Health and Safety
Executive

Failure Rate and Event Data for use within Risk Assessments (06/11/17)

Introduction

1. The Chemicals, Explosives and Microbiological Hazardous Division 5, CEMHD5, has an established set of failure rates that have been in use for several years. This document 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 rates 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 document. For the full structure, see Figure 2. This introductory section also outlines a framework used in CEMHD5 to keep references pertaining to failure rates and a system for recording the use of non-generic failure rates used in particular cases.

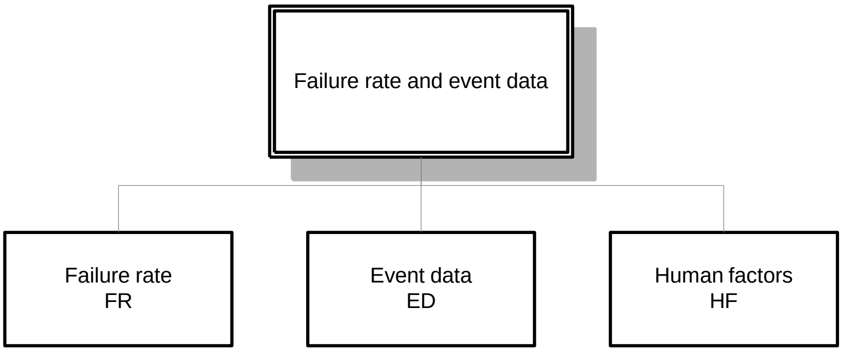

Figure 1 Information covered in Chapter 6K

3. The first section covers failure rates. CEMHD5 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.

4. The second section (see page 87) contains information on event data. The derivation of the rates to be used and how to use them are described.

5. The third section (see page 98) covers human factors. This aim of this section is to help non-human factors specialists determine whether the use of human reliability analysis, and associated values, is adequate or not.

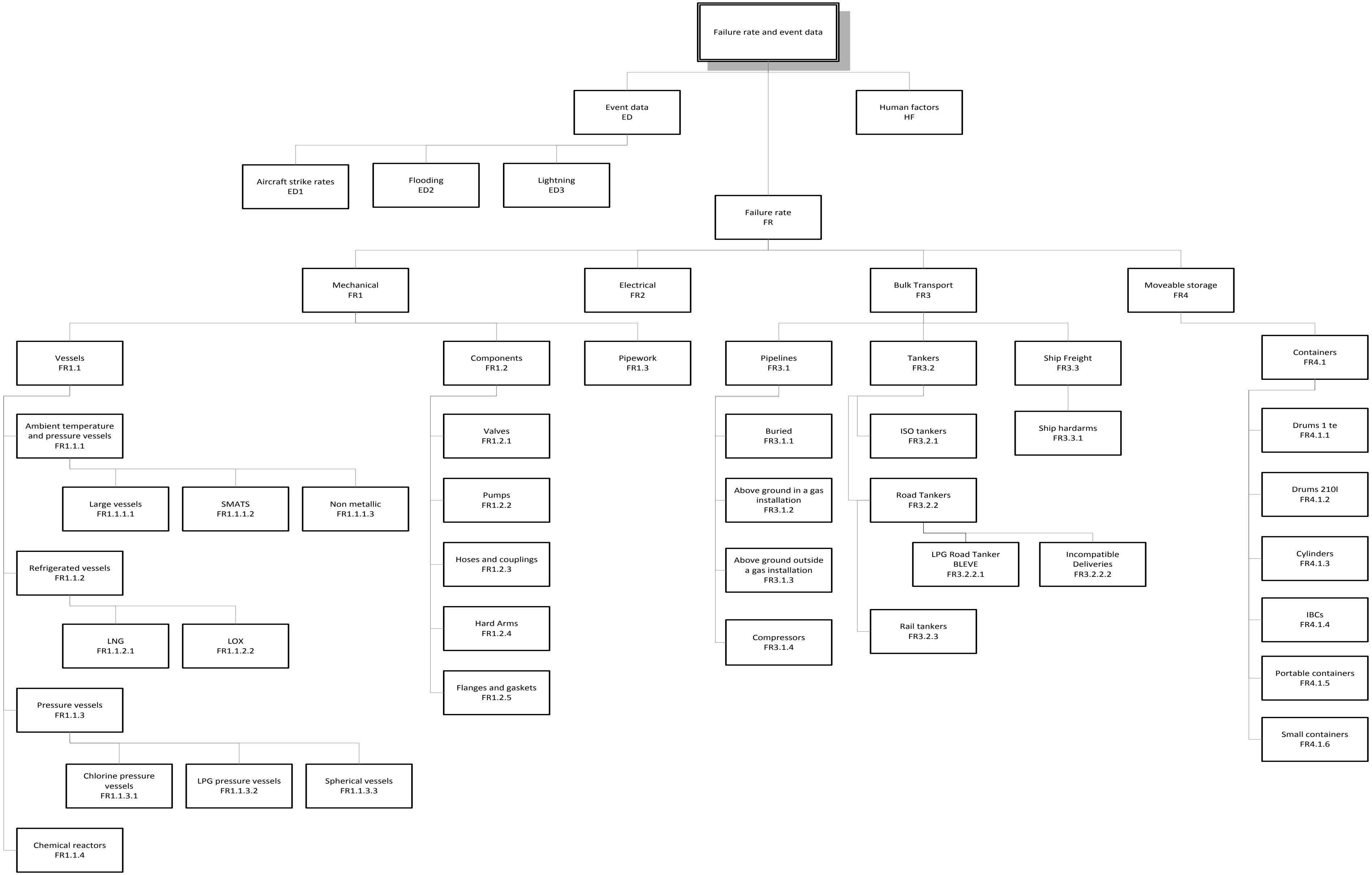

Figure 2 Overview of PCAG 6K structure

Failure Rates

Generic Failure Rates

6. Many of the failure rates used in risk assessments within CEMHD5 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 document for 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

7. 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.

8. When non-generic values are used in CEMHD5 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 CEMHD5 inspectors can endorse the value(s) used. The Topic Specialist will place completed FR notes on TRIM and a note made alongside the appropriate generic failure rate.

Description of the Information Required

FAILURE RATE ADVICE	
Requested By:	**Request No:**
Date:	
Request:	
Advice:	
Basis of Advice:	
Associated Documents:	
Signed:	**Date:**

Item FR 1 Mechanical

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

Item FR 1.1 Vessels

10. 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.

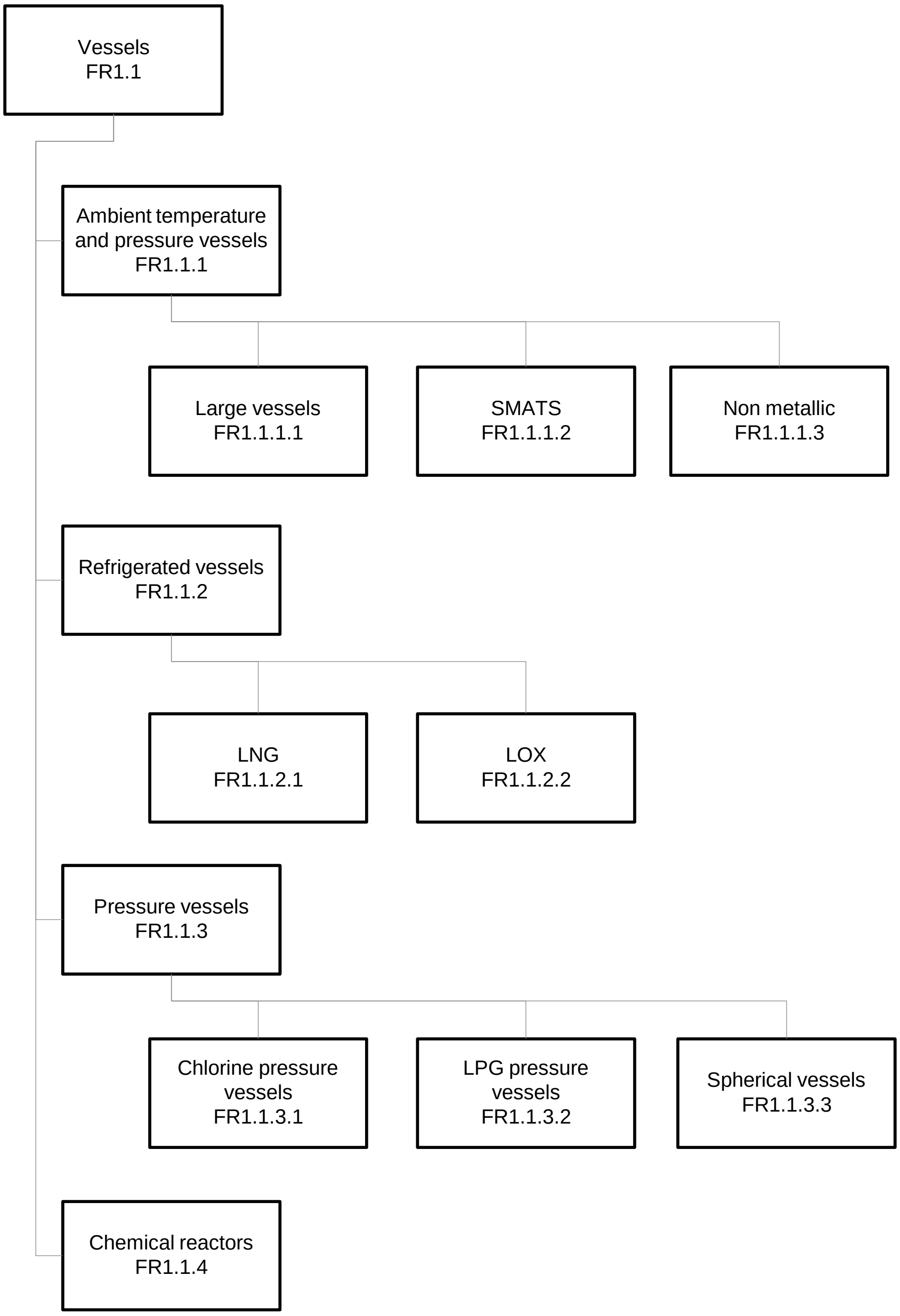

Figure 3 Hierarchical Diagram for Vessels

Item FR 1.1.1 Ambient Temperature and Pressure Vessels

11. 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

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

13. Roof failures includes all failures of the roof and 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.

14. 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)

15. See individual advice notes for specific details.

FR No	Application	Comments
FR128	Large mounded kerosene tanks shrouded in concrete	Rates are provided that give credit for the concrete shroud

Item FR 1.1.1.2 Small and Medium Atmospheric Tanks

16. Small and Medium Atmospheric Tanks (SMATs) have a capacity of less than 450m^3, and can be 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}

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

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

19. 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).

20. 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 19 (250/75mm), in which case the default 250mm and 75mm holes should be chosen.

Derivation

21. 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)

22. 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. Provides generic hole sizes for tanks of unknown capacity.

Item FR 1.1.1.3 Non Metallic/Plastic

23. 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)

24. 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

25. 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.

26. 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.

27. 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 Item 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.

28. 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.

29. 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)

30. See individual advice notes for specific details.

FR No	Application	Comments
105	Cryogenic ethylene (pressurised, semi-refrigerated), 20 te, temperature -53°C, pressure 12 barg.	Refrigerated pressure vessel. BLEVE frequency given.
89	Liquefied HCl.	Refrigerated pressure vessel. Catastrophic failure rate given.
84	Single skinned LPG tanks.	Catastrophic failure rate, 2000 mm, 1000 mm and 300 mm diameter holes and vapour release failure rates are provided.
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.

Bibliography

31. 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

Title	Author	Date	Comments
			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	Significant liquid release: 5.8 x 10^{-5} per vessel yr
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; the suggested value is 5 x 10^{-6} per vessel yr for catastrophic failure.
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	A value of 10^{-5} per vessel yr is quoted for LOX vessels, which are designed, constructed and maintained to high standards.
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	Catastrophic tank failure rate: 5 x 10^{-4} per vessel yr. ‘Significant’ release frequency: 5.8 x 10^{-5} per vessel yr.
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

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

33. 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 Item FR 1.1.2.

34. The failure rates for single walled LNG tanks are unchanged and the generic values in Item 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.

35. Where single walled LNG tanks have reinforced concrete high collared bunds they may be regarded as equivalent to double walled vessels and the double wall failure rates shown above may be used in assessments.

References

Title	Author	Date	Comments
Review of LNG storage tank failure rates. HSL internal report RAS/06/05. Confidential, not in the public domain.	D Keeley	2006	

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

36. See individual advice notes for specific details.

FR No	Application	Comments
FR126	Failure rates for LNG tanks with reinforced concrete high collar bunds	Considered to be equivalent to double wall tanks

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
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.
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.
9	LOX cluster tanks and internal explosions.	LOX cluster tanks and internal explosions. Catastrophic and major failure rates are derived.

Item FR 1.1.3 Pressure Vessels

43. Failure rates for pressure vessels are further subdivided into those for chlorine vessels, Item FR 1.1.3.1, LPG vessels, Item FR 1.1.3.2, and spherical vessels, Item FR 1.1.3.3. 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. Confidential, not in the public domain.	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
139	LNG stored in Vacuum Insulated Tanks (VITs)	Catastrophic failure rate given.
135	LNG storage tank BLEVE frequency	Use LPG BLEVE rate.
134	Glass lined bromine pressure vessel	Catastrophic failure rate given.
105	Cryogenic ethylene (pressurised, semi-refrigerated), 20 te. Temperature -53°C, pressure 12 barg.	BLEVE frequency given.
89	Liquefied HCl, 13.5 bar g and temperature of -40°C.	Catastrophic failure rate produced.
63	High pressure gas bullets.	Cold and hot catastrophic, full manhole, 50 mm and 25 mm diameter hole failure rates produced.
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.
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.
14	29.6 te fixed bromine tanks.	Catastrophic failure rate produced.

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	6 x 10^{-6} per yr, catastrophic failure, average values for failure rate data.
Review of failure rate data used in risk assessment.	G Simpson	Sep 93	7.4 x 10^{-6}
Guidelines for process equipment reliability data.	American Institute of Chemical Engineers	1989	9.5 x 10^{-5}, catastrophic failure of pressure vessels page 205.
“Covo” report.	Rijnmond public authority	Nov 81	6 x 10^{-6}, 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. Confidential, not in the public domain.	W S Atkins	Jun 94	2 x 10^{-6} per yr, catastrophic failure.
CIMAH safety case support. Confidential, not in the public domain.	Technica (USA)	May 1989	6.5 x 10^{-6} per yr, catastrophic data (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 x 10^{-5} per vessel yr, catastrophic data (includes boilers).
Reliability Technology.	Green & Bourne	1972	Two values are given for pressure vessels: General – 3.0 x 10^{-6} per hr High standard – 0.3 x 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 x 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	9.4 x 10^{-7} per year, catastrophic failure.
A further survey of pressure vessel failures in the UK (1983 – 1988) – public domain version.	T J Davenport	1991	Value of 5.1 x 10^{-5} per yr derived for all pressure vessels. Also individual values derived for air receivers, steam receivers and boilers.
Proposed gas terminal. Confidential, not in the public domain.	Technica	Aug 1991	6.5 x 10^{-6}per yr, catastrophic failure.
CIMAH safety report for gas terminal. Confidential, not in the public domain.	Technica	Jun 94	6.5 x 10^{-6}per yr, rupture. 5, 25 and 100 mm diameter hole size failure rates also given.
Gas terminal study. SRD review of Cremer and Warner failure rates. Confidential, not in the public domain.	P L Holden	Sep 81	1 x 10^{-6} per yr, catastrophic, not including nozzle failures. Process vessels rise to 3 cpm.
QRA data. Confidential, not in the public domain.	Technica	May 89	6.5 x 10^{-6} per yr catastrophic failure rate, also contains failure rates for partial failures.

Title	Author	Date	Comments
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	6 x 10^{-6} per yr catastrophic, 50 mm diameter hole size also given.
Safety report R2000 reactor rupture fault tree analysis. Confidential, not in the public domain.	Not given	1994	3.65 x 10^{-5} per yr, reactor bursts.
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	A value of 2.7 x 10^{-8} per vessel yr is derived for the cold catastrophic failure of LPG pressure vessels.
Calculation of release frequencies. Confidential, not in the public domain.	WS Atkins	Jul 95	1.2 x 10^{-8} per yr for catastrophic rupture of pressure relief vessel (intermittent use only).
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	5 x 10^{-6} per yr, for bulk storage tank.
Loss prevention in the process industries.	F P Lees	1986	General pressure vessel: 3 High standard: 0.3 (units of failures x10^{-6} per yr)
SR module. Confidential, not in the public domain.	Unknown	1978	1 x 10^{-6} per yr catastrophic failure.
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	Cold failure 6.5 x 10^{-6} per yr Hot failure (BLEVE) 26 x 10^{-6} per yr
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	2 x 10^{-6}per yr, rupture.
Generic land use planning consultation zones - chlorine. Confidential, not in the public domain.	Not given	Oct 94	Catastrophic failure of chlorine storage vessel 2 x 10^{-6} per yr (lower bound).
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	Small leaks (0 – 25 mm): 2 x 10^{-4} per vessel yr Medium leaks (25 – 100 mm): 2 x 10^{-5} per vessel yr Large leaks (> 100 mm): 2 x 10^{-6} per vessel yr
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	Estimates the failure rate of pressure vessels for LOX storage to be in the order of 10^{-5}per yr.
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.

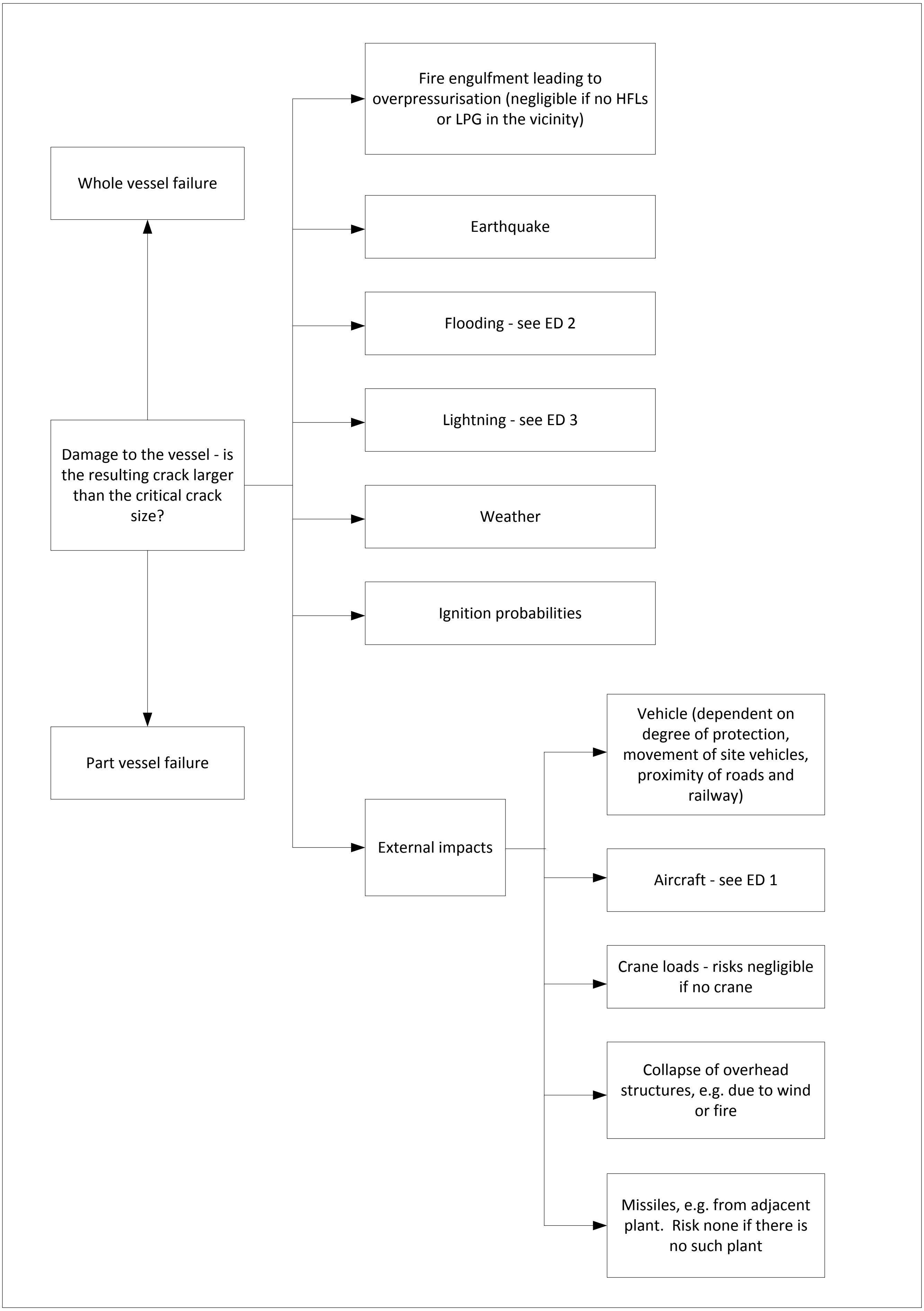

Figure 4 External Hazards for Pressure Vessels

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. Confidential, not in the public domain.	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	$6x10^{-6}$per yr, catastrophic failure. Average values for failure rate data. Page 2.
Guidelines for Process Equipment Reliability Data.	Centre for Chemical Process Safety of the American Institute of Chemical Engineers	1989	$9.5x10^{-5}$, catastrophic failure of pressure vessels page 205.
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	Derives a catastrophic failure rate of $5x10^{-6}$ per yr.
Chlorine Safety Report– The Likelihood of Accidental Chlorine Release Events. Confidential, not in the public domain.	W S Atkins	October 1995	Derives a catastrophic failure rate of $5x10^{-6}$ per yr. Probably the same derivation as above.
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	$4.1x10^{-5}$per yr, catastrophic failure.

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. Pape 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 1×10^{-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. Confidential, not in the public domain.	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	$6x10^{-6}$per yr, catastrophic failure. Average values for failure rate data. Page 2.
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} per yr, catastrophic failures. Table IX.I.
Loss prevention in the process industries.	F P Lees	1980	1×10^{-5} per yr, catastrophic failure based on Canvey data. Page 1018.
CIMAH safety case support.	Technica (USA)	May 89	6.5×10^{-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	9.4×10^{-7} per yr, catastrophic failure.
Estimation of cold failure frequency of LPG tanks in Europe. Confidential, not in the	W Sooby & J M	1994	A value of 2.7×10^{-8} per vessel yr is derived for the cold catastrophic

public domain.	Tolchard		failure of LPG pressure vessels.
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	Quotes value for hot failure (BLEVE) of 26 x 10^{-6} per yr, probably for an LPG vessel.

Item FR 1.1.3.3 Spherical Vessels

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

67. The failure rates are taken from RSU/SR/2010/02 by Z Chaplin.

68. No evidence was found in the literature to suggest that the failure rates for spherical vessels would differ significantly from those used for pressure vessels.

69. However, it was considered that the supporting legs of spherical vessels provide an additional failure mode for this type of vessel, although there was no firm evidence in the literature.

70. It is therefore recommended that a cautious approach is taken and the median value for catastrophic failure is used.

References

Title	Author	Date	Comments
Failure rates for spherical tanks. HSL short report RSU/SR/2010/02. Confidential, not in the public domain.	Z Chaplin	2010	

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

71. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

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}	
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

72. The catastrophic failure rate is taken from the panel paper by P Betteridge (Panel Paper 1999-003) and has been reviewed by Chaplin (MSU/LET/2013/37/1). The value is for pressurised chemical reactors, and includes both batch and continuous, but not non-metallic reactors or small lab-scale reactors. It includes both reactors that are capable of thermal runaway and those that are not. 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.

73. 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 1.2×10^{-5} per reactor year with an equivalent hole size of 13 mm for a 2 mm gasket.

References

Title	Author	Date	Comments
HSE Panel Paper 1999-003. (Confidential, not in the public domain)	P. Betteridge	1999	
Chemical Reactor Failure Rates MSU/LET/2013/37/1. Confidential, not in the public domain.	Z. Chaplin	2013	

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

74. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 1.2 Components

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

Spray Releases

76. 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.

77. 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)

78. 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.

79. Spray releases frequencies are given for Items FR 1.2.1- FR 1.2.3 and FR 1.2.5.

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	2×10^{-4} per valve per year	Shaft circumference

Derivation

80. 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.

81. 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).

82. 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.

83. 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.

84. 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.

85. 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)

86. See individual advice notes for specific details.

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

Bibliography

87. 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.
“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	External leak: 2.3×10^{-4} per yr Passing: 3×10^{-4} per yr
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. Failure of ESD valve to close of 0.1 per demand including all control systems.
CIMAH safety report for gas terminal. Confidential, not in the public domain.	Technica	Jun 94	Derives a value of 1.6×10^{-5} per valve year for rupture.
CIMAH safety report. Confidential, not in the public domain.	WS Atkins	May 94	Shut off valve 1.3×10^{-2} per demand. Manual valve 0.05 (probability).

Title	Author	Date	Comments
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	Rupture failure frequency for a valve is given as 8.76 x 10^{-5} per yr.
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	EFV failure to close 2.6 x 10^{-2} per yr probability for fail on demand 6.5 x 10^{-2} per yr.
Loss prevention in the process industries.	F P Lees	1986	Values given in failures x 10^{-6} per hr 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	EFV failure 10^{-2} per demand (taken from Covo report).
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	Internal fischer valve fails (due to mechanical damage), probability 1 x 10^{-4}.
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 demand
The likelihood of accidental release events. Confidential, not in the public domain.	Unknown	Not given	Probability valve failure to close (assuming a proof test period of 3 months), 4 x 10^{-2} on demand.
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	3 leak sizes are considered for 3 valve sizes. Values range from 1 x 10^{-3} to 1 x 10^{-5} (units are assumed to be per year)
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	Valve failure rate quoted as 3.6 x 10^{-5} per valve per yr.
Site specific assessment. Confidential, not in the public domain.	AD Little	Apr 94	There are several valve failures (to operate) considered in this

Title	Author	Date	Comments
			reference. Values given for valve fails closed vary from 1 x 10^{-3} to 3 x 10^{-4} per yr.
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	The likelihood of a pipe/valve failure is estimated to be 10^{-4} per yr. Also the probability of a release (1kg/s) from the pressure reducing valve was estimated to be 10^{-2} per yr.
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.
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: Motor operated and check valve: 5 x 10^{-7} per hr.

Item FR 1.2.2 Pumps

ITEM FAILURE RATES

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

SPRAY RELEASE FREQUENCY

	Frequency	**Effective length of crack**
Pump single seal	5 x 10^{-4} per pump per year	Shaft circumference
Pump double seal	5 x 10^{-5} per pump per year	Shaft circumference

Derivation

88. 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)

89. See individual advice notes for specific details.

FR No	Values	Application
	No specific advice	

Bibliography

90. 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).

Title	Author	Date	Comments
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	Pump seal failure: 25 mm hole: 2.4 x 10^{-3} per yr Full bore: 6.8 x 10^{-4} per yr
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	Pump seals: Gland 0.7 per yr Simple mechanical 0.57 per yr Double mechanical 0.45 per yr
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	100 x 10^{-3} per yr for catastrophic failure
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	3 leak sizes are considered for pumps. Values range from 6 x 10^{-2} to 6 x 10^{-4} – units probably $(\text{pump.y})^{-1}$.
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	For a pump on standby the failure rate is 3.1 x 10^{-4} per demand.
Site specific assessment. Confidential, not in the public domain.	AD Little	Apr 94	Reflux pump trips off: 2 per yr. Spare pump fails to start on demand: 1x 10^{-2} per yr.

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 x 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

	Probability of failure per transfer 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	1.2 x 10^{-7} per transfer	Hose diameter

Derivation

91. The hose and coupling probabilities of failure apply to road tanker transfers. The guillotine probabilities of failure are taken from the report by Gould and Glossop, RAS/00/10. An extension of this work by Keeley (RAS/04/03/1) derived the smaller hole probabilities of failure. 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 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.

92. 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.

93. 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 hard arms. Probabilities of failure for hard arms can be found in Item FR 1.2.4.

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)

94. 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

95. 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	1.6 x 10^{-6} per connection, average values for failure rate data.
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 substances.	Advisory Committee on Dangerous Substances	1991	5.5 to 11 x 10^{-5}, spills of motor spirit per delivery (p. 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	Failure rates for flexi pipe: Partial failure: 7.6 x 10^{-7} per operation

Title	Author	Date	Comments
			Guillotine: 7.6 x 10^{-8} per operation Failure rates for coupling: Partial failure: 4.4 x 10^{-5} per yr Guillotine failure: 4.4 x 10^{-6} per yr.
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 in the public domain.	Technica	Jul 91	Hose spill frequency estimated at 6.8 x 10^{-5} per cargo (for ship to shore transfers), p. XI.11.
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	2.9 x 10^{-4} per yr for guillotine failure.
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	Coupling fail: 3 x 10^{-6} per operation. Two flexihoses quoted: 7.2 x 10^{-4} and 3.1 x 10^{-2} per yr.
SR module. Confidential, not in the public domain.	Unknown	1978	Heavily/ lightly stressed 0.35 per yr / 0.035 per yr
HF QRA. Confidential, not in the public domain.	Unknown	Jul 94	Guillotine failure of drum coupling 10^{-5} per operation. ISO tanker coupling 3 x 10^{-6} per op.
Handbook of risk analysis. Confidential, not in the public domain.	Hydro	Not given	0.01 yr^{-1} for flexible hose.
Transport of dangerous substances. Confidential, not in the public domain.	ACDS	Mar 90	Leak through ‘snap tight’ coupling 4 x 10^{-7} per transfer (p. 8).
Generic land-use planning consultation zones - chlorine. Confidential, not in the public domain.	Unknown	1994	Probability of 3 x 10^{-6} per delivery operation.
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	Catastrophic failure of flexible pipe 7.6 x 10^{-8} per operation.
Survey of catastrophic failure statistics for cryogenic storage tanks. Confidential, not in the public domain.	BOC	1989	Hose and coupling failure rate of 3 x 10^{-6} per hour operation (p. 14).
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	Coupling failure (total): 4.4 x 10^{-5} per yr. Coupling failure (partial): 4.4 x 10^{-4}

Title	Author	Date	Comments
			per yr.
The hazard analysis of the chlorine and sulphur dioxide storage installation plant. Confidential, not in the public domain.	Cremer and Warner	Nov 77	A value of 10^{-4} to 10^{-6} per yr has been assumed for a major rupture on a loading line.
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 Hard Arms

ITEM FAILURE RATES

Type of Release	**Probability of failure per transfer**
Guillotine failure	2×10^{-7}
15 mm diameter hole	4×10^{-7}
5 mm diameter hole	6×10^{-6}

Derivation

96. These probabilities of failure apply to hard arms that are used to transfer material between a road tanker and fixed storage tanks. The values are derived in a report by Keeley, MSU/LET/2013/20, and are based on the hose and coupling work detailed in Item FR 1.2.3 (Gould and Anderson, 2000, Keeley and Collins, 2004).

97. A simple analysis of the fault trees used to derive the hose and coupling probabilities of failure was carried out. The hose and coupling fault trees were re-analysed to determine which failure modes were applicable to hard arm transfers and which were specific to flexible hoses. In addition, any unique failure modes that were specific to hard arms were also identified.

98. For guillotine failure a number of events were not considered to be relevant for hard arms and the fault trees were reanalysed with the following events removed:

    - hose damaged due to vehicle impact prior to transfer
    - hose of incorrect specification
    - guillotine failure due to overpressurisation
    - brittle hose

99. For less than catastrophic hole sizes the following events were not considered to be relevant to hard arms and therefore removed from the fault trees:

    - vehicle runs over hose
    - unrelieved overpressure in hose
    - wrong type of hose

100. An additional failure mode for hard arms that needed to included was failure of the swivel joints and a typical hard arm was assumed to have five swivel joints per arm.

101. The fault trees were re-evaluated and the calculated probabilities of failure were found to be similar to those for flexible hoses at multi-safety system sites. Given the uncertainty in the analysis the hose and coupling probabilities of failure have been adopted for sites with multi-safety systems and average type facilities.

102. For basic type facilities which may not carry out such rigorous inspection, a site specific probability of failure will need to be calculated.

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 rates for hard arms. HSL internal report MSU/LET/2013/20. Confidential, not in the public domain.	D Keeley	2013	

Item FR 1.2.5 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

103. 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)

104. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice.	

Bibliography

105. 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	R Hankin	Dec 91	2.4×10^{-6} per join per year, average values for failure rate data.

Title	Author	Date	Comments
RISKAT. Confidential, not in the public domain.			
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	For a pinhole leak through a gasket a failure rate of 8.8 x 10^{-5} per yr. For the loss of a piece of gasket between two adjacent bolts 5.6 x 10^{-6} per yr is used.
CIMAH safety case support. Confidential, not in the public domain.	Technica (USA)	May 89	A failure rate of 1 x 10^{-5} per yr is given for high quality flanges e.g. raised face, ring type or grey lock flanges (p. VII.16).
Reliability Technology.	Green & Bourne	1972	Failure rate for gaskets is 0.5 x 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 x 10^{-6} per yr Medium (1”) leak: 3.5 x 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	5.6 x 10^{-5} per yr.
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	8.4 x 10^{-5} y^{-1}, data for 3 flange sizes
Acrylonitrile safety report. Confidential, not in the public domain.	Technica	1994	1.8 x 10^{-4} y^{-1} for rupture. Also values given for smaller hole sizes
Chlorine safety report. Confidential, not in the public domain.	WS Atkins	Oct 95	8.4 x 10^{-5} $(\text{gasket.y})^{-1}$
Loss prevention in the process industries.	F P Lees	1986	0.5 failures x 10^{-6} per hr.
SR module. Confidential, not in the public domain.	Unknown	1978	Failure rate of 4.4 x 10^{-3} per yr given.
Safety cases within the Control of Industrial Major Accident Hazard (CIMAH) regs.	M L Ang & F P Lees	1989	3 x 10^{-6} per yr for 0.6 mm thick

Title	Author	Date	Comments
			5 x 10^{-6} per yr for 3 mm thick.
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	3 leak sizes are considered for 3 flange sizes. Values range from 1 x 10^{-4} to 2 x 10^{-6} per yr.
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 failure rate of a flange connection is given as 2 x 10^{-3} per yr per flange.
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	Gasket failure 5.6 x 10^{-5} per joint per yr.
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

106. 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.

107. 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.

108. Further detail on the derivation of the pipework failure rates is given in FRED, Failure Rate and Event Data for Use in Risk Assessment (Betteridge and Gould, 1999).

109. For pipework with diameter greater than 1000mm discussion with the topic specialist is required.

References

Title	Author	Date	Comments
Components Failure Rates. Confidential, not in the public domain.	E M Pape	1985	From the Chlorine Siting Policy Colloquium.
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 and Event Data for Use in Risk Assessment	P Betteridge and J Gould	1999	

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

110. See individual advice notes for specific details.

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

Bibliography

111. 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	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	Gives a value of 8.8 x 10^{-7} per m per yr for guillotine failure.
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 public domain.	Technica	Jul 91	A detailed numerical analysis of the pipework failure by pipe size and hole size for process and transport pipes is given.

Title	Author	Date	Comments
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	Guillotine failure frequencies for protected (x 10^{-6} per m per hr): d ≤ 50 mm: 0.1 d = 50-150 mm: 0.03 d > 50 mm: 0.01
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	10 mm holes 3.3 x 10^{-}per m per yr, 50 mm pipes. FB 7 x 10^{-6} per m per yr, rates not including welds.
Risk assessment. Confidential, not in the public domain.	A D Little	Sep 94	80 mm hole 5.3 x 10^{-6} per m per yr, 150 mm dia FBR 2.6 x 10^{-7} per m per yr.
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.
SR module. Confidential, not in the public domain.	Unknown	1978	≤ 50 mm: 8.8 x 10^{-7} per m per yr > 50 and ≤ 150 mm: 2.6 x 10^{-7} per m per yr > 150 mm: 8.8 x 10^{-8} per m per yr.
HF QRA. Confidential, not in the public domain.	Unknown	Jul 94	Guillotine failure for ¼” piping 1.1 x 10^{-6} per m per yr.
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	For average diameter failure rate is 3 x 10^{-7} per m per yr.
Generic land-use planning consultation zones - chlorine. Confidential, not in the public domain.	Unknown	1994	For guillotine failure (both liquid and gas lines) 1 x 10^{-6} per m per yr.
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.	Unknown	Not given	For catastrophic failures:

Title	Author	Date	Comments
Confidential, not in the public domain.			≤ 50 mm: 8.8 x 10^{-7} per m per yr > 50 mm: 2.6 x 10^{-7} per m per yr.
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.
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	A rate of 10^{-4} to 10^{-6} per reactor per yr for large pipes is quoted, with higher rates for smaller pipes. This range covers all failure modes.
Quantified risk assessment. Confidential, not in the public domain.	AEA Technology	1996	3 different leak sizes are considered for 6 pipe sizes. Values range from 1 x 10^{-4} to 1 x 10^{-7}, units are assumed to be per m per yr.
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	Serious leakage from pipework given as 10^{-5} per yr per section (10 ft).
The likelihood of accidental chlorine release events (extract from CIMAH safety case). Confidential, not in the public domain.	WS Atkins	1994	Fixed pipework (guillotine): 8.8 x 10^{-6} per m per yr. Fixed pipework (partial): 8.8 x 10^{-5} per m per yr. Connection pipework (guillotine): 7.6 x 10^{-7} per m per yr per operation. Connection pipework (partial): 7.6 x 10^{-6} per m per yr per operation.
Site specific assessment. Confidential, not in the public domain.	AD Little	Apr 94	Line corrosion: 1 x 10^{-4} per yr. Several values are given for frost heaves.
The hazard analysis of the chlorine and sulphur dioxide storage installation plant. Confidential, not in the public domain.	Cremer and Warner	Nov 77	Assuming that pipework is reinstated and then checked after maintenance the failure rate will be 10^{-4} to 10^{-5} per yr (presumably per m).
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	The likelihood of a pipe/valve failure is estimated to be 10^{-4} per yr.
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 given.

Item FR 2 Electrical

112. 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

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

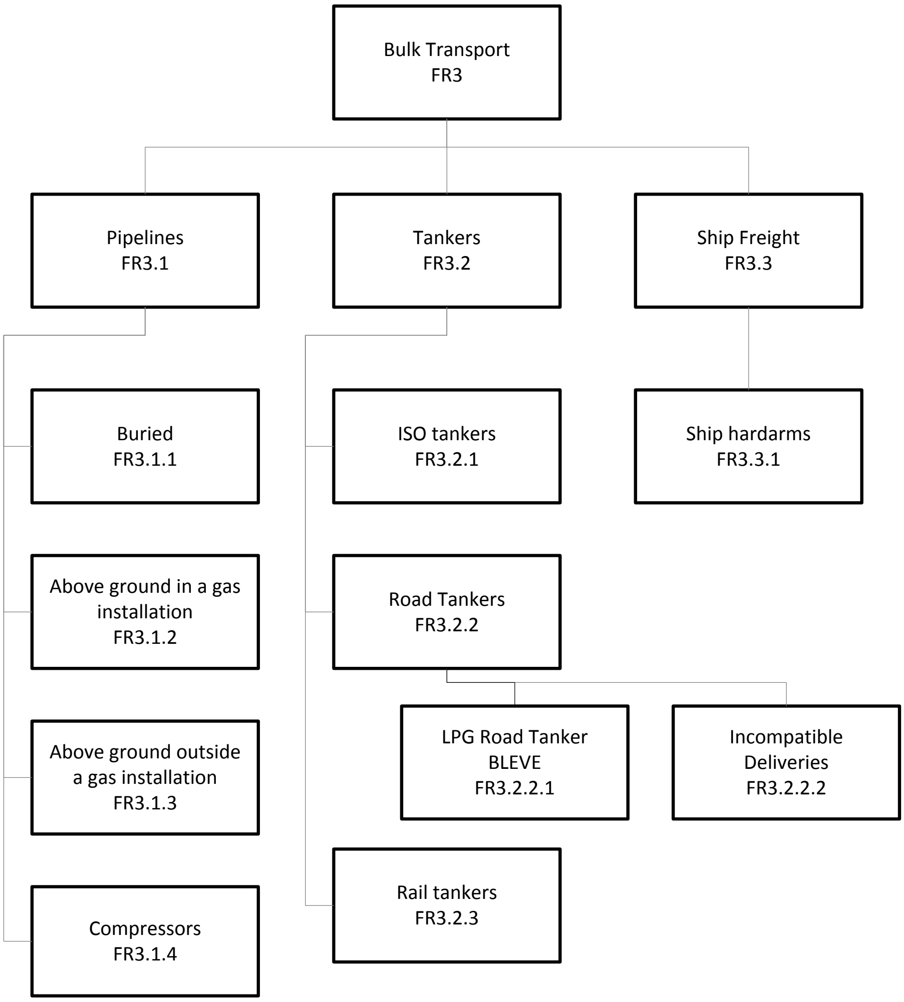

Figure 5 Hierarchical diagram for bulk transport

Item FR 3.1 Pipelines

Introduction

114. Assessors carrying out Land Use Planning assessment may have cause to assess pipelines carrying a range of substances. The report by Chaplin, RR1035, listed under FR 3.1.1, provides failure rates for a number of different substances.

115. The failure frequencies fall into three categories, those for buried pipelines, those where the pipeline is above ground at a gas installation and those where the pipeline is above ground but not within a gas installation.

116. More information can also be found in PCAG Chapter 6O and PCAS Chapter 6O.

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

Item FR 3.1.1 Buried Pipelines

118. CEMHD5's PIPIN (**PIP**eline **IN**tegrity) Version 3 software package calculates failure frequencies for buried transmission pipelines transporting a range of substances. The failure frequencies are used as inputs to the pipeline risk assessment program MISHAP12, which is described in Chaplin, RR1040 and in PCAS 6C. The failure frequencies are automatically calculated by PIPIN from within MISHAP12, or they may be input manually. PIPIN is described in more detail in the references and in PCAS 6O.

PIPIN Description

119. PIPIN contains two principal models: -

Operational Experience: using a generic approach derived from historical records of pipeline releases.

Predictive: a predictive probabilistic approach using a Monte Carlo solution method with fracture mechanics models to calculate failure frequencies due to third party damage for transmission pipelines.

Current policy is to use a combination of both models: Operational Experience for Mechanical, Corrosion, and Ground movement and other failures, and Predictive for Third Party Failures. An option is available to enable this combination to be calculated automatically.

120. Assessors should refer to PCAG Chapter 6O for details on running the PIPIN software.

Current advice

121. 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.

	Data set			
Cause	CONCAWE	UKOPA	EGIG	PIPIN predictive
Mechanical	Gasoline Vinyl Chloride Carbon dioxide	Natural Gas Ethylene Spike crude oil (factored values based on a ratio between EGIG and CONCAWE data)	LPG	
Natural		All commodity types		
Corrosion	Gasoline Spike crude oil Vinyl Chloride Carbon dioxide	Natural Gas Ethylene	LPG	
TPA				All commodity types*

122. *May underestimate values for substances that lead to embrittlement of pipeline, for example, CO_2.

123. PIPIN calculates failure rates for three hole sizes and ruptures, the definitions of which are shown in the subsequent table. These were selected a number of years ago and represent HID CEMHD5 policy.

Release name	**Hole diameter (mm)**
Rupture	>110
Large Hole	>75 – ≤110
Small Hole	>25 mm – ≤75
Pin Hole	≤25

References

Title	Author	Date	Comments
Rewriting the PIPIN code to use a Monte Carlo solution approach. HSE Research Report RR1036.	Z Chaplin	2014	
Science updates to HSE's PIPeline INtegrity model (PIPIN). HSE Research Report RR1037.	Z Chaplin	2014	
Data updates to HSE's PIPeline Integrity (PIPIN) model. HSE Research Report RR1038.	Z Chaplin	2014	
Summary of the rewrite of HSE's PIPeline INtegrity (PIPIN) model. HSE Research Report 1039.	Z Chaplin	2014	
Gas pipeline failure frequency predictions – probabilistic fracture models. WSA Report No. AM5076/RSU8000/R1.	D Linkens	1997	
Update of pipeline failure rates for land use planning assessments. HSE Research Report RR1035.	Z Chaplin	2014	
Ethylene pipeline failure rates for Land Use Planning assessments. HSL report RSU/SR/08/03. Confidential, not in the public domain.	Z Chaplin	2008	
Rewriting MISHAP: The development of MISHAP12. HSE Research Report RR1040.	Z Chaplin	2014	

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

124. See individual advice notes for specific details

FR No	Application	Comments
116-3	Carbon dioxide pipeline	Cautious best estimate – assume rates for hazardous

		liquid pipelines

Item FR 3.1.2 Above Ground Pipelines in a Gas Installation

ITEM FAILURE RATES

Failure Category	**Failure Rate (per m per year)**
Rupture (>110mm diameter)	6.5×10^{-9}
Large Hole (>75 – ≤110mm diameter)	3.3×10^{-8}
Small Hole (>25 mm – ≤75 mm diameter)	6.7×10^{-8}
Pin Hole (≤25 mm diameter)	1.6×10^{-7}

Applicability

125. The values above are applicable to general natural gas above ground installations where no site specific information is available. The values are 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.

126. Where site specific information (e.g. pipeline diameter, wall thickness, pipeline length, number of lifts and vehicle movements) is known, a spreadsheet (Chaplin, 2011), which calculates site specific failure rates, is available from the topic specialist.

Derivation

127. The generic failure rates are taken from a panel paper by S Pointer.

References

Title	Author	Date	Comments
Above ground pipelines. HSL letter report MSU/LET/2011/36. Confidential, not in the public domain.	Z Chaplin	2011	
Failure frequencies for above ground natural gas pipelines.	S Pointer	2004	

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

128. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 3.1.3 Above Ground Pipelines That Are Not Within a Gas Installation

129. CEMHD5 have a software package to calculate the failure rates associated with above ground pipelines that are not contained within an installation. The program can be used for the same substances currently considered for buried pipelines in PIPIN (Item FR 3.1.1).

Above Ground Pipelines That Are Not Within a Gas Installation Program Description

130. The program calculates contributions to the failure rates from roads and railways in the vicinity of the pipeline. These are combined with historical information on failures due to corrosion, mechanical, ground movement and other natural causes. The program can also incorporate aircraft crash frequencies into the calculations.

131. Failure rates are derived for three hole sizes and ruptures, the definitions of which are shown in the subsequent table. These were selected a number of years ago for buried pipelines and represent HID CEMHD5 policy.

Release name	**Hole diameter (mm)**
Rupture	>110
Large Hole	>75 – ≤110
Small Hole	>25 mm – ≤75
Pin Hole	≤25

Derivation

132. The derivation of the computer program is detailed in a report by Chaplin (2016).

References

Title	Author	Date	Comments
Failure rates for above ground pipelines that are not within an above ground installation (AGI)	Z Chaplin	2016	To be published as an HSE Research Report

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

133. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 3.1.4 Compressors

ITEM FAILURE RATES

Failure Category	**Failure Rate (per compressor year)**	
	Centrifugal	**Reciprocating**
Rupture (>110mm diameter)	2.9×10^{-6}	1.4×10^{-5}
Large Hole (>75 – ≤110mm diameter)	2.9×10^{-6}	1.4×10^{-5}
Small Hole (>25 mm – ≤75 mm diameter)	2.7×10^{-4}	3.3×10^{-3}
Pin Hole (≤25 mm diameter)	1.2×10^{-2}	8.6×10^{-2}

Derivation

134. The above values are taken from MSU/LET/2012/16 by Chaplin.

135. MSU/LET/2012/16 reviews compressor failure rates available in the literature and accident databases. The recommended failure rates are derived from incident data in the HSE Hydrocarbons Release database.

136. The choice of hole size categories is based on those defined for pipelines in the absence of any other data. However, it is recommended that, if known, the size of the inlet or outlet to the compressor should be used as the rupture size.

References

Title	Author	Date	Comments
Compressor failure rates MSU/LET/2012/16. Confidential, not in the public domain.	Z Chaplin	2012	

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

137. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 3.2 Tankers

138. 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	4×10^{-6} per vessel year	With no pressure relief system
Catastrophic failure	3×10^{-6} per vessel year	With a pressure relief system
50 mm diameter hole	3×10^{-5} per vessel year	This includes releases due to the valve being left open by the operator.
25 mm diameter hole	3×10^{-5} per vessel year	
13 mm diameter hole	6×10^{-5} per vessel year	
4 mm diameter hole	3×10^{-4} per vessel year	
Vapour release	5×10^{-4} per vessel year	50 mm diameter hole
50 mm diameter hole	6×10^{-7} per lift	Failures due to dropping of the tank < 5 metres.
Catastrophic failure	3×10^{-8} per lift	Failures due to dropping of the tank > 5 metres.
50 mm diameter hole	6×10^{-7} per lift	Failures due to dropping of the tank > 5 metres
50 mm diameter hole	9×10^{-11} per pass	Failures due to a container being dropped on to the tank.

Derivation

139. 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.

140. 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)

141. See individual advice notes for specific details.

FR No	Application	Comments
133	ISO tanks storing LNG	Rates derived from the generic rates with open valve contribution removed.
132	Liquid hydrogen tanker offloading facility	Use generic rates ignoring those associated with lifting. Rates for hose and coupling failure also given.
121	Liquid hydrogen isotank used as semi-permanent storage tank	Use generic rates ignoring those associated with lifting

Bibliography

142. 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	Catastrophic: 6.5 x 10^{-6} per yr, also gives rates for lesser leaks.

Item FR 3.2.2 Road Tankers

ITEM FAILURE RATES

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

Derivation

143. 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. Confidential, not in the public domain.	Z Chaplin	2009	

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

144. See individual advice notes for specific details.

FR No	Application	Comments
66	Unloading Ethylene oxide from road tankers	Catastrophic failure rate
13	Road tanker unloading rates for chlorine and bromine tank containers	Catastrophic failure rate

Bibliography

145. 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 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

Title	Author	Date	Comments
			ammonia unloading (p288).
CIMAH Safety Case. Confidential, not in the public domain.	W S Atkins	June 1994	Assuming 600 deliveries per year the catastrophic failure rate is given as 3.6×10^{-6} per yr.
Calculation of Release Events Frequencies. Confidential, not in the public domain.	W S Atkins	2 July 1995	Serious accident rate of 1.2×10^{-6} per km, used to derive a catastrophic rupture frequency of 3.9×10^{-8} per yr.
Chlorine Safety Report – The Likelihood of Accidental Chlorine Release Events. Confidential, not in the public domain.	W S Atkins	October 1995	Accident rate 1.8×10^{-7} per journey^{-} estimated frequency 2.2×10^{-6} per yr.
Risk Assessment Acrylonitrile. Risk Assessment Butadiene. Confidential, not in the public domain.	Courtaulds Research	August 1988	Tanker failure for acrylonitrile delivery; 9×10^{-8} – 3.3×10^{-6} per yr.
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.
The Likelihood of Accidental Release Events. Confidential, not in the public domain.	Rhone-Poulenc Chemicals Ltd – Avonmouth Site	Not Given	A value of 1×10^{-6} per yr for catastrophic failure of a road tanker.
The Likelihood of Accidental Chlorine Release Events (Extract From a CIMAH Safety Case). Confidential, not in the public domain.	W S Atkins	1994	Catastrophic rupture: 2.9×10^{-7} per yr. Partial rupture: 2.9×10^{-6} per yr.
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	Assumes 5×10^{-5} per yr as a base rate for catastrophic failure.

Item FR 3.2.2.1 LPG Road Tanker BLEVE

ITEM FAILURE RATES

Failure Category	Failure Rate (per delivery)	Applicability
Sites with small tanks	1 x 10^{-7}	Few/no mitigation measures
Sites with large tanks	1.1 x 10^{-8}	Significant number of mitigation measures present

TYPICAL MITIGATION MEASURES

Fixed water sprays/ deluge system
Passive fire protection coating on vessels
Portable fire fighting equipment
Fire wall
Storage compound protection (e.g. fencing)
Control of ignition sources
Hazard warning notices

Derivation

146. All rates are based on the report by Z. Chaplin, MSU/LET/2011/38. Typical mitigation measures are detailed in the LP Gas Association Code of Practice 1.

147. Small tanks are considered to typically have a capacity of less than 5 tonnes. Such tanks are likely to be found at domestic or educational sites and are unlikely to have any built-in mitigation systems.

148. Large tanks are more likely to be found at larger industrial installations and have capacities of around 25 tonnes or greater. These types of site are likely to contain a significant number of the mitigation measures listed.

149. If a site has manifolded tanks, then this should be treated as one visit, otherwise, each individual tank will be counted as a tanker delivery operation.

References

Title	Author	Date	Comments
LPG road tanker BLEVE frequencies. HSL internal report MSU/LET/2011/38. Confidential, not in the public domain.	Z Chaplin	2011	
Code of practice 1. Bulk LPG storage at fixed installations. Part 1:2009. Design, installation and operation of vessels located above ground.	LP Gas Association	2009	

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

150. See individual advice notes for specific details.

FR No	Application	Comments
108	BLEVE of road tanker carrying 26 te LPG	

Item FR 3.2.2.2 Incompatible Deliveries

ITEM FAILURE RATES

Site type	**Failure Frequency (per delivery)**
Below Average	6 x 10^{-6}
Average	1 x 10^{-7}
Above Average	5 x 10^{-8}

Derivation

151. The incompatible deliveries failure rates apply to scenarios whereby two incompatible substances are accidentally mixed during a delivery, for example, the contents of a tanker being offloaded into the wrong tank. The failure rates are based on the report by Bell and Keeley, MSU/LET/2011/39.

152. Three site type classifications have been defined based on safety management system standards:

Below average	The process of receiving a tanker to site and the delivery itself is not always well managed. The offloading points are not locked and are not clearly separated, well laid out or well labelled. Incompatible connectors are generally used.
Average	The process of receiving a tanker to site and the delivery itself are well controlled by operating procedures. The offloading points are normally locked and are well laid out and labelled. Incompatible connectors are used.
Above average	The process of receiving a tanker to site and the delivery itself are well controlled by operating procedures. In addition, there is evidence that the site is working to maximise the safety and reliability benefits of the acknowledged operating conditions and to continuously improve. The offloading points are normally locked and keys are controlled. The offloading points are physically separated, well laid out and clearly labelled. Incompatible connectors are used.

153. For all site types, work is completed free of unreasonable time pressures.

154. The site type definitions do not refer to the site’s ability to comply with their legal requirements but to their success at meeting their own safety management standards. The choice of site type will be an operational issue.

References

Title	Author	Date	Comments
Failure frequency for incompatible deliveries MSU/LET/2011/39.	J Bell and D Keeley	2011	

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

155. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 3.2.3 Rail Tankers

156. 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

157. The transfer of substances via ship hardarms is covered in Item FR 3.3.1.

Item FR 3.3.1 Ship Hardarms

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

159. 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	3.4e-7	3.1e-6	
Coupler (3)	5.1e-6	-	
Operator error (4)	5.4e-7	4.9e-6	
Sub-total per arm	**6.0e-6**	**8.0e-6**	
Ranging failures (5)			
Mooring fault	6e-7	-	
Passing ships (6)	2e-7	-	
Sub-total per system	**0.8e-6**		**0.8e-7 When multiple arms used (7)**
Total failure rate when one arm used (8)	**7e-6**	**8e-6**	**-**
Total failure rate when 2 arms used (8)	**13e-6**	**16e-6**	**1e-7**
Total failure rate when 3 arms used (8)	**19e-6**	**24e-6**	**1e-7**

160. 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	3.2e-6	29.0e-6	
Coupler (3)	5.1e-6	-	
Operator error (4)	3.6e-6	3.6e-6	
Sub-total per arm	**1.2e-5**	**3.3e-5**	
Ranging failures (5)			
Mooring fault	19.2e-6	-	
Passing ships (6)	6.6e-6	-	
Sub-total per system	**2.6e-5**		**2.6e-6 When multiple arms used (7)**
Total failure rates when one arm used (8)	**3.8e-5**	**3.3e-5**	**-**
Total failure rates when 2 arms used (8)	**5.0e-5**	**6.6e-5**	**2.6e-6**

Total failure rates when 3 arms used (8)	**6.2e-5**	**9.9e-5**	**2.6e-6**

161. 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

162. 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	DNV	1992	

public domain.			
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)

163. 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

164. Moveable storage is further subdivided as follows:

165. For Items FR 4.1.3 and FR 4.1.6 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 (cpm yr^{-1})	Modifier	Notes
Spontaneous drum failure	2	× l	Liquid and gas off-take plants
Holes in drum (large)	1.2	× m.n	Liquid and gas off-take plants
Holes in drum (small)	5	× m.n	Liquid and gas off-take plants
Sheared liquid valve	4.5	× m.n	Liquid and gas off-take plants Increased by a factor of 5 if valve points towards centre of room
Sheared vapour valve	4.5	× m.n	Liquid and gas off-take plants Increased by a factor of 5 if valve points towards centre of room
Coupling failure (guillotine)	10	× m	Liquid and gas off-take plants
Coupling failure (leak)	90	× m	Liquid off-take plants
Coupling error (liquid)	1	× m	Liquid off-take plants x 10 for sites with automatic change over
Coupling error (liquid)	0.01	× m	Gas off-take plant
Coupling error (vapour)	1	× m	Liquid and gas off-take plants
Uncoupling error (liquid)	10	× m	Liquid off-take plant
Uncoupling error (vapour)	100	× m	Gas off-take plant
Pipework	3	× p	Liquid and gas off-take plants

166. Where:

l is the average number of drums stored on site

m is the total number of drums used on the site per year

n is the number of movements per drum

p is the length of liquid or vapour line in metres

Derivation

167. 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)

168. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Bibliography

169. 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	2×10^{-7} per drum per yr.
Generic land use planning consultation zones - chlorine. Confidential, not in the public domain.	Not given	Oct 94	Catastrophic failure rate 1.5×10^{-6} per drum per yr.

Item FR 4.1.2 Drums 210 litre

ITEM FAILURE RATES

Type of event	Failure Rate (per year)
Catastrophic (2 × drum contents released)	8.4×10^{-5} T/4
Catastrophic (1 × drum contents released)	2.0×10^{-6} T/4
Major failure of 2 drums (10 mm hole)	3.6×10^{-5} T/4
Major failure of 1 drum (10 mm hole)	2.0×10^{-6} T/4
Minor failure of 1 drum (5 mm hole)	6.0×10^{-6} T/4 + 8.0×10^{-5} Q

170. Where:

T is the throughput per year

Q is the maximum number of drums in storage at any time

Derivation

171. The assumptions in the derivation of the failure rates are:

- The drums are constructed in steel;
- The drums have a dimension of 585 mm in diameter and 880 mm in height;
- Four drums are stored on a wooden pallet;
- Pallets may be stored on top of each other;
- A maximum of two pallets form a stack;
- The drums are not secured to the pallet;
- The drums have openings on the top that are sealed or capped, but no valves;
- Two movements are associated with each drum, both by fork-lift truck (FLT);
- The drums are on a storage site; and
- If a FLT driver misjudges the location of the pallet, there is the potential for the forks to impinge on 2 drums simultaneously.

172. Values for 210 l drums have been derived using a combination of information in the FR notes, the Vectra work on Intermediate Bulk Containers (IBCs), and the review of the IBC Vectra work. The hole sizes are the same as those used for IBCs.

173. A large hole in the base of the drum could lead to the release of all the contents. This will have similar effects to a catastrophic failure. Assessors should model a catastrophic failure as an instantaneous release, rather than a hole.

References

Title	Author	Date	Comments
Review of Failure Rates for Drums Storing Hazardous Materials, MSU/2014/16. Confidential, not in the public domain.	Zoe Chaplin	2014	
Failure rates for Intermediate Bulk Containers (IBCs) MSU/2013/21. Confidential, not in the public domain.	Zoe Chaplin	2013	
Report No. 300-232-R01, Revision A. Confidential, not in the public domain.	Vectra	2001	

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

174. See individual advice notes for specific details.

FR No	Application	Comments
	No specific advice issued.	

Item FR 4.1.3 Cylinders

175. 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)

176. 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

ITEM FAILURE RATES

Type of event	**IBC failure rates (cpm/yr)**
Catastrophic	71n + 14N
Major (10 mm hole)	113n + 13N
Minor (5 mm hole)	52n + 930N

177. Where:

N is the average number of containers continuously in store

n is the number of containers passing through the site per year

Derivation

178. Values for IBCs were initially derived by Vectra in 2001 using a fault tree approach, but the failure rates were never formally adopted. Various FR notes have been issued since the Vectra analysis to provide failure rates for non-UN IBCs and to allow for 2 movements per container on site. A review of the FR notes and the Vectra analysis was performed in 2013, leading to a restructure of the fault trees and revised failure rates. A review of the representative hole sizes was also performed which concluded that the definitions for the minor, major and catastrophic releases should be revised to 5 mm for minor releases, 10 mm for major releases and 25 mm for catastrophic releases. The advice has since been modified so that catastrophic failures should be modelled as an instantaneous release, rather than a hole. It was found that there was minimal difference in the failure rates calculated for UN and non-UN IBCs and so the same failure rates should be applied to all types of IBC.

179. The failure rates include leaks from the cap and valves as well as from the main body of the IBC. They are split between failures that may occur during movement (e.g. fork lift truck puncture) and those that may occur during storage (e.g. degradation of the body of the IBC over time). The failure rate due to movement should be multiplied by the number of IBCs passing through the site per year, and assumes that each IBC will be subject to two movements on the site. The failure rate due to storage should be multiplied by the average number of IBCs continuously in store.

180. It should be noted that a large hole half way up an IBC will lead to the loss of approximately half the contents. If the hole is in the base of the IBC, however, the full contents of a 1 m^3 IBC will be lost within 30 minutes. This will have similar effects to a catastrophic failure for this size of IBC. Some IBCs can have larger volumes and hence assessors should model a catastrophic failure as an instantaneous release, rather than a hole.

181. In order to derive a value for N, the applied for quantity should be divided by the density of the substance (either named or exemplar). For example, for 50 te of B1 very toxic material, assuming methyl chloroformate as the exemplar, N will be 41 (50000 kg of substance divided by the density of methyl chloroformate at 15°C, which is 1229 kg m^{-3}).

References

Title	Author	Date	Comments

Failure rates for Intermediate Bulk Containers (IBCs) MSU/2013/21. Confidential, not in the public domain.	Zoe Chaplin	2013	
Report No. 300-232-R01, Revision A. Confidential, not in the public domain.	Vectra	2001	

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

182. See individual advice notes for specific details

FR No	Application	Comments
	No specific advice issued.	

Item FR 4.1.5 Portable Containers

ITEM FAILURE RATES

Type of event	**Failure rate (cpm yr^{-1})**	**Modifier**
Catastrophic container failure	2	× N
Holes in container (large -10 mm)	1.2	× n
Holes in container (small – 5 mm)	5	× n

183. Where:

N is the average number of containers stored on site

n is the number of movements per container x the total number of containers passing through the site per year

Derivation

184. The values have been derived in a Failure Rate Advice Note (FR 136) where a portable container has been defined as:

- Having a test pressure from 1.5 bar to 10 bar;
- Having a minimum shell thickness in stainless steel (typically 6 mm);
- Being required to have a pressure release device (disk, gauge and PRV or just PRV); and
- If a bottom opening is allowed, there have to be 3 independent shut offs.

185. A typical portable container is 1 m^3 and rated to ~5 bar, containing very toxic or volatile substances.

186. The failure rates are based on the 1 te drum failure rates (see Item FR 4.1.1), and the hole sizes are consistent with IBCs.

187. A large hole in the base of the portable container could lead to the release of all the contents. This will have similar effects to a catastrophic failure. Some portable containers can have larger volumes and hence assessors should model a catastrophic failure as an instantaneous release, rather than a hole.

References

Title	Author	Date	Comments

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

188. See individual advice notes for specific details.

FR No	Application	Comments
138	800 litre portable cylinders, operating at 9.8 barg.	Catastrophic, large and small hole rates derived, together with valve and coupling failures and errors.
137-2	Portable storage tanks, type T22, for acrolein, pressurised to a minimum of 10 bar.	Catastrophic, large and small hole rates derived.
136	Portable stainless steel containers, pressurised between 1.5 and 10 bar.	Catastrophic, large and small hole rates derived.

Item FR 4.1.6 Small Container

189. 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)

190. See individual advice notes for specific details

FR No	Application	Comments
106	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 and 50 mm, 25 mm, 13 mm and 6 mm hole failure rates provided for 52 l and 8 l containers.
67	5 l UN-certified HF drums.	Catastrophic (2 types of release), major and minor 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.
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.

Event Data

191. 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

Introduction

192. The following is taken from Chaplin (2017), with additional information 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

The first stage in calculating the frequency of an aircraft striking an installation is to establish a background crash rate. The values in

193. Table 1 have been derived by Chaplin (2017) and are updates to Chaplin (RSU/SR/2009/06). The earlier work was based on Atkinson and Thompson (2008), which was an update to the report by Byrne (1997).

Table 1 Aircraft crash rates

Aircraft Category	**Crash rate (km^{-2} yr^{-1} x10^{-5})**
Light aircraft	1.85
Helicopters	1.03
Small transport aircraft	0.22
Large transport aircraft	0.07
Military combat aircraft	0.67
Total	**3.84**

Airfield Rates

The values reported in

194. Table 1 assume that the site is not within 5 miles of an airfield. For sites within this distance, a different set of values has been derived. According to the report by Byrne, 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 Chaplin (2017).

Table 2 Airfield-related crash rates

Aircraft Category	**Crash rate (per take-off or landing x10^{-6})**
Light Aircraft	2.5
Civil helicopters	2.4
Small transport	3.8
Large transport	0.08

Military combat	3.50

195. 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:

$$g = NRf(r, \theta) \qquad (1)$$

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 6). 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

196. Table 1 to provide a total crash rate for a specific location if it is near an airfield.

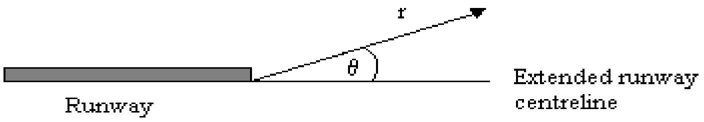

Figure 6 The r, θ coordinate system for accident locations in the vicinity of an airfield

Flight Paths

197. 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. These values have not been updated and 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

The values in

Table 1 can be used to calculate catastrophic failures and leaks from different hole sizes for vessels. The methodology illustrated in

198. Table 4 can also be seen in FR19.

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

199. 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^{-8} yr^{-1})**
Light	Cat	≤ 50	7.85	18.5	14.5
	50 mm	50 < distance ≤ 70	7.54	18.5	13.9
	25 mm	70 < distance ≤ 90	10.1	18.5	18.7
	13 mm	90 < distance ≤ 100	5.97	18.5	11.0
	6 mm	100 < distance ≤ 120	13.8	18.5	25.5
Helicopter	Cat	≤ 50	7.85	10.3	8.1
	50 mm	50 < distance ≤ 70	7.54	10.3	7.8
	25 mm	70 < distance ≤ 90	10.1	10.3	10.4
	13 mm	90 < distance ≤ 100	5.97	10.3	6.1
	6 mm	100 < distance ≤ 120	13.8	10.3	14.2
Small Transport	Cat	≤ 60	11.3	2.2	2.5
	50 mm	60 < distance ≤ 100	20.1	2.2	4.4
	25 mm	100 < distance ≤ 125	17.7	2.2	3.9
	13 mm	125 < distance ≤ 150	21.6	2.2	4.8
	6 mm	150 < distance ≤ 170	20.1	2.2	4.4
Large Transport	Cat	≤ 100	31.4	0.7	2.2
	50 mm	100 < distance ≤ 150	39.3	0.7	2.8
	25 mm	150 < distance ≤ 200	55.0	0.7	3.9
	13 mm	200 < distance ≤ 220	26.4	0.7	1.8
	6 mm	220 < distance ≤ 230	14.1	0.7	1.0
Military Combat	Cat	≤ 30	2.83	6.7	1.9

	50 mm	30 < distance ≤ 60	8.48	6.7	5.7
	25 mm	60 < distance ≤ 90	14.1	6.7	9.4
	13 mm	90 < distance ≤ 120	19.8	6.7	13.3
	6 mm	120 < distance ≤ 150	25.4	6.7	17.0
Total Catastrophic Failure					**29.2**
Total 50 mm hole					**34.5**
Total 25 mm hole					**46.3**
Total 13 mm hole					**37.1**
Total 6 mm hole					**62.1**

A second example illustrates the use of the values in

200. Table 1, Table 2 and Table 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 F_T of 0.013. Next it is necessary to have information on the number of movements at the airfield. Example values 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

201. These values 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 value 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	2.5	5.25
Small transport aircraft	100	0.013	3.8	4.94
Large transport aircraft	100	0.013	0.08	0.10
Military combat aircraft	0	0.013	3.5	0

The total frequency can be found by adding these together, giving a rate of 10.29 x 10^{-6} /year. Next the values in

202. Table 1 need to be added to this value to take into account the background crash rate. This gives a new total of 4.87 x 10^{-5} /year.

203. 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 values 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

204. 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 7.73 x 10^{-5} crashes/year

References

Title	Author	Date	Comments
Update of aircraft crash rates used in HSE's Failure Rate and Event Data document. MSU/2015/19. To be published on HSE's website.	Chaplin Z	2017	
Aircraft crash rates, HSL internal report RSU/SR/2009/06. Confidential, not in the public domain.	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)

205. See individual advice notes for specific details.

FR No	Application	Comments
19	Liquid hydrogen vessels	Demonstrates methodology

Item ED 2 Flooding

206. The first stage when trying to derive a value 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.

207. 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.

208. 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 value 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.aspx 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 3 Lightning Strike Rates

209. 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.

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

210. This is illustrated in Figure 7 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.

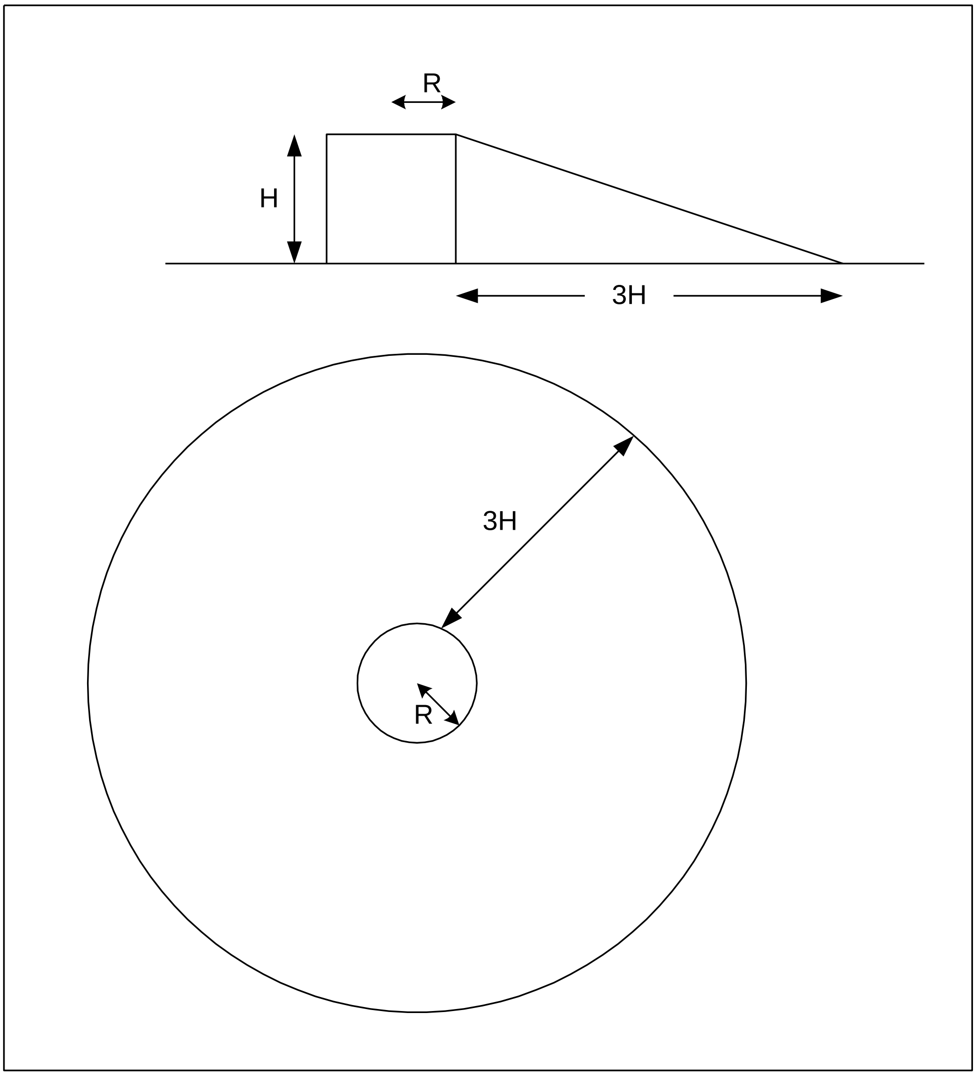

Figure 7 Collection area of an isolated cylindrical structure

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

$$N_D = L_{gfd} \times A \times F_{loc} \times 10^{-6} \qquad (3)$$

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).

212. 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 8 and were obtained from BS EN 62305-2:2006.

Table 8 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

213. 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 9 and were obtained from BS EN 62305-2:2006.

Table 9 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

214. These probabilities can then be multiplied by the number of dangerous events, N_D, 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

215. To show how the data in Table 8 and Table 9 and equations 2 and 3 may be used, consider a storage tank of radius 10 m and height 20 m. Using equation 2, 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 8) 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 N_D is then 0.0054 per year (from equation 3). 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 9). When multiplied by N_D, 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	

Human Factors

Guidance for assessors on the use of human reliability data in quantified risk assessments

216. The aim of this document is to help non-human factors specialists determine whether the use of human reliability analysis (HRA), and associated values, is adequate or not. Often, human factors specialists are not available to comment on HRA and, for example during COMAH safety report assessments, it is the predictive assessor who makes the judgement. This document provides

- A comment on the use of human error potential (HEP) values; both observed and generated by HRA techniques
- A brief description of the techniques that are commonly used for determining human reliability values
- Guidance on the limits that should be placed on the use of those techniques

Overview

217. In most cases, a human error potential of 0.1 can be considered a conservative or cautious estimate of the risk of human failure. This value can generally be accepted as appropriate for use in order of magnitude tools, like Layers of Protection Analysis (LOPA). However, human factors specialists would still expect to see the duty holder demonstrate a thorough understanding of the tasks being undertaken and the conditions in which they are performed.

218. Claims of reliability beyond 0.1 will require significantly more demonstration and justification; typically this is when a site might use a human reliability assessment tool but quantification is not always necessary. The HID Human Factors Specialist Inspectors team advocate using a qualitative approach to ensure the duty holder has a thorough understanding of the issues. Where quantified methods are used, HSE has found that values are often taken from publicly available data sources and HRA methods without any justification or consideration of the site-specific conditions that might influence their applicability. For example, documents such as ‘BS EN 61511-3:2004 (annex F) and the Center for Chemical Process Safety (CCPS) book on LOPA have tables that provide examples of HEPs. While these values are probably appropriate in many situations, the associated text to describe the context is extremely limited; duty holders need to consider how applicable the data are to the situation being assessed and to justify their use. If a duty holder has adequate site-specific performance data regarding human reliability, this data could be used to support HEPs obtained from HRA methods and other sources. This historical data can be considered adequate if it has been collected over a sufficient timescale to be statistically significant. However, in many cases such data are not readily available and duty holders, having decided on a quantitative analysis, must draw upon their knowledge of the task to work through a HRA method.

219. In order to complete a HRA correctly, qualitative knowledge is essential because without a thorough analysis of the site-specific issues the assessor cannot adequately assess the risk, determine a realistic HEP or identify ways to improve safety. It is important to note that even with a good qualitative underpinning to the assessment, the uncertainties inherent in all HRA techniques mean that the generated HEP can only ever be an estimate. Therefore, when using HEP data, for example in COMAH safety reports, we should expect to see the duty holder express caution about the claims they make and how data have been used in risk assessments.

Expectations of a HRA tool generated value

220. If a duty holder has used human reliability data we would expect to see the details of the assessment and not just the values. Ideally, this should include:

1. A description of the safety critical task
2. A task analysis to break it into its component parts and identify the conditions in which the task is completed
3. Human error identification to demonstrate an understanding of how and when errors could occur
4. Details of how the HRA method was applied to identify the human error potential. This should include details of the selected performance influencing factors (the factors that make an error more likely) and how influential they are judged to be (based on human factors knowledge).
5. Ideally, and particularly where human action is safety critical or reliability is assessed as being poor, the assessment should lead to recommendations for improving reliability.

221. At a minimum, it is realistic to expect that the duty holder has provided information about points 1 and 4, with reference to points 2 and 3.

Techniques for determining human reliability values

222. This section provides an overview of the main approaches to generating human error potential (HEPs), a brief summary of some of the most commonly used techniques, comment on their appropriateness/ suitability and what an assessor should expect to see from an assessment.

Overview of methods

223. There are a large number of HRA techniques and approaches available, many are publicly available but others are proprietary methods.Typically, tools are assigned into the following three groups.

First generation tools (e.g. THERP and HEART)

224. These were the first methods developed to help risk assessors predict and quantify the likelihood of human error. They encourage the assessor to break a task into component parts and then consider the potential impact of modifying factors such as time pressure, equipment design and stress etc. By combining these elements the assessor can determine a nominal HEP. First generation methods focus on the skill and rule base level of human action and are often criticised for failing to consider such things as the impact of context, organisational factors and errors of commission. Despite these criticisms they are useful and many are in regular use for quantitative risk assessments.

Expert judgement methods (e.g. APJ and PC)

225. Expert judgement methods were developed around the same time as the first generation tools. These methods are popular, particularly in less safety critical environments than major hazard industries. They provide a structured means for experts to consider how likely an error is in a particular scenario. The validity of some approaches has been questioned, but they continue to be used and also to inform the development of new tools.

Second generation tools (e.g. CREAM and ATHEANA)

226. The development of ‘second generation’ tools began in the 1990s and is on-going. They attempt to consider context and errors of commission in human error prediction, however due to the lack

of uptake in the UK the benefits of the second generation over first generation approaches are yet to be established. They have also yet to be empirically validated.

227. New tools are emerging based on earlier first generation tools such as HEART, and are being referred to as third generation methods.

A summary of the most commonly used tools

HEART - Human Error Assessment and Reduction Technique (First generation tool, outlined by Williams, 1985)

228. HEART is designed to be a relatively quick and simple method for quantifying the risk of human error. It is a generic method that is applicable to any situation or industry where human reliability is important; it was primarily used by the nuclear industry when first developed. Elements of the technique are highly subjective, so, like many other methods, a human factors specialist should be involved in the process to ensure appropriate consideration of the issues.

229. There are 9 Generic Task Types (GTTs) described in HEART, each with an associated nominal HEP, and 38 Error Producing Conditions (EPCs) that may affect task reliability, each with a maximum amount by which the nominal HEP can be multiplied. The assessor must determine an Assessed Proportion of Affect (APOA) for each EPC; APOA is a concept that relates to how ‘present’ each EPC is.

What an assessor should expect to see

230. The basics of a qualitative assessment are required to demonstrate a good understanding of the tasks; this should support the justification of the choice of GTT and EPC(s). In addition, some explanation should be provided for assigning the APOA.

231. The assessment should not contain more than a maximum of 3 to 4 EPCs; if there are more it indicates a problem with either the analysts’ understanding of HEART or a poorly designed task that is highly likely to fail. If an assessment truly reveals a high number of EPCs, the task should be investigated further and appropriate changes made to address the issues.

THERP - Technique for Human Error Rate Prediction first developed by Swain (1983).

232. THERP is a total methodology for assessing human reliability that deals with task analyses (e.g. documentation reviews and walk/ talk through), error identification and representation, as well as the quantification of human error potential (HEPs). The THERP handbook is extensive and presents methods, models and estimated HEPs to enable qualified analysts to make quantitative or qualitative assessments of occurrences of human errors in nuclear power plants.

233. The handbook presents tabled entries of HEPs that can be modified by the effects of plant specific Performance Shaping Factors (PSFs) using other tables. HSE has found data is taken from the tables without following the THERP methodology and applied without appropriate justification for its applicability to the task being assessed.

What an assessor should expect to see

- Decomposition of tasks into elements
- Assignment of nominal HEPs to each element

- Determination of effects of PSF on each element
- Calculation of effects of dependence between tasks
- Modelling in an HRA event tree
- Quantification of total task HEP

SPAR-H Simplified Plant Analysis Risk Human Reliability Assessment (Gertman et al, 2004).

234. The SPAR-H method is similar to HEART but assigns human activity to one of only two general task categories: action or diagnosis.

235. Action tasks – carrying out one or more activities indicated by diagnosis, operating rules or written procedures. For example, operating equipment, performing line-ups, starting pumps, conducting calibration or testing, carrying out actions in response to alarms, and other activities performed during the course of following plant procedures or work orders. (Generic error rate of 0.001)

236. Diagnosis tasks – reliance on knowledge and experience to understand existing conditions, planning and prioritising activities, and determining appropriate courses of action. (Generic error rate 0.01)

237. Eight PSFs were identified as being capable of influencing human performance and are accounted for in the SPAR-H quantification process. When using SPAR-H for general purposes, only three of the eight PSFs are evaluated: time available, stress and stressors, and complexity. The remaining five PSFs are generally considered to be event, plant or personnel specific and would be evaluated when a plant-specific model is being developed.

What an assessor should expect to see

238. The basics of a qualitative assessment are required to demonstrate a good understanding of the tasks; this should support the justification of the choice of task and performance shaping factors

Absolute Probability Judgements (APJ) and Paired comparisons (PC)

239. The APJ approach is conceptually the most straightforward human reliability quantification approach. It simply assumes that people can estimate the likelihood of a human error. There are different APJ approaches that can be applied to determine human reliability. A ‘single expert APJ’ would require one expert to make their own judgements on the chances of a human error. An arguably better approach is a ‘group APJ’ (e.g. Aggregated individual method, Delphi method, Nominal group technique, Consensus-group method).

240. The APJ technique is prone to biases, as well as to personality/group problems and conflicts, which can significantly undermine the validity of the technique. The technique is often likened to ‘guessing’, and therefore, has a low degree of ‘face’ validity.

241. The PC approach differs from APJs in that subject matter experts (SMEs) make simple comparative judgements rather than absolute judgements. Each expert compares pairs of error descriptions and decides, in each case, which of the two errors is more probable. When comparisons made by different experts are combined, a relative scaling of error likelihood can then be constructed. This is then calibrated using a logarithmic calibration equation, which

requires that the HEPs be known for at least two of the errors within the task set. Paired comparisons are relatively easy for the experts to carry out, however, there is no good evidence of predictive validity and it is heavily dependent on the knowledge of the SMEs.

What an assessor should expect to see

242. Users of expert judgement techniques should demonstrate a structured approach with clear task definitions and scale values that reflect the estimated range of the true probabilities of the tasks. If using a group APJ, then an analysis of variance should be performed to determine inter-judge consistency. If using a single expert APJ, calculating the geometric mean should aggregate the individual's estimates.

243. If using PC, the SMEs should have experience of the tasks being assessed. Each pair of tasks should be presented on its own, so that the expert only considers one pair at any one time. The process should include a determination of the within-judge level of consistency and the inter-judge level of consistency. As with APJ, to determine the levels of consistency between SMEs an analysis of variance could be performed. Some estimation of the uncertainty bounds should also be made.

Further information on HRA Methods

244. More detail on each of the tools described above is provided in the HSL review of HRA methods (Bell and Holroyd, 2008). The review also includes information on some of the many other tools available.

References

Title	Author	Date	Comments
Review of Human Reliability Assessment Methods. HSL internal report RSU/08/20	J Bell and J Holroyd	2009	Overview of the various HRA methods and their applicability for use by HSE
BS EN 61511-3:2004 (annex F) Functional safety —Safety instrumented systems for the process industry sector — Part 3: Guidance for the determination of the required safety integrity levels. Incorporating Amendment No. 1 to BS IEC 61511-3:2003	British Standard	2004	
Layer of Protection Analysis. Simplified Process Risk Assessment	Center for Chemical Process Safety	2001	
A Guide to Practical Human Reliability Assessment	B Kirwan	1994	Details the HRA process including useful techniques and approaches for each stage of an assessment.