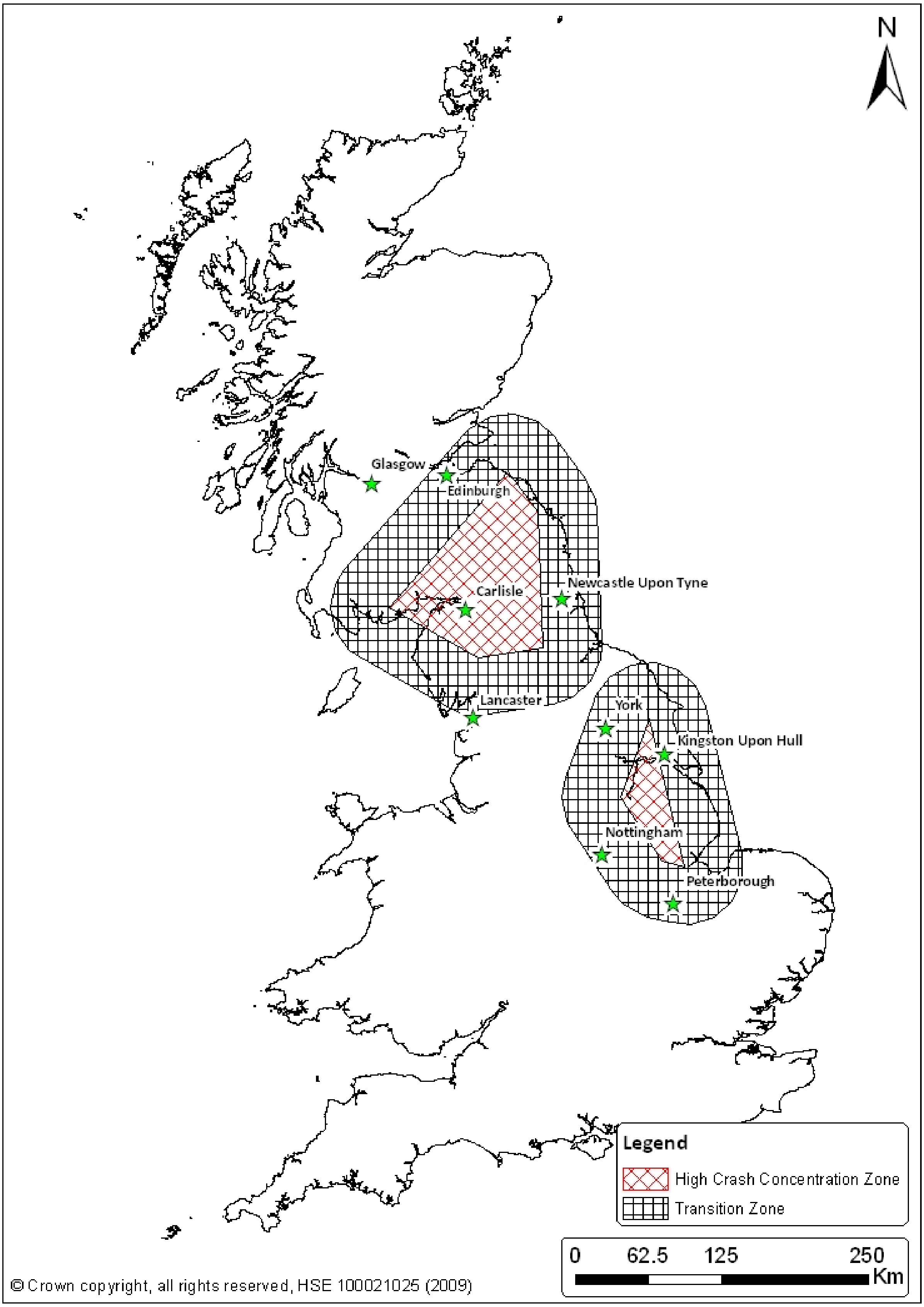


Figure 6 Military Combat Aircraft background accidents, 1996-2006

Airfield Rates

151. The figures reported in Table 1 and within the text assume that the site is not within 5 miles of an airfield. For sites within this distance, a different set of figures has been derived. According to the report by Byrne, which Atkinson and Thompson updated, consideration should only be given “to airfields within 10 km of the site unless the airfield is particularly busy (> 20,000 movements annually), or if the runway orientation is unfavourable for the site (i.e. the runway is pointing roughly in the direction of the site)”. Table 2 reports the probability of an aircraft crashing on take-off or landing as calculated by Atkinson and Thompson.

Table 2 Airfield-related crash rates

Aircraft Category	**Crash rate from Atkinson and Thompson (per take-off or landing x10^{-6})**
Light Aircraft	1.91
Civil helicopters	2.96
Small transport	2.40
Large transport	0.144
Military combat	3.60

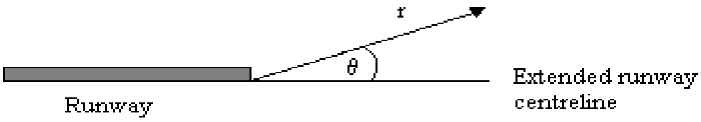
152. The value for MCAs comes from Byrne as that calculated by Atkinson and Thompson is a worldwide figure for UK military aircraft, rather than being UK specific. It would be expected that more crashes are likely to occur at unfamiliar airfield sites, some of which may be in war zones (although crashes arising from combat activities are excluded from this calculation). The figure from Byrne is considered to be more representative of the situation within the UK.

153. Using the values in Table 2 is not straightforward as it depends on the direction of the site from the airfield and the directions of the runways. The equation that determines the frequency, g, with which a unit ground area at position (r,θ) relative to the runway would suffer an impact as a result of N runway movements per year is given by:

$$g = NRf\,(r,\theta) \quad (2)$$

where R is the probability per movement of a landing or take-off accident and f(r,θ) is the probability of unit ground area at (r,θ) suffering an impact, given that an accident has occurred. Unit ground area is defined as 1 km^2 whilst r is measured in km from the runway threshold and θ is the angle measured in degrees between the extended runway centreline and a vector parallel to r (see Figure 7). R can be found from Table 2 whilst different expressions exist for calculating f(r,θ) depending on the category of aircraft. For some categories of aircraft, alternative equations have been derived using an (x,y) coordinate system to generate probabilities of accidents for take-offs and landings separately (FT(x,y) and FL(x,y) respectively). See Byrne for more detail. The calculated values of g would need to be added to those in Table 1 to provide a total crash rate for a specific location if it is near an airfield.

Figure 7 The r, θ coordinate system for accident locations in the vicinity of an airfield



Flight Paths

154. It is possible to calculate crash rates associated with particular airways so that a specific rate may be derived if the site lies beneath a flight path. This will also take into account whether the site is below an upper or lower airway. The calculation is based on the assumption that crashes are normally distributed about the airway centreline, with a standard deviation equal to the airway altitude. The actual equations can be found in Byrne but the in-flight reliabilities for each aircraft category are also required and these are shown in Table 3. It appears that these have not been updated by Atkinson and Thompson and so these figures are taken from Byrne.

Table 3 In-flight aircraft reliabilities

Aircraft Category	Reliability (crashes per flight km)
Light Aircraft	1×10^{-7}
Civil helicopters	1×10^{-7}
Small transport	3.9×10^{-10}
Large transport	4.7×10^{-11}
Military combat	2×10^{-8}

Worked Example

155. The figures in Table 1 can be used to calculate catastrophic failures and leaks from different hole sizes for vessels. The methodology illustrated in Table 4 can also be seen in FR19.

156. The consequences of a crash within a specified distance of the vessel are assumed for various aircraft types. For example, it is assumed that a light aircraft crashing within a 50 m radius of the vessel will cause a catastrophic failure, whereas, if it falls between 50 m and 70 m from the vessel, it will generate a 50 mm hole, etc. The values are shown in Table 4. Note that the values calculated differ from FR19 as there were errors in the original work, which have been corrected in Table 4. Also, the distances used are for the purposes of illustration only. Each site will require a specific assessment to determine at what distance each aircraft

type is likely to cause damage. This may depend on the construction of the site, the topology of the land or any other factor that could affect how much damage an aircraft crash would cause.

Table 4 Example of how to use the background crash rates

Aircraft Type	**Failure**	**Distance (m)**	**Area (x 10^{-3} km^2)**	**Background Rate (x 10^{-6} km^{-2} yr^{-1})**	**Vessel Rate (x 10^{-7} yr^{-1})**
Light	Cat	≤ 50	7.85	20.4	16.0
	50 mm	50 < distance ≤ 70	7.54	20.4	15.4
	25 mm	70 < distance ≤ 90	10.1	20.4	20.6
	13 mm	90 < distance ≤ 100	5.97	20.4	12.2
	6 mm	100 < distance ≤ 120	13.8	20.4	28.2
Helicopter	Cat	≤ 50	7.85	10.5	8.24
	50 mm	50 < distance ≤ 70	7.54	10.5	7.92
	25 mm	70 < distance ≤ 90	10.1	10.5	10.6
	13 mm	90 < distance ≤ 100	5.97	10.5	6.27
	6 mm	100 < distance ≤ 120	13.8	10.5	14.5
Small Transport	Cat	≤ 60	11.3	2.60	2.94
	50 mm	60 < distance ≤ 100	20.1	2.60	5.23
	25 mm	100 < distance ≤ 125	17.7	2.60	4.60
	13 mm	125 < distance ≤ 150	21.6	2.60	5.62
	6 mm	150 < distance ≤ 170	20.1	2.60	5.23
Large Transport	Cat	≤ 100	31.4	1.10	3.45

	50 mm	100 < distance ≤ 150	39.3	1.10	4.32
	25 mm	150 < distance ≤ 200	55.0	1.10	6.05
	13 mm	200 < distance ≤ 220	26.4	1.10	2.90
	6 mm	220 < distance ≤ 230	14.1	1.10	1.55
Military Combat	Cat	≤ 30	2.83	4.10	1.16
	50 mm	30 < distance ≤ 60	8.48	4.10	3.48
	25 mm	60 < distance ≤ 90	14.1	4.10	5.78
	13 mm	90 < distance ≤ 120	19.8	4.10	8.12
	6 mm	120 < distance ≤ 150	25.4	4.10	10.4
Total Catastrophic Failure					31.8
Total 50 mm hole					36.4
Total 25 mm hole					47.6
Total 13 mm hole					35.1
Total 6 mm hole					59.9

157. A second example illustrates the use of the values in Tables 1, 2 and 3. Assume a site of 1 km^2 that is located 1 km to the west and 1 km to the north of an airfield where the prevailing winds mean that aircraft take-off from east to west at all times, meaning that only take-offs need to be considered for this exercise. This is equivalent to an r value of $\sqrt{2}$ km and a θ of 45°. Using equation (6) from Byrne gives a value of f of 0.021, which should be used for light aircraft and can be applied to either take-offs or landings. For the other aircraft categories (excluding helicopters), as only take-offs need to be considered, equation (8) from Byrne should be used. This gives a value for FT of 0.013. Next it is necessary to have information on the number of movements at the airfield. Example figures for an imaginary airfield are shown in Table 5.

Table 5 Aircraft movements at imaginary airfield

Aircraft Category	Number of movements (take-offs and landings)
Light aircraft	200
Small transport aircraft	200
Large transport aircraft	200
Military combat aircraft	0

158. These figures are then halved to take into account that it is only take-offs that are of interest (landings occur in the same direction as take-offs so it is assumed that they do not pass over the site) and they are then multiplied by the relevant f or F figure and the values in Table 2. This is shown in Table 6.

Table 6 Calculation of the frequency of an area suffering an impact

Aircraft Category	No. of take-offs	F or f value	Crash rate (x10^{-6})	Frequency (x10^{-6}/year)
Light aircraft	100	0.021	1.91	4.01
Small transport aircraft	100	0.013	2.40	3.12
Large transport aircraft	100	0.013	0.144	0.187
Military combat aircraft	0	0.013	3.6	0

159. The total frequency can be found by adding these together, giving a rate of 7.32 x 10^{-6} /year. Next the values in Table 1 need to be added to this value to take into account the background crash rate. This gives a new total of 4.60 x 10^{-5} /year, assuming that the site is not in an area of high MCA crash concentration.

160. The final step is to calculate the contribution from an airway. Assume the site is directly below a lower airway (i.e. the aircraft altitude is 5 km). This gives, according to Byrne, an area factor of 0.395. The in-flight reliabilities (Table 3) can then be multiplied by the number of movements on that airway per year to give a crash rate. This is shown in Table 7, assuming figures for the number of movements for each of the aircraft types.

Table 7 Crash rates below an airway

Aircraft Category	No. aircraft using airway	Area factor	In-flight reliability ($x10^{-10}$)	Crash rate ($x10^{-7}$)
Light aircraft	500	0.395	1000	197.5
Helicopters	200	0.395	1000	79.0
Small transport aircraft	1000	0.395	3.9	1.54
Large transport aircraft	2000	0.395	0.47	0.37
Military combat aircraft	100	0.395	200	7.9

161. The total crash rate below an airway is 2.86 x 10^{-5} /year. This can then be added to the previous total to give an overall rate of 7.46 x 10^{-5} crashes/year

References

Title	Author	Date	Comments
Aircraft crash rates, HSL internal report RSU/SR/2009/06.	Chaplin Z	2009	
Review of aircraft crash rates for the UK up to 2006. ESR/D1000646/001/Issue 1. Confidential, not in the public domain.	Atkinson T and Thompson P	2008	This is an update of the report by Byrne
The calculation of aircraft crash risk in the UK. AEA Technology, Contract Research Report 150/1997.	Byrne JP	1997	

Failure Rate Advice (Confidential, not in the public domain)

162. See individual advice notes for specific details.

FR No	Application	Comments
19	Liquid hydrogen vessels	Demonstrates methodology

Item ED 3 Flooding

163. The first stage when trying to derive a figure for frequency of flooding for a specific site is to determine whether or not the site falls within a coastal or river flood plain. The Environment Agency (EA) website, which covers England and Wales, or the Scottish Environment Protection Agency (SEPA) website, can be used to assess where a particular site falls. If it is outside a flood plain then the risk from flooding can be considered to be negligible and the contribution from this event can be ignored.

164. If the site does fall within a flood plain, then more information on the probability of flooding per year can be obtained from either the EA or the SEPA. In the case of the former, they identify three areas to which they assign low, moderate or significant likelihood categories. Low likelihood areas correspond to a 1 in 200 chance per year or less of flooding, moderate is between a 1 in 200 chance per year and a 1 in 75 chance per year and significant likelihood corresponds to a greater than 1 in 75 chance per year of flooding. The SEPA website indicates areas in Scotland with a greater than 1 in 200 chance per year of flooding.

165. Even if the site is considered to be within one of the areas at risk of flooding, further information would be required to assess the likelihood of flood waters reaching a level at which damage could be caused to the site. This would require expert judgement and liaison with the relevant environment regulatory body. Once a probability of reaching this level of flooding has been determined, it would then be necessary to use further expert judgement to determine the level of plant damage sustained, e.g. the relative chance of a catastrophic failure occurring, or holes of differing sizes. It is not possible to produce a generic figure as each site will have a different level of flood protection in place and will be potentially subject to different levels of flooding.

References

Title	Author	Date	Comments
http://www.environment-agency.gov.uk/default (accessed on 2 September 2009)			Specifically, the flood maps were viewed.
http://www.sepa.org.uk/flooding/flood/map.aspx (accessed on 2 September 2009)			

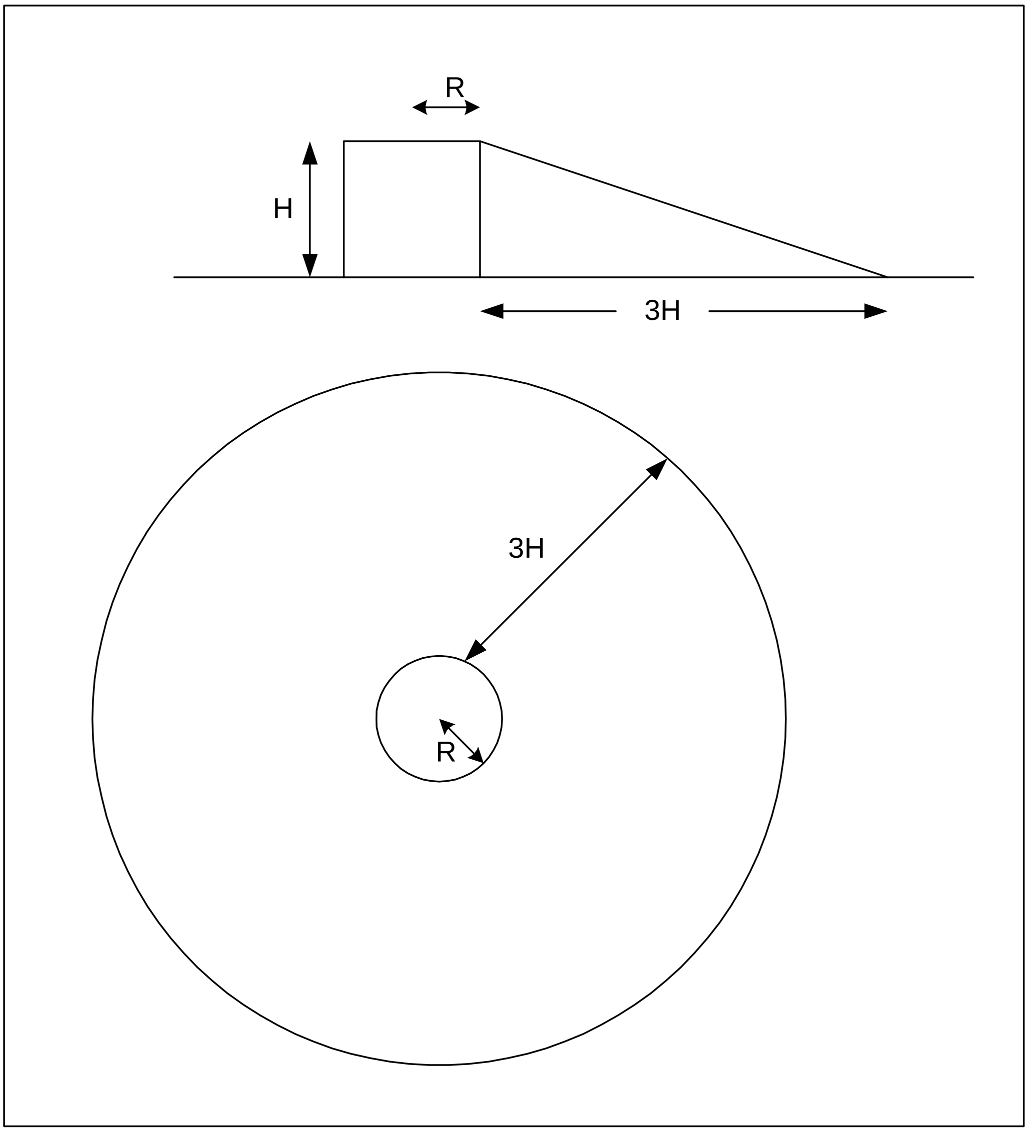
Item ED 4 Lightning Strike Rates

166. The British Standards Institute document, BS EN 62305-2:2006, details the calculations required to determine the frequency with which lightning will strike a structure and cause damage to it. The first stage is to calculate the average annual number of events that have the potential to cause damage. In order to do this, it is first necessary to calculate the collection area around the structure in question. For isolated structures on flat ground, this is defined as “the intersection between the ground surface and a straight line with 1/3 slope which passes from the upper parts of the structure (touching it there) and rotating around it” (in BS EN 62305-2:2006). For the simplest structure of a cylinder with height H and radius R, this would equate to an area, A, enclosed by the radius 3H + R, i.e.

$$A = \pi(3H + R)^2 \qquad (3)$$

167. This is illustrated in Figure 1 and all dimensions are measured in metres. As the shape of the structure becomes more complex, so approximations may need to be made to calculate the collection area but the general principle remains the same. Refer to BS EN 62305-2:2006 for more detail. For complex sites it is possible to divide the site into various zones, calculate the collection area of each zone and then follow all further calculations for each of the zones. The results from each zone are then summed together to give an overall damage probability.

Figure 8 Collection area of an isolated cylindrical structure



168. The second stage is to calculate the number of dangerous events, ND, for a structure using the equation:

$$N_D = L_{gfd} \times A \times F_{loc} \times 10^{-6} \qquad (4)$$

where:

L_{gfd} = lightning ground flash density (/km^2/year)

F_{loc} = location factor of the structure

A = collection area calculated in equation 1 (m^2).

169. The lightning ground flash density varies across the UK, from 0.02 /km^2/year in the north of Scotland, to 1.0 /km^2/year in parts of central England. The values can be found from Figure 1 in BS EN 62305-2:2006. The location factors are listed in Table 12 and were obtained from BS EN 62305-2:2006.

Table 12 Location factors

Location	**F_{loc}**
Surrounded by higher objects or trees	0.25
Surrounded by objects or trees of the same height or smaller	0.5
No other objects in the area	1
No other objects in the area and on top of a hill or knoll	2

170. To calculate the probability that a structure will be damaged, given a lightning strike, it is first necessary to consider whether there is a lightning protection system (LPS) in place. According to BS EN 62305-1:2006 there are four levels of protection that these systems can offer, I through to IV with I offering the highest level of protection. These are detailed in Table 5 of BS EN 62305-1:2006. The probabilities of damage being caused are listed in Table 13 and were obtained from BS EN 62305-2:2006.

Table 13 Probabilities of damage given a lightning strike, depending on the lightning protection measures in place

Details of structure	**Class of lightning protection system (LPS)**	**Probability**
Not protected by LPS	-	1
Protected by LPS	IV	0.2
	III	0.1
	II	0.05
	I	0.02
Air-termination system conforming to LPS I and a continuous metal or reinforced concrete framework acting as a natural down-conductor system.		0.01
Metal roof or an air-termination system, possibly including natural components, with complete protection of any roof installations against direct lightning strikes and a continuous metal or reinforced concrete framework acting as a natural down-conductor system.		0.001

171. These probabilities can then be multiplied by the number of dangerous events, ND, to produce an overall frequency of damage to a structure. The type of failure associated with the damage is likely to be structure dependent. Expert judgement may be required to produce factors that can be used as multipliers to the existing results to determine the likelihood of catastrophic failures and holes of varying sizes.

Worked example

172. To show how the data in Tables 12 and 13 and equations 1 and 2 may be used, consider a storage tank of radius 10 m and height 20 m. Using equation 1, the collection area is 15394 m^2. Assume there are nearby structures of the same height, which will give a location factor of 0.5 (from Table 12) and also assume that the site is located in an area with a lightning ground flash density of 0.7 per km^2 per year. The value of ND is then 0.0054 per year (from equation 2). Next assume that the structure has a lightning protection system of class I, which implies a probability of damage, given a lightning strike, of 0.02 (from Table 13). When multiplied by ND, this gives an overall frequency of damage of 1.08×10^{-4} per year. This number can then be multiplied by factors to give frequencies of different types of failure.

References

Title	Author	Date	Comments
Protection against lightning – Part 2: Risk management. BS EN 62305-2:2006.	British Standard	2006	
Protection against lightning – Part 1: General principles. BS EN 62305-1:2006.	British Standard	2006	