 

# ANALYSIS OF PAST INCIDENTS IN THE PROCESS INDUSTRIES

I. M. Duguid
Consultant

This article is the culmination of 15 years work on the quantitative analysis of major hazards incidents (Ref. 1 Duguid August 1998, Ref. 2 Duguid July 2001, Ref. 3 Duguid December 2005). It will only deal with items which are new. However to make use of this in a safety system to minimize future incidents it is necessary to include previous studies as well. The source article doing this is available from the author.

Table 1 is the first sheet of the 1000 item database. The format is unchanged from the earlier versions. However it is now an EXCEL database and so much easier to analyse. One point not made fully clear in the previous articles is that "Causes" are physical items such as corrosion and "Responsibilities" cover the requirement for provision of adequate safety equipment and procedures by management and for the workers to make proper use of these. There the lack of safety alarms and shutdowns which are in use elsewhere is an example. Also the total reliance on such alarms and shutdowns by operators when they are only meant as a second line of defense. Some extra codes, such as PTWF – Permit to Work Failure have been added where the new data made this appropriate.

One of the major new points in this analysis is the quantitative assessment of the Pareto effect (Table 2). For responsibilities and causes it is confirmed that the 20% of most frequent items are involved in close to 80% of the total incidents. This makes possible a very cost effective concentration of the safety effort on these items. Purists might say that all problems should be tackled equally. However until the top 20% have been dealt with this would slow progress.

Table 3 and Figure 1 including new data covering the past 10 years demonstrates the lack of progress in addressing the top 20% of problems. On a statistical basis the frequency with which these are involved in incidents has dropped little in the last 50 years. Note that the total incidents in the periods before 1970 and after 1999 contain less than half the numbers of incidents of those in each of the intervening decades. They are thus less significant statistically. There are two exceptions to this lack of progress. Firstly the major drop in frequency in HAZOP. Incidents involving a missing or inadequate HAZOP have dropped continuously from around 60 to 30% since the introduction of HAZOP's. Secondly the reduction in incidents involving poor design for safety. In view of recent interest in "Management of Change" it is disappointing that there is no indication yet of a fall in code MODI – Incidents involving modifications to plant or operations.

Safety audits for the most frequent problems have been proposed in earlier articles (Ref. 4 Duguid April 2004, Ref. 3 Duguid December 2005). However these can now be substantially reduced by limiting them to the Pareto top 20% items for causes and responsibilities and a few other important items (Table 4). The answers required are simply yes/no and in a majority of cases someone in the organization should be able to answer each

**Table 1.** Database of major hazards incidents

| Item | Decade | ACT/POT | Industry | Process | Substance | Ignition | Equipment | Responsibilities | | | Causes | | | Hazop | Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12005 | 7 | A | O | ALK | LPG | NON | VALV | OPER | PROC | PTWF | OPEN | PLUG | | S | SU |
| 12005 | 7 | A | O | ALK | HYF | EXP | VESL | INST | | | INCO | OFIL | SVAP | U | NR |
| 12006 | 7 | A | O | ALK | LPG | NON | HEEX | PROC | SAFE | | PRES | SHUT | | U | MN |
| 12006 | 7 | A | O | ALK | LPG | FLA | FURN | PROS | | | CORE | | | S | AB |
| 12008 | 7 | A | O | ALK | LPG | NON | TANK | OPER | PROC | | RUNA | | | U | AB |
| 12009 | 7 | A | O | ALK | LPG | FLA | TANK | OPER | PROC | | DRVT | | | U | SD |
| 12016 | 7 | A | O | CRD | WAT | NON | VESL | OPER | PROC | | SVAP | | | S | SU |
| 12017 | 7 | P | O | CRD | CRD | NON | HEEX | MECH | | | PLUG | | | U | NR |
| 12017 | 7 | A | O | CRD | CRD | HOT | PVRV | INST | SAFE | | DRVT | MODI | | U | AB |
| 12018 | 7 | A | O | CRD | CRD | HOT | FLAN | MECH | | | MATR | | | U | SU |
| 12019 | 7 | A | O | CRD | DIE | NON | VESL | OPER | | | SVAP | VLPS | | S | SU |
| 12019 | 7 | A | O | CRD | WAT | NON | VESL | OPER | PROC | | SVAP | VLPS | | S | SU |
| 12022 | 7 | P | O | CRD | CRD | FLA | FURN | INSC | | | EROS | MATR | | S | SU |
| 12023 | 7 | A | O | CRD | DIE | AUT | PUMP | INSM | MAIN | | SEAL | VIBR | | S | MN |
| 12023 | 7 | A | O | CRD | CRD | SPA | PUMP | MAIN | SAFE | | SEAL | VIBR | | S | MN |
| 12027 | 7 | P | O | FCC | GAS | NON | REAC | MECH | | | FATI | TSHK | | S | SU |
| 12029 | 7 | A | O | FCC | GAS | AUT | REAC | OPER | PROC | | VFLR | | | S | SD |
| 12030 | 7 | A | O | FCC | GAS | AUT | PIPE | OPER | PROC | | SUPL | | | S | AB |
| 12031 | 7 | P | O | FCC | GAS | AUT | VALV | INSM | MAIN | | EROS | | | S | NR |
| 12033 | 7 | A | O | FCC | DIE | ELE | VESL | PROC | | | VLPS | | | S | AB |
| 12035 | 7 | A | O | FCC | HVY | AUT | PIPE | OPER | | | CORI | | | S | NR |
| 12036 | 7 | P | O | FCC | GAS | AUT | VESL | MECH | | | FATI | TSHK | | S | NR |
| 12037 | 7 | P | O | FCC | OTH | NON | PIPE | OPER | PROC | | SUPL | VLPS | | S | SU |
| 12040 | 7 | A | O | FCC | GAS | HOT | FURN | SAFE | | | FLOU | | | U | SD |
| 12041 | 7 | A | O | FCC | GAS | AUT | VALV | INSM | MAIN | | FAIL | | | U | AB |

 

**Table 2.** Pareto effect analysis

A) Responsibilities
1. The total number of categories is 14
2. Of these three: OPER – Operator error, PROC – Inadequate written procedures, and SAFE – Inadequate design for safety were involved in 823 or 82% of the incidents
3. Three out of fourteen is 25% of the categories

B) Causes
1. The total number of categories is 45
2. Of these nine: RUNA – Runaway reaction, TEMP – Above design temperature MODI – Plant or operation modified, VFLR – Flammable vapours in enclosed space, DRVT – Uncontrolled flow through drain or vent, MATR – Material of construction unsuitable, SAIN – Safety instrument fails, CORI – Corrosion internal, and OPEN – Equipment under pressure opened up, were involved in 833 or 83% of the incidents
3. Nine out of 45 is 20% of the categories

C) Other

Other items which were involved in a high percentage of incidents include:
1. HAZOP U – Unsatisfactory or absent hazard and operability study – 38%
2. STB – Storage and Blending – 24%
3. MODE – Plant not in normal operation – 45%

D) Conclusion
1. The figures confirm the Pareto effect which says that the 20% of problems which occur most often are responsible for 80% of the incidents

**Table 3.** Variation of frequency of problems over time

| | Percentage of incidents with this problem | | | | |
|---|---|---|---|---|---|
| Problem | 1940–1969 | 1970–1979 | 1980–1989 | 1990–1999 | 2000–2005 |
| Responsibilities | | | | | |
| Operator error | 31 | 23 | 23 | 27 | 27 |
| Written procedures inadequate | 31 | 34 | 38 | 34 | 44 |
| Design for safety inadequate | 49 | 30 | 37 | 30 | 22 |
| Causes | | | | | |
| Runaway reaction | 25 | 8 | 18 | 23 | 25 |
| Above design temperatures | 10 | 13 | 9 | 12 | 5 |
| Modification to plant or operations | 4 | 13 | 8 | 9 | 11 |
| Flammable vapours in enclosed space | 5 | 7 | 9 | 10 | 17 |

(*Continued*)

 

**Table 3.** Continued

| Problem | Percentage of incidents with this problem | | | | |
|---|---|---|---|---|---|
| | 1940–1969 | 1970–1979 | 1980–1989 | 1990–1999 | 2000–2005 |
| Uncontrolled flow through drain or event | 11 | 9 | 6 | 6 | 7 |
| Material of construction unsuitable | 6 | 7 | 6 | 9 | 8 |
| Safety instrument failure | 10 | 8 | 8 | 7 | 5 |
| Corrosion (internal) | 3 | 8 | 9 | 7 | 9 |
| Equipment under pressure opened up | 1 | 2 | 9 | 9 | 13 |
| Other | | | | | |
| Storage and blending | 26 | 28 | 20 | 23 | 24 |
| HAZOP unsatisfactory or absent | 60 | 40 | 37 | 33 | 27 |
| Incidents not during normal operation | 37 | 50 | 47 | 42 | 47 |

Note: The number of incidents in the first and last columns are less than half those for the intervening decades. In the case of 1940–1969 this was due to the paucity of incidents for which adequate information was available to permit inclusion. After 1999 only five years data was available at the time the database was finalised. This makes the figures in these columns less significant statistically than the rest.

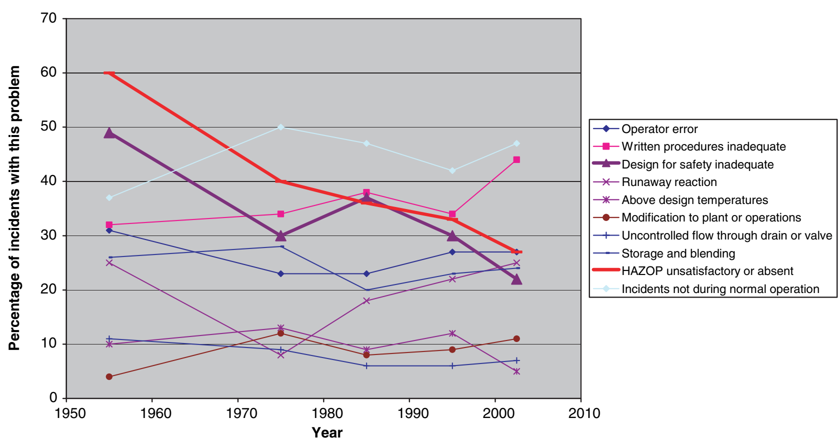


**Figure 1.**

one without further investigation. Thus the percent of "yes" replies is a simple metric for progress in major hazards safety. Where there are multiple frequent problems related to a particular question, these are listed in Table 4. This will help ensure that the answers cover the main problems. This information could be of use in deciding on Key Performance Indicators for major hazards.

New information has been used to revise the cost/benefit analysis (Table 5) previously given in Ref. 5 Duguid March 2006. This analysis covers the nine petroleum refineries in the UK over a period of 18 years. That should be long enough to provide a significant average figure. The benefits now include a figure for the fifth major incident in the period. It had been suggested that for some companies who are less far down the road of implementing safety measures than others, the previous figure for the cost of correcting problems found by the first audit was too low. This has therefore been increased. Overall the cost/benefit ratio is now 1:2.2. Thus in the long term there is a good payout on the cost of the new safety measures. In addition this figure should be quite conservative because:

1) Data on loss of profits due to long plant shutdowns for repair were not always available.
2) It was assumed that only one of the five incidents could have been prevented by the proposed safety measures. Surely we can do better than that.

The substantial increase in the number of total and particularly chemical industry incidents in the database has made a quantitative analysis of the differences between the chemical and petroleum industries practical. Most of the common problems are the same for the two industries. Significant differences are as follows:

1) On HAZOP's the involvement of unsatisfactory or absent ones in major incidents dropped from 40% to 15% in the petroleum industry since the 1970's. In the chemical industry the corresponding figures are 45% to 43%. This indicates how effective HAZOP can be and how much catching up the chemical industry has to do.
2) In the petroleum industry a full third of the major incidents occurred in storage, that is tank farms. This indicates too much concentration of safety effort on process units compared with ancillaries, which is a mistake. Table 6 details the more frequent problems. It should be noted that all incidents occurring at petroleum distribution terminals are included in these figures. It was not always possible to determine whether or not they were located at refineries. They do form a significant proportion of the total. The much smaller use of storage tanks in the chemical industry means that this is less of a problem there. Only a sixth of the incidents there are involved. However it is replaced by incidents in warehouse storage.
3) In the chemical industry major incidents involving runaway reactions actually rose from 32% in the 1940's to 1980's to 47% after 1990. Clearly this industry needs to concentrate a substantial part of their safety efforts on tackling that problem. This is underlined by the fact that of 90 incidents involving unstable chemicals 73 resulted from runaway reactions occurring. For obvious reasons this is not a sserious problem in petroleum refining. Details of the frequent problems involved are given in Table 6.

 

**Table 4.** Proposed annual audit covering pareto top 20% problems

| No | Code | Questions | Reply yes/no |
|---|---|---|---|
| | | Responsibilities | |
| 1 | OPER | Are Operators trained on top 20% items which involve them (Table 6) | |
| 2 | OPER | Does Operator training include start up, shutdown and likely abnormal operations | |
| 3 | OPER | Do Operators attend a presentation such as "Remember Charlie" stressing their vulnerability in an incident | |
| 4 | PROC | Are operating procedure manuals standardized or audited to ensure consistent quality | |
| 5 | PROC (MODE) | Do these manuals cover shutdown and start up and likely abnormal operations fully. One off cases require temporary instructions | |
| 6 | PROC (MODE) | Do these manuals warn Operators not to go outside written operating procedures without advising supervision | |
| 7 | PROC | Are these procedures designed to eliminate split responsibility | |
| 8 | SAFE (HAZOP) | Are design safety features fully up to best industry standards (Table 6) | |
| | | Causes | |
| 1 | RUNA (HAZOP) | Have all possibilities for runaway reactions to occur been checked and action taken where a problem was found (Table 6) | |
| 2 | TEMP (HAZOP) | Have all causes of above design temperatures been checked and action taken where problems were found (Table 6) | |
| 3 | MODI (HAZOP) | Are all substantial modifications and/or changes to operations covered by a HAZOP | |
| 4 | MODI | Are all minor modifications to plant and/or changes to operations covered by a safety check | |
| 5 | VFLR | Are the vapour spaces of all cone roof and internal floating roof tanks checked for flammable vapours regularly | |
| 6 | VFLR | Are the vapour spaces of tanks and vessels being cleared of sludge and/or scale during maintenance monitored continuously for flammable vapours | |
| 7 | DRVT | Do all operating drains and vents discharge to safe locations. (Including relief valve discharges) | |
| 8 | DRVT | Are all drains and vents not required for normal operation plugged off | |
| 9 | DRVT | Do operating drains with an open discharge which could release hydrocarbons/chemicals have two valves one of which is spring closed. | |
| | | Where under automatic interface level control do they have an independent low interface level shutdown | |
| 10 | MATR | Is there a system for spot checking that the right materials are installed, particularly during maintenance | |

| | | |
|---|---|---|
| 11 | SAIN | Is all safety instrumentation, including relief valves, checked for correct operation at least on each planned shutdown |
| 12 | SAIN (MODI) | If any safety instrumentation has been taken out of service has it been reinstated or replaced by a more reliable system performing the same function |
| 13 | SAIN | When any safety equipment, including relief valves, fails is every effort made to determine the cause of the failure and eliminate it. |
| 14 | CORI | Is corrosion monitoring concentrated on the most likely places for to it to occur (Table 6) |
| 15 | CORI | Where high corrosion rates are found, is the use of more corrosion resistant material evaluated |
| 16 | OPEN | Is there a system in place where an operator must demonstrate physically to the maintenance crew that the equipment is fully depressured and drained directly before they work on it |
| 17 | OPEN | At the same time does he make it clear exactly what items they can work on |
| | | Other |
| 1 | STB | Have likely problems in tank farms been fully investigated and action taken where required. (This includes carrying out a HAZOP.) (Table 6) |
| 2 | HAZOP | Have HAZOPs been carried out on all parts of the site including utilities and other ancillaries |
| 3 | HAZOP | Have HAZOPs been updated when any substantial changes have been made to plant or operations |
| 4 | – | Has the five yearly audit been carried out as scheduled. (Ref. 4) |
| 5 | – | Have the actions recommended in previous safety audits and HAZOPs been completed or where not have reasons for not doing so been documented |

| | |
|---|---|
| Total Yes Answers | a |
| Total Questions | 30 |
| Safety audit score % | $\frac{a \times 100}{30}$ |

Notes

1. Where questions call for a check on all possible problems, details of the most frequent ones are given in Table 6. Each such question concerned is tagged Table 6 here.
2. See Table 2 for the meaning of the codes given here
3. As my old boss used to say “To make as if” is worse than useless. The safety audits and the HAZOPs must be carried out thoroughly by experienced personnel. At least one in each team should have studied the source article so that they are aware of the more frequent problems and actions required.
4. The reply to each question should be initialed by the auditor who made it. He is responsible if it proves to be wrong.

**Table 5.** Cost/benefit analysis on proposed safety measures

A) Basis

1. This analysis is based on the record of the nine petroleum refineries in the UK over a period of 18 years
2. It covers the five very major incidents in this period
3. The costs for these incidents come mainly from Ref. 7. The benefits are the reduction in these costs by preventing only one of the five incidents by use of the proposed safety measures.
4. It is known that not all the figures available for these incidents included loss of profits due to the long plant shutdowns for repairs
5. The costs for the proposed safety measures are estimates based on experience. They allow for the fact that a substantial portion of the safety measures required, such as HAZOPs will already be in place.

B) Benefits

| | |
|---|---|
| | $US |
| 1. Costs for all five incidents | 600,000,000 |
| 2. Average cost per incident | 120,000,000 |
| Benefit | 120,000,000 |

C) Costs

| | |
|---|---|
| 1. These include the cost of the audit itself and the cost of correcting any deficiencies found | |
| 2. Initial five year safety audit per refinery (See Ref. 4) | 2,000,000 |
| 3. Subsequent two five year safety audits per refinery | 1,000,000 |
| 4. Annual safety audit per refinery | 200,000 |
| 5. Total for 15 annual audits per refinery | 3,000,000 |
| 6. Total cost of audits per refinery | 6,000,000 |
| 7. Total cost of audits for nine refineries | 54,000,000 |

D) Cost Benefit

1. From the above figures the benefits are more than twice the costs in the long term
2. These figures are felt to be very conservative. It would be a sad comment on the thoroughness of the audits and consequential improvements of safety measures if at least two of the incidents could not have been prevented. This would raise the benefits to costs ratio from 2.2:1 to 4.4:1. This still does not take into account the missing loss of profits due to long plant shutdowns.
3. For the Chemical Industry the figures could be poorer due to the larger numbers of smaller plants. However, it is difficult to believe that they would fail to break even.

 

**Table 6.** Most frequent problems relating to Table 6 questions

Question – Operator Training

1) Are they made aware that over half all incidents occur during shutdown, startup, maintenance, and abnormal operations
2) Are they made aware of the risks of runaway reaction due to changes in operation such as charging an incorrect reactant, changing the order or rate of charging, temporary shutdowns, or loss of cooling
3) Are they made aware that they should not depart from written operating procedures without advising supervision. In emergency situations this may have to be after the event.
4) Are they aware of the need to only use alarms/shutdowns as a backup, rather than relying on them completely
5) Are they made aware of the need to physically check that equipment is depressured and drained in the presence of the maintenance crew directly before work on it starts. Also that the crew know exactly what they may work on
6) Are they made aware of the dangers that their operations can cause in tank farms. See Code STB (Table 6) & Storage tankage below.

Question – Design for safety inadequate

70 % of the design errors here would have been picked up by an adequate HAZOP. The most frequent specific problems are:

1) Alarms to detect high temperatures at critical locations or loss of cooling, particularly where runaway reactions are possible. Also lack of skin thermocouples to detect high temperatures in fired heater tubes.
2) High level Alarms/Shutdowns totally independent of the normal level control system to minimize the risk of overflow from tanks or vessels.
3) Spring closed valves to remind operators to remain in attendance while draining water bottoms from equipment containing flammables or toxics to an open drain. Also installing a totally independent low interface level shutdown system where such drainage is under automatic control.
4) Over reliance on check valves to prevent reverse flow.
5) Inadequate attention to design for safety when implementing modifications to plant or operation.

Question – Runaway reaction

1) Use of an incorrect reactant.
2) Sending a chemical to the wrong storage tank.
3) Temperatures not measured where maximums are likely.
4) Loss of cooling or mixing.
5) Feeding reactants at the wrong rate, ratio, or order.
6) Inadequate checking that safety instrumentation is reliable.
7) Inadequate precautions to prevent carryover or reverse flow mixing incompatible chemicals (e.g. $H_2SO_4$ and NaOH).
8) Inadequate testing to confirm whether runaway reaction is possible.

(*Continued*)

**Table 6.** Continued

| |
|---|
| Question – Above design temperature |
| 1) Inadequate design for safety, including lack of effective alarms/trips and temperatures not measured where maximums are likely. |
| 2) Inadequate procedures for handling likely abnormal situations. |
| 3) See Runaway Reaction above |
| Question – Corrosion Internal |
| 1) Monitor downstream of chemical and water injection points. |
| 2) Monitor where initial condensation of water occurs from mixed process streams |
| 3) Monitor low points, dead ends, and drop legs in piping. |
| 4) Monitor bends and other maximum velocity points, particularly where solids are present. |
| Question – Storage tankage |
| 1) See Code VFLR (Table 4) |
| 2) Have the risks of sending high temperature streams to tankage been addressed, particularly where water bottoms are present. |
| 3) See also Codes MODI, OFIL, RUNA, and DRVT (Table 4). |

It must be emphasized that this presentation only deals with major hazards incidents. Lost time accidents (LTA) require a different approach. Recent reports on the Longford gas recovery plant, Texas City refinery, and Buncefield storage terminal incidents have highlighted the fact that concentration on achieving a good LTA performance is not a good measure of protection against major hazards incidents. It should be added that the causes involved in these three incidents were all highlighted in the earlier articles on analysis of past incidents. This further reinforces the case for carrying out the safety audits proposed here. Finally Oscar Wilde has a pithy saying for most occasions. The following one encapsulates what this article is about. "To lose one parent, Mr Worthing, could be regarded as a misfortune, to lose two seems like carelessness".

## REFERENCES


1) Duguid I.M., 1998, Analysis of past incidents in the oil, petrochemical, and chemical industries, *Loss Prevention Bulletin*, Issues 142 pages 3–6, 143 pages 3–7, and 144 pages 26–30.
2) Duguid I.M., 2001, Preventing plant mishaps, *Chemical Engineering,* July 2001 issue, pages 80–84.
3) Duguid I.M., 2005, A framework for the use of key performance indicators of major hazards in petroleum refining, *IP Research report,* December 2005.
4) Duguid I.M., 2004, Proposal for a process plant safety audit, *Loss Prevention Bulletin,* Issue 176 pages 13–16.
5) Duguid I.M., 2006, Lessons from the past, *Petroleum Review,* March 2006 Issue pages 36–38 & 42.

 

6) European Commission Major Accidents Bureau, 2006, MARS Database of major hazards incidents, *http://mahbserv.jrc.it/mars/default.html*, Version dated January 2006
7) Marsh's Risk Consulting Practice, 2003, The 100 largest losses 1972 to 2001. *MAHB 20th edition. Also 11th and 16th editions.*
8) American Petroleum Institute, 1979, Safety digest of lessons learned, *API Publication 758.* Sections 2 to 9.
9) Institute of Chemical Engineers, *Loss Prevention Bulletin, Issues* 80 to 176.
10) Lees F., 1983, Loss prevention in the process industries, *Butterworth & Co Ltd,* Appendix 3.
11) Kletz T., 1999, What went wrong, *Gulf Professional Publishing,* 4th Edition.