Failure frequencies for major failures of high pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands

by
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1 Introduction

1. HSE has been criticised for using failure frequencies that are pessimistic when compared to values used in the Netherlands. These failure frequencies are used for formulating land-use-planning advice and for testing compliance with the Seveso directive, which is implemented in the UK by the COMAH regulations. If the criticism is valid there may be cost implications for Local Authorities and companies. The cost implications will depend on other factors such as any differences in LUP systems or approaches to cost benefit analysis, CBA. A discussion of such factors is beyond the scope of this paper but some related issues are raised below.

2. To assess the validity of the criticism, the paper reviews the justification of the failure frequencies used by HSE and the Netherlands for failure scenarios of above-ground-pressurised storage vessels (excluding spheres). The paper shows that the criticism of HSE is not warranted for such vessels. This conclusion is based mainly on an examination of:

   a. the ‘Frequency and Event Data (FRED)’ (Betteridge and Gould, 1999), the Planning Case Assessment Guide Chapter 6K (PCAG) (HSE,2004), and relevant supporting documents which are referenced in FRED; and

   b. the Dutch ‘purple’ book (PB99, 1999) and the documents referenced therein.

3. The vessel failure scenarios relevant to COMAH establishments are:

   a. Catastrophic failure of the vessel leading to the instantaneous release of its entire contents; and

   b. Limited vessel failures leading to holes (up to about 50 mm equivalent diameter) in the vessel wall which give rise to semi-continuous releases of the vessel contents.

4. These types of vessel failure can arise from a variety of different causes. A simplified fault-tree representation of the main failure mechanisms is shown in Figure 1 (adapted from HSE material cited in FRED; see also Singleton (1989)). The figure shows that vessel failure frequencies are determined by contributions from: external events; overpressurisation; and, defects developing in service. Realistic estimates of failure frequencies need to be based on a suitable and sufficient consideration of all the contributors to such failure mechanisms; otherwise the estimates adopted are likely to be optimistic.

5. The relative importance of the different branches of the fault tree will be circumstance specific and will depend on whether catastrophic failure or more limited failure is being considered. For example corrosion could be important for chlorine vessels but may be discounted for well designed and maintained LPG vessels (unless the vessel is coated with insulation that can mask the process). Similarly the contribution from external factors (flooding, earthquakes etc) will be site specific and is considered to be more significant for limited failure (eg nozzle failure) than for catastrophic failure.

2 HSE failure frequencies for pressure vessels

6. HSE's failure frequencies for pressure vessels are based on the values adopted for chlorine vessels.

2.1 Pressurised chlorine storage vessels

7. Chlorine pressure storage vessels are designed and operated to the requirements of PD5500 (2006), BSEN 13445 (2002), ASME VIII or equivalent standards, and HSE guidance HS(G) 28 (HSE, 1999). The standards are high and it is widely accepted that since 1939 there have been no catastrophic failures worldwide of chlorine vessels conforming to these or equivalent standards, though significant failures have occurred – see Table A of the Second report of HSC's Advisory Committee on Major Hazards (HSC,1979).

8. The HSE failure frequencies for chlorine pressure vessels were developed in the 1980s to enable HSE to formulate land-use-planning (LUP) advice for Local Planning Authorities (LPAs) on the siting of chlorine installations and the development of land in the vicinity of such installations. This advice is based on QRA which requires, inter alia, estimates of failure frequencies for a representative range of loss-of-containment accidents.

9. Owing to the lack of data on actual failures of chlorine vessels HSE had to rely on a generic approach based on pooled data sets covering a variety of vessel types, particularly the data set due to Smith and Warwick (1981). The data were mainly from conventional UK plant and similar plant registered with the National Board of Boiler and Pressure Vessel Inspectorates in the USA. An informative summary of these and other data on failure information for pressure vessels can be found in Lees (1996, Vol 1 p12/94 et seq). The main quantitative information from Lees is summarised in Appendix 1.

10. Two HSE specialist mechanical engineering inspectors independently examined the available information on pressure vessel failures. Such generic data had to be tailored to the chlorine industry where standards are generally considered higher. This judgemental process had to consider:

    a. the differences in design, operational standards, and operational environments that apply to the chlorine industry and those where major failures had occurred; and

b. the need for caution when uncertainties are appreciable as LUP decisions have a long time scale and are almost impossible to reverse. (Optimistic estimates of failure frequency would lead to developments being placed too close to sites. Should any ‘cautious’ values be subsequently shown to be ‘too cautious’ it would be easy – unlike the converse situation - to release land for development.)

11. The evidence and arguments (summarised in Appendix 2) justifying the proposed failure frequencies included a factor of 10 reduction of the estimates derived from the Smith and Warwick data for catastrophic failure (less for vessel holes) to allow for high standards. The evidence and arguments were subjected to peer review by a panel of specialist inspectors with further deliberations over a period of 2 to 3 years. The outcome of this process was a decision to adopt the failure frequencies for catastrophic failure and limited vessel failure (ie holes in the vessel wall and nozzle failures) shown in Table 1. These are appropriate for high standards and are deemed to be ‘best estimates’. The aggregated frequency for failures leading to a loss-of-containment accident is 62 or 64 chances per million per year (cpm).

Table 1. HSE failure frequencies for chlorine storage vessels

Type of release	Failure frequency, cpm*
Catastrophic – normal value	2
Catastrophic – where site factors increase likelihood	4
50 mm hole	5
25 mm hole	5
13 mm hole	10
6 mm hole	40

* cpm = chances per million per year; 1 cpm is 10^{-6} failures per year

12. The best estimate for catastrophic failure is regarded as being made up from a contribution from external factors of 1 cpm (regarded as a ‘minimum’ value as HSE internal guidance only refers to an increase in this contribution, though reductions are not explicitly ruled out if exceptional measures are in place), and 1 cpm to cover overpressurisation and defects (see Fig 1), mainly failures due to crack growth (see Appendix 2). The 1 cpm for other causes is similar to an estimate of the 95% lower bound failure frequency from an independent analysis of the Smith and Warwick (1981) data, see Appendix 3. It should be noted that if external factors (earthquake, fire engulfment, flooding, lightning, external impacts etc) are judged to exceed 1 cpm then the value for catastrophic failure could be increased to 4 cpm. This seems somewhat arbitrary as there is little justification by HSE for the 4 cpm upper limit, other than the link to the Smith and Warwick data.

13. HSE state (see Appendix 2) that external factors will make a larger contribution to limited vessel failure frequencies (eg flooding and earthquakes could lead to nozzle failure) than to catastrophic failure. However, HSE do not indicate how the limited failure frequencies should be amended when such factors are more

important. The choice of vessel hole sizes is clearly influenced by the sizes of vessel penetrations and the hole sizes adopted for pipework failures. The corresponding failure frequencies are based on an estimate of the aggregated failure frequency for limited vessel failure; this is apportioned amongst the adopted hole sizes by professional judgement – see also Appendix 2.

2.2 Above ground LPG pressurised storage vessels (not BLEVE)

14. The value adopted by HSE for cold catastrophic failure is based on a survey carried out by the Liquefied Pressurised Gas Association in 1983 (know as LPGITA at the time) and a subsequent one in 1992. Allowing for the fact that no catastrophic failures had been observed the information is consistent (based on the upper 50% confidence interval) with a failure frequency of about 1 cpm for this type of event. However, around 95% of the tanks surveyed were less than 5 te capacity and it was judged that larger tanks such as those found on COMAH sites may have more onerous operational regimes and hence higher failure frequencies. HSE therefore decided to adopt the same failure frequencies used for chlorine vessels - see Table 1. However, for LUP purposes a consequence based approach is currently adopted for pressurised LPG vessels rather than a QRA based one.

15. Sooby and Tolchard (1993) of SHELL derive a failure rate of 2.7×10^{-8} failures per vessel year *(50% confidence)* for cold catastrophic failure of LPG pressure vessels. This figure has been considered by HSE but the decision has been taken to retain the recommended generic value of 2×10^{-6} failures per vessel year for reasons given in the next paragraph. Other references in FRED give values ranging from 9.4×10^{-7} to 9.5×10^{-5} failures per year for catastrophic failures. The HSE value is at the low end of this failure rate range.

16. It should be noted that LPGA and HSE agreed to differ on the definition of cold catastrophic failure. HSE define this as any significant failure from whatever initiating event (except attack by fire/flame), whereas LPGA and Shell were only concerned with "constructional" failure (presumably pre-service undetected defects.). In other words the HSE value includes all the failure mechanisms in Fig 1 (though internal corrosion is discounted); rare external events eg earthquakes, major impacts etc may not be adequately represented in the data base considered by LPGA and Shell.

17. O'Donnell et al (2004) derive new estimates of the cold catastrophic failure frequency for LPG vessels. The values recommended are supported by worldwide-historical statistics and a Monte Carlo simulation using a fracture mechanics model of failure. Vessels are divided into large and small on the basis that capacities >6600 kg are 'large'. For LUP purposes it is the information for 'large' vessels that is mostly relevant. At the larger LPG sites, vessels with 25 te or greater capacity are of interest and judgements will have to be made about any differences affecting the failure frequency for this population of vessels and that for smaller ones. If the difference is likely to be significant – as HSE has previously judged – then the operational experience of relevance is that for 25 $^{+}$ te vessels. As no information is given about the distribution of operational

experience by tank size assumptions will have to be made. The operational experience for tanks >6.6 te capacity (totalling 3.36 million vessel-years) is shown below.

Tank size> 6.6 te	N America	W&C Europe	Rest of World
Vessel-years	3.6×10^5	1.2×10^6	1.8×10^6

18. An extensive search by O'Donnell et al of different accident and incident databases failed to identify any cold catastrophic failures of LPG vessels during normal operation. They therefore assumed 1 and zero failures and derived the following failure frequency estimates (Table 2) of cold catastrophic failure for tanks >6.6te capacity:

Table 2. Estimates (O'Donnell et al 2004) of failure frequencies (cpm) for LPG vessels >6.6te capacity

Confidence limit	50%	90%	95%	Mean
Lower bound (1 failure)	0.087	0.016	0.0077	0.3
Upper bound (1 failure)	0.82	1.4	1.7	Not given
Upper bound (zero cases)	0.21	0.7	0.91	0

19. O'Donnell et al conclude for large tanks (>6.6 te) that the analysis supports a cold catastrophic failure frequency of 0.1 cpm. This is debatable as it depends on the confidence required and assumptions made about the experience with tank sizes of interest to COMAH establishments. More importantly, the influence of external factors and overpressurisation are not adequately considered ie two branches from the fault tree shown in Fig1 are not represented.

20. Thus far HSE has not given a view on this paper, but alternative interpretations of the information are possible. For example, if we assume only 1/3 of the experience for large vessels is relevant (ie ~ 10^6 vessel years) and adopt a confidence (based on the Poisson distribution) of about 65% (equivalent to assuming about 1 failure) then the information suggests a failure frequency of $-\ln(1-0.65)/10^6 \sim 1$ cpm. Taking 50% confidence and assuming half the experience is relevant gives a failure frequency of ~ 0.4 cpm; the corresponding figure for 65% confidence is 0.62 cpm and for 95% confidence 1.8 cpm. The conclusions are therefore sensitive to the relevant operational experience and the adopted confidence level.

21. The fracture mechanics study reported by O'Donnell et al (2004) identified some implications for pressure vessel design codes underlining the importance of proof testing, and test pressure and temperature in screening out defective vessels pre-service. The extent to which these factors apply to vessels in service is unknown but given that the vessel population is ~ 50 million it seems likely that some will have significant defects which may lead to failures subsequently eg as a result of crack growth (though these are usually identified within the first 5

years or so of service – see Smith and Warwick, 1981). There is therefore uncertainty, so larger levels of confidence may be appropriate when judging an appropriate failure frequency to adopt for LUP purposes; this will increase the value adopted – see above.

22. Based on the above discussion a frequency for cold catastrophic failure for LPG vessels based on a contribution of 1 cpm for external factors and 1 cpm for defects developing in service ie 2 cpm does not seem unreasonable as a starting point.

2.3 Other pressure vessels

23. HSE uses the failure frequencies shown in Table 1 as a starting point supplemented by a value of 6 cpm for the upper bound value for catastrophic failure. Inspectors use these values as a starting point and can exercise professional judgement, provided there is suitable evidence and arguments to support any deviations (such variations are uncommon and would usually be ratified by a panel of inspectors). Given that the aggregated frequency of ~ 60 cpm applies to vessels of high standards, consideration should be given to adopting an aggregated frequency of ~100 cpm (see Appendix 2) as the starting point for limited vessels failures with a breakdown of (say) 5, 10, 35, and 60 cpm for holes of 50mm, 25mm, 13mm, and 6mm respectively.

2.4 Review of FRED failure frequencies by AEAT

24. Because of the pivotal role of failure frequencies for LUP advice HSE commissioned an independent review by AEAT (Turner 2001) of its adopted failure frequencies. The review compared the FRED values with values in the information sources quoted in FRED, and another comparison with data available to AEAT. There was insufficient information to derive meaningful estimates specifically for Chlorine and LPG vessels. Turner's remarks therefore apply to pressure vessels in general and include the following statements:

   a. ***Catastrophic failure – FRED sources***: "the failure rates fall roughly in the middle of the failure rate range for this item type in FRED, the generic failure rates quoted can be regarded as a good representative value based on the sources available."

   b. ***Catastrophic failure – comparison with information available to AEAT***: "These [AEAT] values are an order of magnitude higher than those recommended in FRED. We would regard the figures in FRED to be a slightly optimistic starting point." This last remark seems to be a judgement based on the outcome of the two comparisons.

   c. ***Limited vessel failure – FRED sources***: " … it was not obvious how the values for the hole failure rates have been derived. ….. It has been assumed that where a leak size is described (e.g. medium leak) its failure rate has been assigned to the range for one of the specific hole sizes. This would account for the recommended failure rates for 50mm, 25mm and 13mm holes in FRED being lower than any of the failure rates quoted in the source references for any of these specific hole sizes. However it is difficult to see the justification for selection of a recommended failure rate at the optimistic end of these ranges".

d. ***Limited vessel failure – AEAT sources***: "The very large leak (50-150mm) and small leak (up to 25mm) failure rates are broadly in agreement with the recommended values in FRED. The large leak (25-50mm) failure rate is an order of magnitude higher than that recommended in FRED."

The author supports Turner's view about the transparency of the adopted hole sizes and corresponding failure frequencies, but see paragraph 13 above.

3 Dutch failure frequencies

25. Chapter 3 of the 'purple book' (PB99, 1999) gives failure frequencies for loss-of-containment events for various systems. The frequencies relevant to this note are those for stationary pressurised storage vessels; it should be noted that the Dutch do not distinguish between chlorine and LPG vessels. Three types of loss-of containment events (LOCs) are considered in PB99:

    a. Instantaneous release of complete inventory
    b. Continuous release of complete inventory in 10 mins at a constant rate (hole size not specified).
    c. Continuous release from a hole of 10mm diameter.

26. The PB99 failure frequencies are taken from the IPO (IPO, 1994) document which is largely based on the COVO study published in 1981 (COVO 1981). The review of the COVO report by HSL (see Betteridge and Gould, 1999) states "Many of the frequencies used are out of date. They were calculated using expert judgement after reviewing data available at the time." A review of some of the documents cited in PB99 (including the COVO report) and some other relevant material is given in Appendix 4.

27. Subsequently the 'purple' book states that the basis of the failure frequencies is a pooled set of data due to Phillips and Warwick (1968), Smith and Warwick (1974) and Bush (1975). The HSE estimates are based mainly on a later set of data due to Smith and Warwick (1981). This will account for some of the difference in the adopted failure frequencies, with the remainder due to the judgements made about how the data relate to the major hazard industry, the allowance for improvement in standards, the completeness of the failure mechanisms represented by the data (ie whether the data cover all failure mechanisms depicted in Fig 1).

28. According to Logtenberg (Ta98, 1998; see also Appendix 4) the IPO failure frequencies – on which the PB99 values are based - are essentially expert judgements. Moreover the IPO definition of catastrophic failure includes the instantaneous release event and the 10 min continuous release event which are assumed to have equal likelihoods ie a 50/50 split. In the author's view this judgement is inconsistent with actual failure statistics for pressure vessels eg the

Smith and Warwick (1981) data set – see also Appendix 4 and Table A4.3. If the IPO definition is adopted then the estimate of the failure frequency for holes ~ 50 – 150 mm diameter has to be included in the estimate for catastrophic failure. There is no evidence that this is the case.

29. The PB99 'default' failure frequencies for storage vessels are shown in Table 3 below. The two most hazardous events are based on a catastrophic failure frequency that was judged to be 1 cpm (split 50/50 between the two most hazardous releases) when standard good practice is in place. These are significantly lower (~ 4 to 10 times lower) than the corresponding HSE values which are based more directly on actual failure data and a systematic consideration of failure mechanisms (see fig 1). The comparison is somewhat spurious because the HSE estimates include contributions for external events, fatigue, corrosion and human factors while note 2 below Table 3.3 of the 'purple' book states: "The failure frequencies given here are default failure frequencies based on the situation that corrosion, fatigue due to vibrations, operating errors and external impacts are excluded." This implies that in the Netherlands standard good practice is assumed to 'eliminate' these failure mechanisms, while HSE take a more realistic view and estimate the residual risk, see Appendix 2.

Table 3. PB99 failure frequencies for pressurised storage vessels

Instantaneous release (G1)	Continuous release 10 min (G2)	Continuous release 10mm hole (G3)
0.5 cpm	0.5 cpm	10 cpm

30. PB99 states that "A deviation of the default failure frequencies is possible in specific cases:

- A lower failure frequency can be used if a tank or vessel has special provisions additional to the standard provisions, e.g. according to the design code, which have an indisputable failure-reducing effect. However, the frequency at which the complete inventory is released (i.e. the sum of the frequencies of the LOCs, G.1 and G.2) should never be less than 1 E-07 per year *(ie 0.1 cpm)*.

- A higher frequency should be used if standard provisions are missing or under uncommon circumstances. If external impact or operating errors cannot be excluded, an extra failure frequency of 5 E-06 per year should be added to LOC G.1, 'Instantaneous' and an extra failure frequency of 5 E-06 per year added to LOC G.2, 'Continuous, 10 min'."

31. A recent paper by Beerens et al (2006) –see also Appendix 4 - provides insight into the Dutch approach to QRA, the PB99 failure frequencies for pressure vessels, and the Dutch plans to improve the quality of the values. They point out a number of inconsistencies in the literature and in the arguments underpinning

the PB99 values. The implications of their analysis are that the PB99 failure frequencies are based on out-of-date information and that they may be optimistic.

4 Observations

32. The HSE failure frequencies are based on a systematic consideration of failure mechanisms and on an analysis of more recent pressure vessel failure data than those underpinning the estimates in the IPO (1994) document. To allow for high standards in the major hazards industry HSE reduced the estimated catastrophic failure frequency by a factor of 10; a lower factor was used for limited vessel failures.

33. The PB99 default failure frequencies are based mainly on the IPO (1994) document. The failure frequencies in this document are basically professional judgements based on relatively old data sets. Also, IPO assumed that the definition of catastrophic failure includes the instantaneous release and the two most hazardous continuous releases. This means that judgements of catastrophic failure frequency based on failure data should also include estimates of the failure frequency for holes of 50 -150 mm diameter. Based on the evidence in Appendix 4 this does not appear to be the case. Consequently, the IPO (and also AMINAL (2004)) approach will, in the Author's view, lead to optimistic estimates - particularly for the 10 min (catastrophic) release - when compared with estimates derived from the analysis of pressure vessel failure data eg see Appendices 3 and 4, Table A4.3.

34. It seems somewhat arbitrary to adopt this definition of catastrophic failure when it is possible to use the Smith and Warwick (1981) data to estimate failure frequencies for different hole sizes eg see Table A4.3.

35. IPO (1994) also assumed that standard good practice will 'eliminate' failures due to external events, human error and corrosion. In the Author's view, this is an optimistic assumption and invalidates a direct comparison with the HSE values because it excludes failure mechanisms represented by some of the branches in Figure 1, whereas the HSE failure frequencies are based on all mechanisms depicted in Figure 1. For example it is not possible to eliminate human error. In fault tree analysis (FTA) terms the PB99 default failure frequencies are based on an 'incomplete' analysis. The PB questions and answers document of 22 July 2003 also states that the standard failure frequencies exclude external impact and gives the following example to illustrate how an air crash would be included: "Example 2: A pressurised tank is situated near an airport at the location-specific risk contour of 1×10^{-6} per year. In this case, the location-specific risk of an aeroplane crash is more than $0.1 \times$ the standard failure frequency of the vessel, and the failure frequency of the tank is now 2×10^{-6} per year (standard failure frequency 1×10^{-6} per year + failure frequency due to external impact of an aeroplane crash 1×10^{-6} per year)." Thus the quasi-instantaneous release scenario has a frequency of 1 cpm and the 10min continuous release scenario has a frequency of 1cpm. If all other possible external hazards and the other causes that are excluded (eg human error, corrosion etc) are considered

systematically it seems likely that these values could increase further in most cases.

36. Taking the statements in the PB99 literally and adding in the suggested frequencies for human error, external impacts etc the PB99 failure frequencies for the most hazardous scenarios are similar to those of HSE – see Table 4.

Table 4. A comparison of HSE and PB99 failure frequencies (cpm) for pressure vessels

Type of failure	PB99 default	PB99 'complete'	HSE
Catastrophic	0.5	5.5	2 - 6
Large hole	0.5	5.5	5
Small hole	10	10	55
All types	11	21	62 - 66

37. Table 4 also shows that the HSE aggregated failure frequency for small holes (6, 13 and 25 mm) is 5 times the PB99 value for 10mm holes. In LUP terms this difference (factor of 5) can significantly influence the location of the inner planning zone; the magnitude of the effect will depend on the choice of hole sizes and the corresponding failure frequencies.

38. The PB99 default failure frequencies for the two most hazardous events are 4 to 10 times lower than the HSE values. This difference would lead to significantly smaller LUP zones (the CD and middle zone), but in the author's view such optimistic values are not justified unless standard good practice is supplemented by indisputable failure-reducing measures which eliminate the mechanisms implicitly discounted in the PB99 default values. It is therefore important to provide evidence and arguments to support the use of failure frequencies at the optimistic end of the range of values. No such evidence was found in the 'purple' book or the documents cited therein (see Appendix 4).

39. That there are differences between the HSE and PB99 default failure frequencies is not surprising as there is appreciable scope for disparity, viz:

    a. the uncertainties in deriving estimates from actual and generic data sets can be appreciable (see Table 2 and Appendices 3 and 4) ie the confidence bounds are quite wide ~ 1 to 2 orders of magnitude); and

    b. the judgemental process of adapting generic failure frequencies for use in the major hazards area (see Appendices 2, 3, and 4).

40. Appendix 3.A of the 'purple book' recognized that the default failure frequencies may be optimistic compared with more recent information available at the time of writing, but decided to defer consideration of this information until a later date. Appendix 4 gives an informative review of this information and the IPO and COVO reports, which form the basis of the purple book failure frequencies. The main conclusion from this review is that there is no convincing evidence to support the view that the HSE failure frequencies are pessimistic; on the contrary

the evidence suggests that the HSE failure frequencies are optimistic when compared with the values recommended in a TNO (TNO, 1998) review of the literature. This review shows that the PB99 failure frequencies are at the low end of the ranges of values found for different failure scenarios and the HSE values are less than the corresponding median values.

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41. The TNO (1998) review of failure frequency data proposes median failure frequencies for use in QRA. The recommended values corresponding to the three PB99 scenarios are: 10, 50 and 100 cpm respectively, ie an aggregated frequency of 160 cpm which is ~ 15 times larger than the aggregated PB99 default values and ~ 2.5 times the HSE aggregated values.

    Although the HSE aggregated failure frequency for holes is about five times larger (~60 cpm cf 11 cpm) than those recommended in PB99, Turner (2001) sees the HSE values as optimistic, see Section 2.4.

42. A paper by Spouge (2005) also provides some evidence which indicates that the PB99 values are optimistic. His paper discusses the use of 'high' quality failure data collected in the UK off-shore sector for onshore QRA. Table 4 in his paper gives the following failure frequencies for process vessels: holes >= 50 mm diameter, 110 cpm; and holes >= 1mm diameter, 500 cpm. These values are about an order of magnitude higher than the median values for pressure vessels reported by Logtenberg (1998), and similar to the maximum values found in the literature – see Table A4.2. Although it could be argued that pressurised storage vessels may have lower failure frequencies than process vessels, it is unlikely that the factor is more than 10.

43. The above remarks demonstrate that the criticism of the HSE failure frequencies is not warranted.

44. The pressure vessel failure frequencies used by HSE are said to be best estimates, but this is not always clear in the supporting documents. Any cautious best estimates should be made clear in the FRED documentation. The use of 'cautious best estimates' by HSE raises two questions:

    a. How cautious do 'cautious best estimates' need to be for LUP purposes?

    b. Should 'best estimates' rather than 'cautious best estimates' be used when deciding whether risk reduction measures are reasonably practicable?

45. Given that LUP aims to mitigate the effects of a major accident, and that LUP decisions have a long time scale, it is not unreasonable, in the author's view, to use 'cautious best estimates' when uncertainties are appreciable eg vessel failure frequencies derived from surrogate data. Despite the uncertainties, HSE have adopted a best estimate value for pressurised storage vessels towards the lower end of the confidence interval. This does not appear particularly cautious when contrasted with the recommendation of median values by the TNO review (TNO, 1998) and the adoption by HSE of a value nearer the top end of the uncertainty range for LPG vessels which is based on comprehensive information

for actual vessels. This seems inconsistent, even though LUP advice for pressurised LPG is not currently QRA based. This inconsistency was also noted by Turner (2001).

46. According to Beerens et al (2006) a Dutch study based on more recent data is underway to derive new failure frequencies. The intention is to use new baseline failure frequencies, but to allow variations of these to be derived by applying modification factors. This approach, in the author's view, has adverse implications for LUP decisions and regulators when credit is given for high standards. As pointed out above LUP decisions have a long time frame and it is not prudent to give credit for (say) high maintenance standards as a future change of ownership may result in reversion to minimal compliant practice. Moreover it is well documented (eg Flixborough, Bhopal, Mexico City, see also ACSNI, 1993) that disasters are invariably due to 'management failures'. For LUP purposes, therefore, cautious failure frequencies are appropriate. Should Regulators decide to give credit (eg see AMINAL 2004) for high management standards or additional measures, then they are – in the author's view - duty bound to carry out sufficient inspection and take any necessary action to uphold those standards throughout the lifetime of the plant

47. However, when using CBA to assess whether further risk reduction measures are reasonably practicable, it is the author's view that best estimate failure frequencies should be used rather than cautious estimates. Issues such as uncertainty, risk aversion etc can then be factored into the decision on 'reasonable practicability' through the adopted factor for gross disproportion (ie measure is reasonably practicable if the annualised cost of risk reduction <= lives saved per year x statistical value of a life x gross disproportion factor). Such an approach means that HSE need only maintain one data base, provided a view is given on the difference between 'cautious best estimate' and best estimate values.

48. In the interests of transparency it is suggested that whenever HSE uses 'cautious best estimates' that the degree of caution adopted is indicated. For example if it is judged that for a particular set of circumstances that the 95% upper bound value is appropriate the evidence and arguments behind that judgement should be summarised eg in FRED.

49. In carrying out this review the author noted that the information contained in FRED and PCAG was broadly similar. This raises the issue of duplication and it may be more resource efficient to maintain only one failure frequency document. Of the two, FRED is more comprehensive and in the author's view should become the authoritative HSE source for failure frequencies.

50. It was also noted that the main evidence and arguments justifying particular values was often 'elsewhere' ie not in PCAG or FRED. This is because the brief reviews of these supporting documents, particularly in FRED were largely descriptive rather than informative. It is therefore suggested that these descriptive summaries are replaced by informative ones, so that FRED becomes an essentially stand alone document. FRED should be published on the HSE

web site for use by industry who should be encouraged to provide information to improve the quality of the failure frequency estimates.

5 Conclusions

51. After careful consideration of the HSE and Dutch sets of failure frequencies and the supporting literature no convincing evidence or arguments were found to support the claim that the HSE failure frequencies for pressurised storage vessels are pessimistic. On the contrary there is evidence in the TNO review (TNO, 1998) and the review by Turner (2001) which suggests the opposite. Given that the HSE failure frequencies apply to high standard situations it is the author's view that they are good estimates for testing compliance with the COMAH regulations, but slightly optimistic for LUP purposes where a degree of caution is justified because of the inherent uncertainty.

52. Based on the review of information presented here, the HSE failure frequencies for pressure vessels are more soundly based and justified than the values adopted in PB99. By comparison the evidence and arguments justifying the PB99 default failure frequencies is weak; see also Beerens et al (2006) and Appendix 4.

53. The PB99 failure frequencies are based largely on professional judgement underpinned by relatively old data sets (compared with HSE) and the assumption that the adoption of standard good practice is sufficient to 'eliminate' important failure mechanisms (eg external events and operator error) which HSE have considered. In the Author's view this assumption is optimistic; HSE have taken account of the residual risk.

54. External events and human error are known to be important contributions to failure and the author has not identified any evidence or arguments in the Dutch literature to justify any assumption that standard good practice is sufficient to "exclude" these contributors eg flooding and earthquakes can lead to vessel nozzle failure and human error (impossible to exclude) may result in overpressurisation. Indeed the two catastrophic failures on which the AMINAL(1994) generic frequency for catastrophic failure is based were due to 'operational loading' – see Appendix 4. If HSE excluded external factors, human error etc the failure frequencies for catastrophic failure would be comparable to the Dutch value.

55. When these mechanisms (external events, human error etc) cannot be excluded the suggested PB99 frequency for large vessel holes becomes 5.5 cpm (ie similar to the HSE value); the PB99 catastrophic failure frequency becomes 5.5 cpm which falls within the HSE range of values - 2 cpm to 6 cpm. Thus an important difference between the Dutch and HSE position is the view taken on the effectiveness of standard good practice and the need to take account of the residual risk.

56. The IPO (1994), AMINAL (2004) and PB99 failure frequencies are the lowest found in this review. The low values appear to be the result of an inconsistency

between the definition of catastrophic failure and the use of actual failure rate data to make estimates. Whereas HSE limit catastrophic failure to the instantaneous release scenario, the Dutch and Belgian approach is to also include the most hazardous continuous releases. However, no evidence was found to suggest that the adopted catastrophic failure frequency was based on failure frequency estimates which included contributions from 50 -150 mm holes. In consequence the values adopted will be optimistic.

57. It seems somewhat arbitrary to adopt the IPO (1994) and the AMINAL (2004) definition of catastrophic failure when it is possible to use the Smith and Warwick (1981) data (see also Spouge (2005)) to estimate failure frequencies for different hole sizes including the 50-150mm range eg see Table A4.3.

58. There is nothing to stop UK companies employing the Dutch failure frequencies. However, in the Author's view, HSE should expect sound evidence and arguments to justify the use of such low failure frequencies given the weight of the evidence suggesting that higher values are appropriate.

59. The authors of PB99 recognised prior to publication that information existed which indicated that the failure frequencies recommended for some systems were optimistic. Indeed a TNO review (TNO, 1998) of over 180 sources of information proposed that median values should be used for QRA. The values suggested for the three vessel scenarios in the TNO review were 10, 50 and 100 cpm respectively ie one to two orders of magnitude higher than the PB99 default values. The review also showed that the PB99 values were the lowest or next lowest of the values found in the sources considered – see Appendix 4.

60. The difference in the number of small holes (less than 50 mm diameter) and the associated frequencies (aggregated 55 cpm for HSE; 10 for PB99 ie a factor of 5) will have implications for LUP. The HSE failure frequencies and scenarios will lead to larger contributions to risk in the near to mid field with possible implications for LUP decisions (ie the HSE approach will lead to a larger inner planning zone for toxic releases). Given that LUP attempts to mitigate the impacts of loss-of-containment accidents the HSE approach seems more consistent with the LUP requirement of the Seveso Directive.

61. For the reason given immediately above, it is the author's view that the intention (stated in Beerens (2006)) to modify failure frequencies has implications for LUP decisions and regulatory enforcement whenever credit is given for high standards as such standards may not be maintained over the lifetime of the plant (eg due to a change of ownership). This may result in land development too close to the plant and undermine the mitigation that a pragmatic approach to LUP should provide.

62. The failure frequencies adopted by HSE are broadly similar for chlorine, LPG and other pressure vessels. The values adopted apply to **high** standard situations. Given the conclusions in the Turner (2001) and Logtenberg (TNO, 1998) reviews, consideration should be given by HSE to making the starting estimates for "other pressure vessels" more pessimistic for LUP purposes, see also Appendix 2.

63. New information for catastrophic failure of LPG tanks has been considered. This claims to support a catastrophic failure frequency of 0.1 cpm. In the author's view this is an artefact of the analysis as rare external events will be under represented in data sets spanning the last 20 years or so. (HSE include a 1cpm contribution for external events so the HSE frequency can not be less than that unless there are measures to mitigate such events).

64. In view of the importance of the contribution of external factors, HSE should review and improve the evidence and arguments supporting the adopted HSE failure frequencies by taking account of research it has funded on earthquakes together with any other relevant developments. The internal consistency of the basis of the adopted values should also be reviewed. Any amendment of the failure frequencies should be published eg see last conclusion.

65. When HSE uses 'cautious best estimates' the evidence and arguments to support the adopted value should be summarised. For example in the case of catastrophic failure HSE has adopted a failure frequency around the upper 50% confidence level based on actual vessel experience for LPG vessels, but in the case of chlorine HSE has used surrogate information and has opted for an estimate at the lower bound end of what seems to be the 95% confidence interval. Both values are regarded as best estimates for catastrophic failure, this seems inconsistent.

66. HSE failure frequencies appear in two main documents, PCAG and FRED. Keeping both documents up-to-date seems to be a duplication of effort. To make more effective use of resources it is suggested that FRED becomes the sole source of information on failure frequencies.

67. In conducting this review it was time consuming to track down the main evidence and arguments supporting the adopted failure frequencies as it is scattered throughout many documents. There is some information in FRED, but it is largely descriptive rather than informative. Consideration should be given to summarising the main evidence and arguments in FRED.

68. FRED should be made available via the HSE web site to help reach a consensus on failure frequencies and to encourage industry to supply information to improve the quality of the estimates.

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The author is grateful to Glyn Hawkins (Mechanical Engineer, HSE) for providing access to HSE documents, for his comments on the various drafts, and for a number of helpful discussions during the course of this work. Andy Rushton (Specialist Inspector, HSE) also provided helpful input. However, the views expressed are those of the author alone and should not be taken as representing those of HSE.

References

ACSNI (1993). ACSNI study group on human factors. Third report: Organising for Safety. HSC, Advisory Committee on the Safety of Nuclear Installations; ISBN 0717608654

AM94: Manual of Probability Statistics for drafting of Safety Reports; AMINAL 1994.

AM2004: Manual of Probability Statistics for drafting of Safety Reports; Coordinated Version 2.0. 01/10/2004 (This superseded the 1994 document).

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Beerens H I, Post J G, Uijt de Haag P A M (2006). The use of failure frequencies in QRA: The quality and use of failure frequencies and how to bring them up-to-date. JHM 130(2006) 265-270.

Betteridge, P; Gould J (1999), Failure Rate and Event Data for Use in risk assessment (FRED) RISKAT. HSL internal report, RAS/99/20.

BS EN 13445: 2002 Unfired Pressure Vessels.

Bush, SH (1975) Pressure Vessel Reliability: Trans of AMSE, J of Pressure Vessel Technology, 97(1) p54-70 1975.

CCPS (1989 & 2000) Guidelines for Chemical Process Quantitative Risk Assessment. AIChE 1989 & 2000

COVO Report (1981), Risk analysis of six potentially hazardous industrial objects in the Rijnmond area, A pilot study, ISBN 90 277 1393 6

HSC (1979), Advisory Committee on Major Hazards, 2nd Report, Table A (list of chlorine incidents).

HSE (2004) Planning Case Assessment Guide (and supporting documents)

HSE (1999) HSG28: Safety advice for bulk chlorine installations ISBN 0717616452

IPO (1994) interprovinciaal overleg, Handleiding voor het opstellen en beordelen van een extern veilgheidsrapport (EVR), Project A73, Jan 1994

Lees F P (1996). Loss Prevention in the Process Industries. Butterworths.

O’Donnell, IJ; Phillips DW and Winter PW (2004) A new estimate of the likelihood of spontaneous catastrophic failure of pressurised LPG storage vessels. Hazards XVIII, IChemE, Nov 2004.

PB99, CPR18E, Purple Book, Guidelines for quantitative risk assessment, Sdu Uitgevers, The Hague, Committee for the Prevention of Disaster, 1st Edition, 1999.

PD 5500: 2006 Specification for unfired fusion welded pressure vessels.

Phillips and Warwick 1968. A survey of defects in pressure vessels built to high standards of construction and its relevance of nuclear primary circuit envelopes. UKAEA R162.

Singleton B (1989). CIMAH Safety Cases 3: Toxics and Ultratoxics. In Lees F P and Ang M L, Safety Cases, p243 Butterworths, 1989.

Smith, T.A. and Warwick, R.G. (1981), A survey of defects in pressure vessels in the UK for the period 1962-1978 and its relevance to nuclear primary circuits. SRD report R203.

Sooby, W. and Tolchard, J.M. (1993), Estimation of cold failure frequency of LPG tanks in Europe. Conference Paper, Shell International Petroleum Company Ltd.

Spouge J (2005). New Generic Leak frequencies for Process Equipment. Process safety Progress vol 24(4), p249, Dec 2005.

TNO (1998) M Th Logtenberg. Derivation of failure frequencies for loss of containment cases. TNO Report MEP-R98/501 December 1998.

Turner J (2001) Review of Failure Rate and Event Data (FRED) for use in Risk Assessment AEA/RSMS/RD02032001/01/Issue 1

Appendix 1: A brief summary of information in Lees (1996; pp 12/94 to 12/97)

Published information on pressure vessel failure is summarised in the above volume. Failure frequencies for failures which required major repair or scrapping of the vessel (ie the Smith and Warwick 'catastrophic' category) are listed in Table A1.1. These failures are considered relevant to catastrophic failure.

Table A1.1: Failure frequencies derived from survey data collected by UKAEA

Source	Sample size, vessel years	Failure frequency, cpm. (Number of failures in service)
Phillips and Warwick (1968) Class 1 vessels designed to BS1500 or BS1515, or equivalent	100,300	70 (7)
Phillips and Warwick (1968) Estimates for pressure vessels used in the nuclear reactor primary circuit envelopes	100,300	20 (2)
Smith and Warwick (1974)	105,402	150
Smith and Warwick (1981) Majority of duties were steam, water or air	310,000	42 (13)

Davenport (1991) has reported the results of a survey covering the period 1983 -88. The survey was not confined to Class 1 vessels and is dominated by relatively thin-walled air receivers so the data are not comparable with the earlier surveys.

Engel (1974) describes an analysis of non-nuclear pressure vessel failure statistics judged applicable to nuclear reactors. He refers to large collections of pressure vessel failure data by the Edison Electric Institute - Tennessee Valley Authority, by the American Boiler Manufacturers Association (ABMA) and by TUV (eg see Kellerman and Seipel, 1967). The most severe failure category considered was 'disruptive failure' viz breaching of the vessel with a release of a large volume of the containment fluid ie a more severe failure than considered by Smith and Warwick. The analysis for the largest data sets are shown in Table A1.2; the analysis of 49 failures by Kellerman and Seipel did not indicate how many were disruptive failures, hence the range in the Table.

Table A1.2: Failure frequencies for a significant loss of containment.

Data Source	Sample size Vessel-years	No. of Failures	Upper bound of failure frequency (cpm) At 99% confidence (one tail test, see Lees, Chapter 7.20.6)
Phillips and Warwick (1968)	100,300	0	46
ABMA (Marx, 1973)	723,000	0	6.4
Kellerman and Seipel (1967)	1,700,000	0 – 49	2.7 to 40

Engel regards the ABMA data as having the best quality and for vessels with a wall thickness greater than 1.5" he concludes that the disruptive failure frequency for nuclear reactors is less than 10 cpm. This figure can not be read across to chlorine vessels as the operational environments are very different.

Lees gives the following adopted failure frequencies used in major hazard QRAs:

- First Canvey report catastrophic vessel failure = 10cpm
- COVO study (1981) catastrophic vessel failure = 1cpm
- COVO study serious leak = 10cpm

References

Davenport, T.J. (1991), A further survey of pressure vessel failures in the UK (1983 – 1988). SRD report. GNSR (HSE) – XSI1/6

Engel J R, 1976. Pressure vessel failure statistics and probabilities. Nucl Safety, 15(4), 387

Kellerman O, and Seipel H G. 1967. Int Atomic Energy Agency Symp. On Containment and Siting of Nuclear Power Reactors (Vienna).

Marx W B 1973. Private communication to R R Maccary, AEC Directorate of Licensing

Phillips and Warwick 1968. A survey of defects in pressure vessels built to high standards of construction and its relevance of nuclear primary circuit envelopes. UKAEA R162.

Smith T A and Warwick R G 1974. Report SRD R30 and J Pres. Ves. Piping 2. 283

Appendix 2: Summary of the evidence and arguments underpinning the HSE adopted failure frequencies for pressurised chlorine storage vessel failures (based on the literature cited in FRED (Betteridge and Gould, 1999))

1. Loss-of-containment accidents arise from vessel failures (catastrophic or limited ie holes in the vessel wall) caused by external damage, over-pressurisation or the development of defects. The failure mode will depend on whether the initial breach is critical or not and whether the vessel is stress relieved. Historical surveys (eg see Smith and Warwick (1981)) show that 90-95% of reported failures are due to cracking. For a stress relieved vessel, a crack that breaks through the wall may result in a leak which should be detected before whole vessel failure can occur. For un-stress relieved vessels the HSE view is that critical cracks may be so short that a leak before break condition can be excluded.

2. The adopted failure frequencies are based on the considerations of two specialist mechanical engineers and the peer review of their colleagues. The following evidence and arguments influenced their collective judgements.

Whole vessel failure

3. The second ACMH report (HSC, 1979) lists 7 chlorine releases from storage vessels in a period of over 60 years (1917 – 1976). Assuming a population of 10^4 vessels suggests a failure frequency of 10 cpm. All of these incidents were abroad and the UK chlorine industry claims that vessels designed and operated to UK standards or equivalent have yet to fail anywhere in the world.
4. Smith and Warwick (1981) consider data from three five-yearly surveys (1962-67; 1968 – 73; and 1973 – 78). Two types of failure were considered:

    a. ***Catastrophic:*** this implies a failure so severe to necessitate major repair or replacement.

    b. ***Potentially dangerous:*** this is a defect requiring action as further operation could result in a dangerous extension of the defect.

5. Over the three periods 216 potentially dangerous failures and 13 catastrophic failures were identified for a population of 20,000 vessels and 310,000 vessel years of experience. For catastrophic failures the data indicate a frequency of 42 cpm with an upper 95% confidence bound of 70 cpm (Smith and Warwick,1981). Of the potentially dangerous failures 76 were identified as a result of leakage. 94% of the failures were due to crack propagation, mainly as a result of 'defects existing prior to service' (29%); fatigue (24%); and corrosion (14%).

6. One of the specialist engineers judged that the 42 cpm figure due to Smith and Warwick (1981) , reduces to 20 cpm if failures not relevant to the chlorine industry ie creep failures and thick-wall vessels are excluded.

7. HSE judged, for unheated vessels of a high standard, that the catastrophic failure rate would be an order of magnitude lower than Smith and Warwick's (1981) 42 cpm value ie ~ 4 cpm. For stress relieved vessels one of the specialist engineers

judged the failure frequency to be about 2 cpm and for non-stressed-relieved vessels to be about 6 cpm.

8. A study funded by HSE of a chlorine site by SRD based on fault tree analysis indicated a failure frequency of 41 cpm, but HSE regarded this as “over-conservative”.

9. In a joint study with ICI in the early 1980s (82-85) HSE adopted a catastrophic failure frequency of 2 cpm. This is said to be a ‘best estimate’ value for the particular ICI plant. ICI adopted 1 cpm.

10. One of the specialist engineers conducted a fracture analysis of data from a 20 te (13.4 mm thick plus 1.6 mm corrosion allowance) and a 2 te (8.2 mm thick plus a 1 mm corrosion allowance) chlorine vessel. He concluded, given the vessel thicknesses that they would leak before splitting apart if they had defects less than the critical crack sizes (100 mm for the thicker stress relieved vessel and 30 mm for the thinner one). (These crack sizes were seen as minimum values as conservative material properties were used). The CIA guidelines for the bulk handling of chlorine call for all vessels to be stress relieved and this is believed to be mostly the case. It should be noted that any welding repairs carried out after the vessel has been commissioned will be very difficult to stress relieve.

11. The Smith and Warwick data indicate that 90-95% of pressure vessel failures were due to cracking; of these 30-35% were detected by leakage; 6 % led to ‘catastrophic’ failure; the remainder were discovered during routine inspection. In the case of chlorine vessels cracks in welds could grow due to internal corrosion or by fatigue induced by pressure changes during operation (filling/ emptying of vessels).

12. One inspector concluded that the failure frequency for whole vessel failure should be taken as 4 cpm unless site specific factors are known to increase this figure. Where it is known that the standards are above average 2cpm should be adopted.

13. The other inspector suggested for vessels which are thoroughly examined and certified (design pressure and temperature range; maximum filling ratio and load) that the probability of failure due to defects or cracks for a stress relieved vessel is low, say 1 cpm. For un-stress-relieved vessels 5cpm was suggested as failure due to defects is higher. He also concluded, following an analysis of external hazards that catastrophic failure due to such events is unlikely to exceed 1 cpm, though the other specialist regarded this as a minimum value. Thus for high standard chlorine vessels a catastrophic failure frequency of 2 cpm was adopted as a best estimate.

Conclusions for catastrophic failure of chlorine storage vessels

14. In September 1986, following lengthy internal debate, HSE decided to adopt the following failure frequencies:

Lower bound – good standards	Median – reasonable standards	Upper bound – poor standards
2 cpm	4 cpm	6 cpm

NB: The original HSE document (AES/MHAU/006/A-4/9.86/SAH (FRED Ref 15)) did not explicitly define the three standards. The author has therefore discussed with HSE the meaning of the descriptors as 'poor' implies criticism of current HSE enforcement policies (and also of the Engineering Inspecting Authorities (e.g. insurance companies) for initial manufacturing issues) ie proper inspection should ensure that no current vessel could be described as 'poor'. HSE has therefore provided the following descriptions for the failure frequency values:

"2cpm: This value is currently considered by HSE appropriate for new assessments and new installations built to current relevant good practice and where there are no extraordinary site-specific factors.

4cpm: This value is used by HSE where it was considered to be justified by site-specific factors or justified because an installation being assessed was built to the standards of its time and upgrading is not considered reasonably practicable.

6cpm: This value was used by HSE in the 1980s when the compliance of some installations remained unresolved. Few if any current assessments use this value."

It should be noted that the UK Health and Safety etc Act requires risks to be reduced until they are as low as is reasonably practicable ie ALARP. This does not mean that standards are uniform for similar processes; they will depend on circumstances (see paragraph 3.4 et seq in http://www.hse.gov.uk/risk/theory/alarp2.htm).

Limited vessel failures

15. These failures include failures of vessel penetrations eg nozzles. External events and over-pressurisation could result in holes and cracks up to the critical crack size. The size of a hole due to crack growth which results in a chlorine leak, should be readily noticed so that action to prevent more serious releases can be taken.

16. Quantification of failure frequencies is likely to be influenced by under reporting and the contribution from external events will be higher than for whole vessel failure. Limited failures due to crack growth were only considered to be likely for stress relieved vessels; once defects in unrelieved vessels reach a critical size the propagation rapidly leads to whole vessel failure.

17. Of the 216 potential failures reported by Smith and Warwick (1981), 33% were detected by leak indicating a failure frequency (excluding catastrophic failure) of 240 cpm. HSE concluded that the order of magnitude reduction applied to the catastrophic failure data set was not appropriate. Instead they argued that some failures were not relevant to chlorine vessels so it was concluded that 100cpm was reasonable for limited failure, reducing to 60 cpm for high standard plant. These failure frequencies were deemed appropriate for the minimum size of a

‘noticeable’ hole. Larger holes up to the critical crack size were thought to have a failure frequency similar to that for whole vessel failure.

18. Crack growth was thought to produce holes equivalent to about 7 mm diameter. No HSE information has been found about larger holes due to cracking. Nozzles and other vessel penetrations are typically 25mm or 50mm diameter.

Conclusion

19. HSE regards the catastrophic failure frequency of 2 cpm as a best estimate for high standard vessels. It is not clear whether HSE gave any credit for the leak before break scenario when deciding the failure frequency for whole tank failures. It may well have been implicitly included in the factor of 10 reduction applied to the Smith and Warwick data. In the absence of more convincing information the 2 cpm catastrophic failure frequency seems a reasonable best estimate for high standard plant. However, owing to the uncertainty (see Appendices 3 and 4) this value does not seem particularly cautious for LUP purposes, given that for pressurised releases it is divided equally between 2 cases: maximum inventory becomes airborne; and half that amount becomes airborne quasi-instantaneously.

20. No justification has been found for the breakdown of hole sizes for limited failures; it seems purely judgemental but is not dissimilar to that used by others for QRA. It is obviously influenced by nozzle sizes. The apportionment of frequencies to the adopted hole sizes is broadly similar to the declared expectations of the specialist mechanical engineers, taking account of the greater influence of external factors.

21. The frequencies adopted (see Table A1.1) apply to plants with high standards. No guidance is given about deviations to account for plant specific external factors, despite the acknowledgement that such factors could be more significant for limited failure than for the catastrophic failure case. For example the frequency of earthquakes or flooding capable of causing nozzle failure might be higher than 6 cpm in some locations. The 6 cpm limit imposed by HSE therefore seems to be arbitrary.

22. An explanation of the frequencies adopted for the 50mm and 25 mm holes is that the contribution due to cracks is ~ 1 -2 cpm (ie a similar frequency to catastrophic failure) with the remainder due to external factors (ie a higher contribution than for whole tank failure). If this explanation is accepted then higher frequencies may be appropriate for some sites and the HSE guidance for inspectors will need amending.

23. Given the significance of the contribution from external factors it is suggested that HSE updates its analysis of these failure causes.

APPENDIX 3: An analysis of data by Smith and Warwick (adapted from CCPS 1989, p358 et seq and 2000. p513 et seq)

CCPS present a simple analysis of the Smith and Warwick (1981) survey data which provides failure data for a population of 20,000 pressure vessels with a total exposure time of 310,000 vessel-years. The analysis provides useful insights into the uncertainty involved in the estimation of failure frequencies.

The data were screened to eliminate pipework failures and then divided into specific groups based on the brief descriptions given in the paper. The data suggest 13 catastrophic failures and 76 leaks, but the analyst decided that only 2 and 42 cases respectively could be attributed to pressure vessels. (This judgement may have implications for the estimated experience, but this was ignored, so the estimates may be optimistic.)

Assuming a constant failure rate, the catastrophic failure frequency is 2/310,000 ie 6.5 cpm. The 95% confidence bounds for the catastrophic failure case were estimated as 1.1 and 20.3 cpm respectively. (A description of the derivation of confidence intervals for failure frequencies is given in CCPS (1989, p350-352) and Lees (1996, Chapter 7.20.6)). It is stated that "the analyst should be very cautious when using a failure rate that lies outside of these 95% confidence limits."

Failure frequencies for different hole sizes are given in Table 5.8 of the 1989 CCPS document , but the number of cases in the Table is 178 not 42 as stated in the text. Apportioning the 42 in the same ratio as in Table 5.8 we have the following failure frequencies:

- <25 – 50mm hole 19 cpm
- 50 – 150 mm hole 115 cpm

The failure frequencies for vessel holes are significantly higher than those adopted by HSE, PB99 and in Table A4.3. The reason for the difference between these values and those in Table A4.3 is not known.

It is interesting to note that the failure frequency for large holes is 6 times higher than for the smaller category; this seems counter intuitive (the largest range in the 2000 Edition of the CCPS document is given as 50 -100 mm). Table 5.5 of the 1989 CCPS document lists 16 factors (design standards, duty, maintenance strategy, age, failure mode, etc) that can influence failure frequencies.

The aggregated frequency is ~ 140 cpm ie about twice as high as that adopted by HSE and 13 times that adopted by PB99. The difference between the HSE and CCPS interpretations is probably due to the judgements made when tailoring generic data to specific types of vessel eg chlorine storage.

This data analysis can be found in more detail in AMINAL (1994), see Appendix 4.

Appendix 4: A review of failure frequency information cited in PB99

Introduction

1. The chapter on failure frequencies in the ‘Purple Book’ (PB99) cites a number of references in support of the values quoted, but also cites material which indicates that higher failure frequencies may be appropriate.

2. This Appendix provides an informative summary of each information source and then draws some conclusions. The relevant references are:
   a. The COVO Report (1981)
   b. Ta98: Taylor JR/Taylor Associates ApS. Review of failure rate data for risk analysis. Version 1. Issue 1. Glumsoe. Neste and Taylor Associates ApS, 1998. (This is a discussion document. Apparently it is still under revision and not yet (May, 2006) publicly available.
   c. TNO98b: M Th Logtenberg. Derivation of failure frequencies for loss of containment cases. TNO Report MEP-R98/501 December 1998.
   d. IPO: Inter-Provisional Consultation Organisation (IPO): Manual for Drafting and Assessment of External Safety Reports (ESR). Project A73, January 1994.
   e. AM94: Manual of Probability Statistics for drafting of Safety Reports; AMINAL 1994.
   f. AM2004: Manual of Probability Statistics for drafting of Safety Reports Coordinated Version 2.0. 01/10/2004 (not cited in PB99, but included here for completeness).
   g. Beerens et al (2006) The use of failure frequencies in QRA (not cited in PB99, but included here for completeness)

The COVO report

3. This report presents the findings of a risk analysis of six installations in the Netherlands. The report is in five parts and represents the state of the art at the time the studies were conducted in 1979. The study objects were: acrylonitrile storage (Part 2; 6.1); ammonia storage (Part 2; 6.2); chlorine storage (Part 2; 6.3); LNG storage (Part 2; 6.4); propylene storage (Part 2; 6.5) and Hydrodesulphurisation plant (Part 2; 6.6).

4. Chapter 6.3 of the COVO report is the most relevant to pressure vessels ie chlorine storage. Fault tree (FT) analysis was used to estimate the reliability of complex systems; and historical data was used to predict failure frequencies for failures that occur independently of other parts of the system eg basic events in the FT. The FTs are presented in Appendix XIII; most basic events are discussed in Appendix IX and Table IX.I gives failure frequencies for different failure modes of different items (pumps hoses; piping etc).

Section 6 of Table IX.I of the report deals with vessels. The values quoted for pressure vessels are listed in Table A4.1:

Table A4.1. COVO Report: failure frequencies for pressure vessels

Failure mode	Failure rate cpm	Range cpm
Serious leak < 50mm hole	10	6 - 2600
Serious leak 50mm hole	3.3 (judged to be a factor of 3 lower than above)	2 – 870 (factor of 3 lower than above)
Catastrophic rupture	1	0.63 - 46

5. To support the catastrophic rupture value the report cites Bush, and the UKAEA studies in 1969 and 1974. The data were tailored to the process industries by reducing the quoted frequencies by a factor of 10. The FT study in Appendix XIII concluded that the 95% confidence bounds were 0.167 cpm and 3 cpm with a median value of 0.74 cpm. However, the estimates used for frequencies of certain external events seem optimistic compared with those used by HSE. Also these events are assumed to affect the tank supports rather than the vessel itself. Tank rupture therefore requires both gross overpressure of the tank AND tank support failure, even for aircraft impact.

6. **Conclusion:** The COVO report predates the Smith and Warwick (1981) study and is now regarded as out of date. The treatment of external events also seems optimistic. Nevertheless, the adopted value for catastrophic rupture of chlorine vessels is similar to that used by HSE (1 cpm cf 2 cpm).

TNO 98b: M Th Logtenberg, Derivation of failure frequencies for loss-of-containment cases. TNO Report MEP-R98/501, 1998

7. This is essentially a literature survey of over 180 documents (up to 1997) covering failure frequencies for: vessels; pipelines; pressure relief devices; loading and unloading facilities and transport units. Ignition probabilities and human error are also covered.

8. One of the conclusions is that "quite a number of authors (even in recent publications) have copied and adapted the original data, the majority of which was published over 25 years ago. Hence the basis of the failure data is much smaller than may be expected from the large number of references and moreover the data are rather old."

9. The median value for a component was compared with values recommended in the IPO manual. For pressure vessels and pressure relief systems the literature data cited are higher than recommended in the IPO document.

10. Many of the sources give no descriptions of the failure mode. For vessels and tanks three failure modes are considered: Instantaneous releases (including holes >150mm) ; large continuous releases –whole inventory, effective hole diameter 50mm; and smaller releases <25mm typically 10mm. The data extracted from the literature are presented in Chapter 3.

11. Chapter 4 ranks the data and summarises it in Table 4.1.7. The ranges are large and are summarised in Table A4.2 below:

Table A4.2: Summary of failure frequency values found in TNO98b for pressure vessels

Type of failure	Largest value cpm	Median cpm (Proposed values for adoption)	Lowest value cpm	Range (largest/ lowest)	No. of values
Instantaneous release of whole inventory	510	10	0.5 (The IPO value, but the AMINAL 2004 value is 0.3 cpm)	1000	13
Large continuous release	500	50	0.04	~12,000	19
Small leak	700	100	50	14	11

12. In Chapter 4 Logtenberg notes that the IPO document is used most for deriving failure frequencies. The author points out that for some types of tank the IPO document is the only data source so it is likely that the values are derived from expert judgement. The IPO document values also tend to be the lowest.

13. In Chapter 5 Logtenberg makes some comments, mainly based on the sources for pressure vessels and pipelines. As a general conclusion he states that it is rather difficult to judge the reliability of the data sources. Most data were published around 1970. Since then the use of hazard studies and improved standards should lead to lower failure frequencies, but no information to support this view was found by Logtenberg.

14. In Section 5.4 on mitigating/aggravating factors he lists the 9 causes of failure (corrosion, overfill, fire, mechanical impact etc) considered by Dutch industry experts and Authorities (letter KO-037-2, 22 June 1990) where measures are needed to 'exclude' them in order to claim a failure frequency of 0.1 cpm for catastrophic failure. The corresponding failure frequencies for standard practice, and when a number of measures have not been taken are 1cpm and 1-10 cpm respectively. He notes "the approach is in fact based on expert opinion …. but the question remains whether the proposed factors plus or minus a factor of 10 can be substantiated by practical experience or a model in which the dependency of influencing factors is elaborated on a scientific basis. A more specific discussion may have to be carried out in order to accept the minimum required measures and their influence on the risk or that the failure frequencies in fact present the residual risk." He also questions whether enough information is available to synthesise a failure frequency from the basic causes of failure. In other words to quantify the fault tree in Fig 1 expert judgement would be needed eg see Appendix 2.

15. Chapter 6 presents the ‘rounded’ median values for the various systems. The Author considers the median the ‘most neutral’ when there are more than 10 values and a log-normal distribution is appropriate, as no specific information is available to explain the differences. However, in most cases the log-normal distribution is not a very good assumption. AMINAL (see below) also recommends the use of median values.

16. **Conclusions:**

    a. The median values proposed for adoption for catastrophic failure and large continuous releases are about 5 to 10 times higher than those adopted by HSE.

    b. The corresponding values in the Purple book are very optimistic when compared to the recommended median values (factors of 20 – 100 lower). It seems likely that the statement in the Purple book referring to being aware of larger failure frequencies may be due to the findings in this document.

IPO: Inter-Provisional Consultation Organisation (IPO): Manual for Drafting and Assessment of External Safety Reports (ESR)

17. Part III of this document was judged to be the most relevant to the failure frequency study. Section 3.1 lists the probabilities for loss of containment events for storage tanks. The values are similar to those in the Purple book and apply to pressurised tanks, single-wall atmospheric tanks and the inner wall of double-walled storage tanks. The values are:

• Catastrophic failure	cpm
a. instantaneous release of contents	0.5
b. continuous release of contents in 10mins	0.25
c. continuous release from largest connection	0.25
• Liquid release from 50mm hole – for each stub:	10
• Liquid release from a 10mm hole	10

18. In the purple book events b. and c. are combined and the 50mm hole scenario is dropped without explanation. No justification for the suggested values is given in the IPO document, but the explanatory text states “See also Problem discussion document KO 37-2”. This document is referred to in Section 5.4 of Logtenberg’s review (see paragraph 15 above). According to Logtenberg the values are based on expert opinion. The catastrophic failure frequency is split 50/50 between the instantaneous release and the large continuous release.

19. **Conclusion:** The failure frequencies in this document are the lowest to be found in the extensive literature survey carried out by TNO and summarised above. No transparent justification of the recommended failure frequencies was found.

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20. The data recommended by AMINAL (the Flemish Competent Authority) are based on a review of available information by DNV Technica. DNV regarded the survey data of Smith and Warwick (1981) as very relevant to most pressure vessels failures used by Western industries as the pressure vessels surveyed were selected according to appropriate criteria, including: constructed in accordance with a recognised code; not more than 40 years old; and subject to regular inspection. The following paragraphs summarise the relevant information in AM94.

The Principal Causes of Pressure Vessel Failure (after Smith and Warwick).

21. Over the period of 310,000 pressure vessel years, 229 failures were identified. 94% (216 cases) provide evidence of "*shear propagation"* with the following underlying causes:

- Fatigue	24%;
- Corrosion	14%;
- Defects present when taken into use	29%;
- Uncertain	28%;
- Other	5%.

Of the 216 cases, 161 (75%) were localised in the area of a weld. Of the total number of failures (229) 140 (61%) were noticed during an inspection (visual, non-destructive test or pressure test). Approximately 39% of failures were belatedly noticed due to:

▪ leakage	33%
▪ catastrophic failure (in operation)	6%.

64% of failures occurred in pressure vessels that were less than 10 years old. The greatest risk lies in an unobserved mechanical defect within the material that manifests itself when shearing occurs. These findings underline the importance of a good maintenance and inspection regime (including inspection during manufacture).

Statistical Analysis of the Failure Data

22. The results of the DNV analyses, based mainly on the Smith and Warwick data are given in Table A4.3. The failures are broken down into the 9 categories shown in the table. The division into 4 failure classes was based on experience with the SAFETI risk analysis tool. Professional judgement would need to be exercised in assigning particular failures to one of the classes as the information in the Smith and Warwick report did not systematically define the hole size associated with leakage. A recommended representative equivalent hole diameter is also given for each range.

23. The term *"catastrophic failure of a pressure vessel*" means: *A defect in the pressure vessel resulting in failure of the wall, a pipe or a man hole, etc, whereby the total contents of the container are released in a very short tim*e. The failure values given in Table A4.3 for catastrophic failure are based on this definition. (Note: this

definition is similar to that used by HSE, but different to the one used in the 2004 AMINAL document and in the IPO and PB99 documents.)

24. Of the 6% of cases categorised as catastrophic failure by Smith and Warwick, the analyst deemed that only 2 were representative of the QRA catastrophic failure scenario – see also Appendix 3.

Table A4.3 also shows (last row) the generic frequencies of occurrence derived for the four different failure scenarios for pressurised storage vessels, together with the 99% confidence interval. The global frequencies for the four failure categories of 150 cpm compares well with the corresponding HSE frequency of 62 – 104 cpm - see Appendix 2.

Table A4.3: Causes of pressure vessel failure in relation to hole size (Adapted from Table 1.6/3 and Table 1.6/4 of the AMINAL (1994) document)

Cause of Failure	**Number of failures detected in relation to hole size (mm)** (Representative hole diameter, mm)			
	< 25 (10 mm)	**25 – 50 (35 mm)**	**50 – 150 (100 mm)**	**Catastrophic**
Design Error	2	1	0	0
Defective Material/Construction	5	3	1	0
Abrasion	1	0	0	0
Metal Fatigue	6	3	0	0
Corrosion	1	3	0	0
Thermal Fatigue	1	0	0	0
Creep	2	0	1	0
Operational Loading	1	2	0	2
Unknown	6	4	1	0
TOTAL	**25**	**16**	**3**	**2**
Failure Frequency cpm 99% confidence interval, cpm	81 45 - 130	52 24 - 95	9.7 1.1 - 35	6.5 0.33 - 30

25. It is interesting to note that the two cases of catastrophic failure which were judged as relevant were assigned to operational loading, despite the earlier caveat about most failures being due to unobserved mechanical faults (see paragraph 22).
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Deviation from the recommended values: Risk Reduction Measures

26. AMINAL require strong and sound justification to be provided if there is any deviation from the recommended medium values, especially for values smaller than the lower confidence interval. The arguments can be based on the causes of failure listed in Table A4.3 ie.design error, defective material/construction, etc. According to AMINAL such an approach has been used in the Netherlands using 10 considerations: Corrosion; Brittleness of the material; Unwanted substances, which includes erroneous charging etc; Modification/repair work; Overfilling (can vessel rupture be ruled out?); Fatigue Failure (vibration, frequently occurring variations in loading and thermal loading); External Fire; Explosion in the vicinity; Mechanical damage due to activities in the vicinity; and External corrosion. (It is not known whether this procedure is still used).

27. **Conclusions:**

    a. The basis of the failure frequencies is similar to that used by HSE ie the Smith and Warwick, 1981 study. The catastrophic failure frequency was based on 2 failures rather than the 13 reported by Smith and Warwick; 11 failures were judged not to be consistent with an instantaneous release.

    b. The definition of catastrophic failure is the same as that used by HSE, but differs from the AMINAL 2004 interpretation.

    c. The proposed median failure frequencies for particular scenarios are generally higher (up to 10 times) than those used by HSE, but the aggregated values are broadly similar (150 cpm cf 62 – 104 cpm).

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28. The purpose of the document is to help those drafting safety reports. In the case of pressurised storage, the two ‘catastrophic failure’ scenarios are the same as in the purple book. Representative hole sizes for continuous releases are: 10, 35, 100, 130, 160, 190, and 220mm.

29. Chapter 3 deals with use of failure frequencies in QRA. It emphasises that median values should be adopted in most cases. Exceptions are:

    a. an increase of the median value when domino effects are possible or safety features are absent (presumably this means minimum compliance standards); and

    b. a reduction of the median value when additional measures (presumable above standard good practice) are in place. Credit may be given for technical and organisational measures.

30. Any deviation from the median value has to be substantiated and requires the agreement of AMINAL's safety reporting unit. Any reduction is limited by the lower limit of the 99% Poisson confidence interval, but must never be more than 10 times lower than the AMINAL median value. No restrictions apply when increasing failure frequencies.

31. Section 4.1 deals with pressure vessels. A generic failure frequency of 6.5 cpm is recommended for catastrophic failure leading to an instantaneous release – see AM94 above. This value is no longer regarded as the frequency for catastrophic failure leading a quasi-instantaneous release. Instead it is apportioned between the instantaneous release scenario and the 10 min release scenario in the ratio 1 to 20 ie about 5% of the releases are instantaneous. This reduces the catastrophic failure frequency by a factor of 20 so that it equates to the lower 99% confidence interval of the adopted medium value.

32. The document states that 'this approach is based on experience and not on statistics'. This 5%/95% split is significantly different from the 50/50 split suggested in the IPO document and the Purple book. It seems there is a difference in the professional judgements made. The AMINAL values for catastrophic failure are shown in Table A4.4 with 99% confidence interval in brackets. (Note that the failure frequency for large holes has not been taken into account.).

Table A4.4: Catastrophic failure frequencies for pressure vessels

Details	Instantaneous release, cpm	Whole contents released in 10 mins, cpm
Except <5 te LPG tanks	0.3 (0.004 – 18)	6.2 (0.44 – 29)
< 5 te LPG tanks	0.01	0.2

The figure for <5te LPG tanks is based on the data from Sooby and Tolchard (1993) and an estimate of the upper 99% confidence interval of 0.21 cpm.

33. The corresponding failure frequencies and 99% confidence interval (shown in brackets) for leaks are shown in Table A4.5:

Table A4.5: Failure frequencies for holes in pressure vessels

Details	10mm diam hole, cpm	35mm hole cpm	100 mm hole, cpm
All except <5te LPG	13 (2.7 - 41)	4.4 (0.2 - 26)	3 (0.033 - 23)
<5te LPG tanks	4	0.2	1

There is no justification given for the failure frequency for the 100mm hole being 5 times larger than that for a 35mm hole. In the author's view a 100mm diameter hole in a <5te LPG tank is essentially a catastrophic failure and would lead to an almost instantaneous loss of the entire contents (a 5te tank empties in about 100 seconds). The associated frequency of 1 cpm is 100 times greater than the figure suggested for an instantaneous release.

Conclusions:

34. AMINAL and Logtenberg (1998) support the use of median failure frequencies in QRA .

35. The 2004 edition of the AMINAL failure frequency manual attaches a very different connotation to catastrophic failure to the one defined in the 1994 document; the 1994 definition limits the term to the quasi-instantaneous release scenario. AMINAL now consider that catastrophic failure includes the quasi-instantaneous releases and scenarios that empty the vessel in 10 mins. In the author's view this is not consistent with the analysis of the Smith and Warwick (1981) data reported in Appendix 2 and in AMINAL (1994) ie the estimated failure frequencies for larger holes have been ignored.

36. The basis of the catastrophic failure frequency adopted by AMINAL (2004) is the Smith and Warwick data (see AM94 above). According to AM94 and Appendix 3 this is based on just two actual catastrophic failures which were judged to lead to a quasi-instantaneous release of the entire contents. AM94 states that hole sizes >150mm are consonant with the quasi-instantaneous release scenario; failure frequencies of holes between 50 and 150 mm – which will include the 10 min scenario - are considered separately. This contradicts the AMINAL 2004 interpretation of the data – see also Conclusions section.

37. The suggested apportionment of the generic catastrophic failure frequency between these two scenarios is appreciably different from that used in the Purple book ie 5%/95% cf 50/50. The justification for taking 5% of the catastrophic failures to be quasi-instantaneous releases is said to be based on 'experience'. Although the adopted ratios are quite different (factor of 10) for the failure frequency for the instantaneous release scenario, the actual 'recommended' base values are similar 0.3 cpm (AMINAL) and 0.5 cpm (Purple book). It seems spurious to adopt this value as a median value.

38. The 'median' value adopted by AMINAL for an instantaneous release is significantly lower than the median value recommended by Logtenberg ie factor of 33 times lower. The new median value (0.3 cpm) is less than the lower 99% confidence interval for the quasi-instantaneous release case quoted in the 1994 document (0.33 cpm). This seems very optimistic given the uncertainty in, and the basis of, the analysis.

Beerens et al (2006): The use of generic failure frequencies in QRA

39. These authors, inter alia, present the historical background underlying the failure frequencies for pressure vessels in PB99. They identify a number of difficulties, inconsistencies and unjustified assumptions in the literature or in the Dutch approach such as:

a. Comparison of the COVO study with the PB99 data is complicated because the COVO estimates included failure modes such as human error and fatigue due to vibration that are excluded in PB99.
b. A lack of precise definitions of terms (eg catastrophic failure) makes meaningful comparisons of failure frequencies difficult.
c. There is “no good basis given” for factors used to convert failure data for pressure vessels such as those surveyed by Smith and Warwick (1974) etc to estimates for pressurised storage vessels.
d. The confidence level attached to values quoted in the literature is often unclear.
e. The way that the failure frequency in PB99 for the large continuous release scenario is derived (see Sections 3.3 and 3.4 of their paper) could lead to it being underestimated.
f. The basis of generic data is not well defined or understood so that such generic values may be used outside the context for which they were originally derived.

40. The authors conclude that “the unclear links between the IPO and the COVO study, as well as between the references of the COVO study and the COVO study itself, seriously hamper the validation of failure data in the Purple Book.”

41. To obtain validated failure data they have initiated a study based on recent data and a fault-tree based model with algorithms and modification factors. This study is a follow up to that referenced in the PB99 as Ta 98. They also refer to an initiative being co-ordinated by the EU to gather information from member states and develop up-to-date failure frequencies for LUP purposes.

Conclusions

42. Of the documents reviewed here the TNO98b literature survey is judged to be the most comprehensive and thorough. It recommends the adoption of median failure frequency values for use in QRA, a view supported by the AMINAL documents.

43. The HSE catastrophic failure frequency is slightly optimistic when compared with the median value of 6.5 cpm in the AM94 document.

44. The term catastrophic failure has different connotations for HSE and PB99/AMINAL (2004); though the AMINAL1994 document used the same interpretation as HSE ie a term confined to the instantaneous release scenario. PB99, IPO and AMINAL (2004) use catastrophic failure to cover the quasi-instantaneous release and an event that results in the entire contents of the tank being discharged in 10 mins. The definition of catastrophic failure should influence the way actual failure data is analysed. For example, based on the IPO definition the failure frequency for 50-150mm holes would need adding to the instantaneous release failure frequency estimate, ie according to Table A4.3 9.7 + 6.5 cpm = 16.2 cpm. The information given in Appendix 3 suggests a higher value may be appropriate. It seems therefore that the IPO and AMINAL (2004) approaches are based on a false premise.

45. The HSE failure frequencies are optimistic when compared with the suggested median values for the instantaneous release and the 10 min release scenarios in TNO98b ie 10 and 50 cpm respectively cf 2 and 5 cpm adopted by HSE.

46. By comparison the AMINAL (2004) median values are 0.3 cpm and 6.2 cpm, but these values are artefacts of the way AMINAL apportioned the adopted generic catastrophic failure frequency of 6.5 cpm between these two scenarios ie a 5%/95% split. The corresponding split used by IPO and TNO is 50/50. Adopting the 50/50 split gives 3.3 cpm for each scenario; values similar to those used by HSE.

47. The 6.5 cpm value used in AMINAL 2004 for catastrophic failure is based on two failures which were deemed to result in holes > 150mm and according to AM94 such failures lead to a quasi-instantaneous release of the vessel's contents – see also Appendix 3. Given the limited data and that the confidence interval spans two orders of magnitude (see Table A4.3) it seems somewhat spurious and very optimistic to adopt a value which essentially coincides with the lower bound (owing to the assumed 5/95 split) and call it a median failure frequency for the quasi-instantaneous release scenario. In the author's view the AMINAL (2004) interpretation is incorrect.

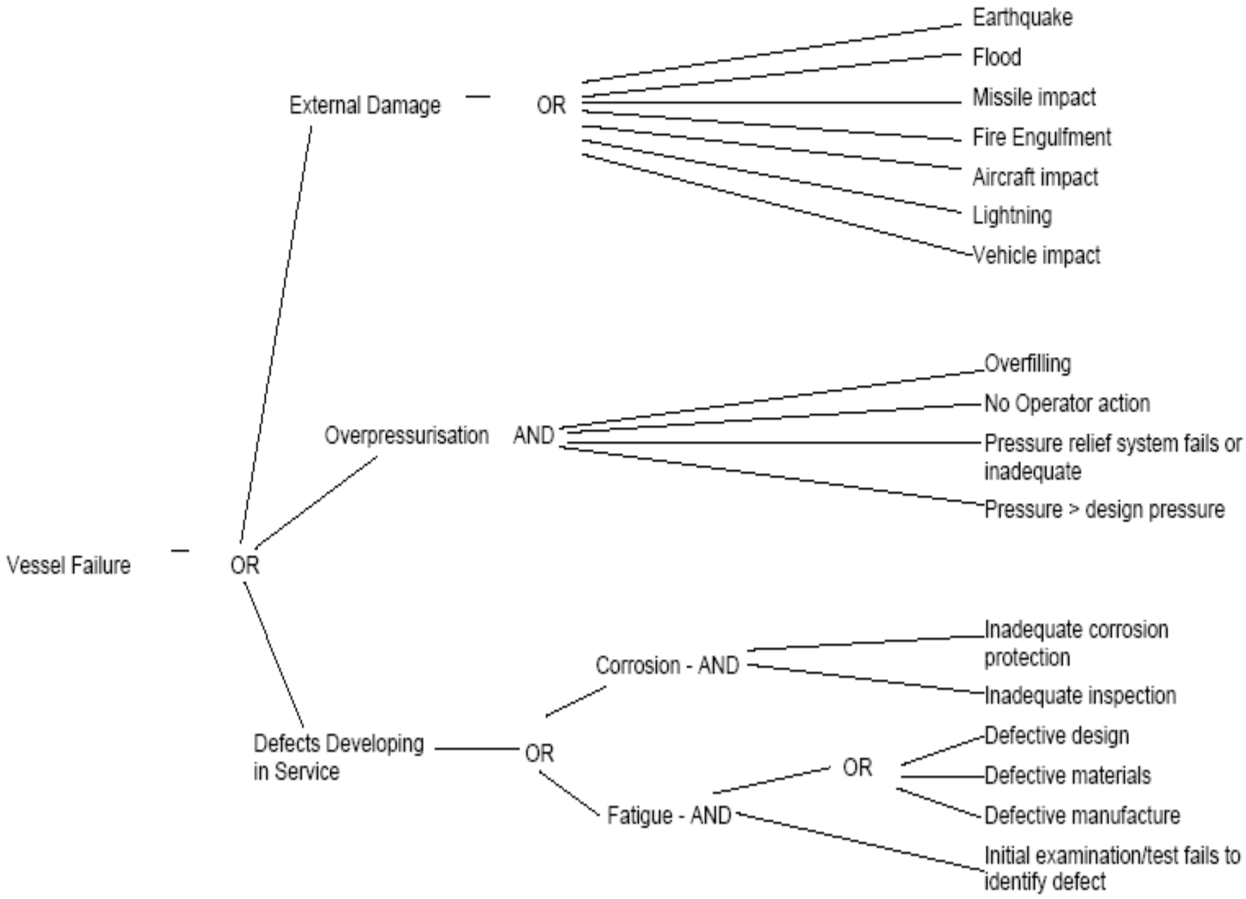
48. The TNO98b literature survey shows that there is considerable variability in the failure frequency values found in the literature – see Table A4.2. Given this uncertainty and the above arguments, the documents reviewed here do not provide convincing evidence to support the view that HSE failure frequencies are pessimistic. On the contrary the evidence suggests that the HSE values seem slightly optimistic for LUP purposes; the degree of optimism will depend on the confidence level adopted.

49. The Purple book default values, the IPO values and the AMINAL(2004) values for the catastrophic failure events are the lowest that can be found in the literature (<5te LPG tanks excepted). The findings in TNO98b and Turner (2001) provide evidence to support the view that these low values are optimistic.

50. The paper by Beerens et al shows that the basis of the PB99 failure frequencies is unclear, possibly optimistic, and in need of updating to take account of more recent data.

51. This review should be updated when the Dutch Ta98 document is released.

Figure 1. Simplified Fault Tree depicting mechanisms leading to vessel failure and a loss of containment



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