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Analysis of equipment failures as contributors to chemical process accidents

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ABSTRACT

A database study of chemical process accident cases was carried out. The objective of the study is was to identify the reasons for equipment based accidents. The most frequent accident causing equipment were piping (25%), reactors and storage tanks (both 14%) and process vessels (10% of equipment accidents). The six most accident-prone equipment is process related involve nearly 80% of accidents.

78% of equipment accident contributors are technically oriented including design and human/technical interface faults. Purely human and organizational reasons are the most common accident contributors for storage tanks (33%), piping (18%) and heat transfer equipment (16% of causes). For other equipment the technical accident causes are most common.

The accident contributors were divided to main and sub-contributors. On average process equipment failures have 2.2 contributors. The contributors, which frequent and act often as main contributors, should be focused. These risky contributors were identified for several equipment types. Also a deeper analysis of the accident causes and their interconnections was made. Based on the analysis a checklist of main risk factors was created for hazard identification on different types of equipment.

Keyword: Accident database study; Process equipment failures; Accident contributors; Hazard identification; Main risk factors

1. Introduction

It is been mentioned by Kletz (1993) that accidents occur and recur in the chemical process industry (CPI) because of poor dissemination and utilization of accident information for preventing accidents. Improvement of experience feedback system can be done by consistently analyzing accident data, publishing lessons learnt and implementing the lessons in practice. These efforts will maintain safety awareness and enable continuous improvement of process safety in plant design and operation.

Many of accident analyses in the CPI are to identify the root cause of accidents and draw lessons learnt from it (Gunasekera and de Alwis, 2008; Konstandinidou et al., 2006; Nivolianitou et al., 2006). Accident causes are often classified as technical and human and organizational causes. The division between these is not clear, since many technical causes involve human related aspects such as design, installation and service errors or faults in the operator–technical interface. The latter is not an error in technical sense but causes operators to make errors in operation. It is also typical that both technical and human and organizational causes contribute to accidents at the same time. Typically there are also more than one causes to an accident. Earlier studies have found as on average 2.3 causes on an accident, the range being 2.0–2.7 causes (Nivolianitou et al., 2006; Sales et al., 2007).

The focus of this paper is the analysis of process equipment failures. Reviews of the previous studies on the equipment related accident contributors suggests that most frequently accidents causing equipment are reactors, storage tanks, pressure vessels, boilers, and piping as discussed later (Duguid, 2001; Instone, 1989; Marsh Inc., 1987; Vílchez et al., 1995). These studies only consider process equipment failures as a sub-topic in the accident cause analysis and provide limited

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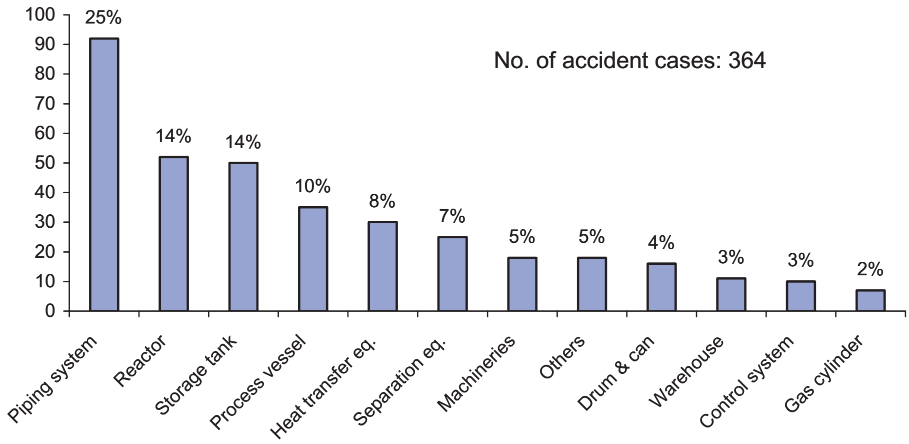

Fig. 1 – Proportions of accidents caused by specific equipment.

discussion on the specific types of failure. Also only a limited discussion on the causes of specific process equipment failures has been given in the articles on CPI accidents and the lessons learned (Gunasekera and de Alwis, 2008; He et al., 2011; Hou and Zhang, 2009; Prem et al., 2010). A more detailed study on the specific process equipment failures still lacking. Therefore, the aim of this work is to make a more in-depth analysis on the specific process equipment related accident contributors for the better understanding of their background and interconnection.

2. Research approach

The research was conducted by studying 549 accident cases gathered from the Japanese Failure Knowledge Database (FKD, 2011). About 66% (364 out of 549) of the cases are CPI related. The objective of the study is to identify the reasons for the process equipment failures and draw conclusions for their reduction. First, the types of equipment failures are identified based on the 364 accident cases. Then, a detailed analysis on the six most common process equipment failure, represented by 284 cases, is done to understand their causes of failures. The most common accident causes are identified and their interactions are analyzed. The accident causes are ranked based on their frequency and recommendations for safer design and operation of process equipment are suggested.

A database study as a research approach has also challenges. Recently, Kletz (2009) mentioned about the weaknesses of the accident reports. He finds the majority of the accident reports incomplete or poorly written due to inadequate investigation and competency. Some of them were pointless or inaccurately reported due to wrong interpretation of the evidence (Kletz, 2003). To minimize this issue, the Failure Knowledge Database was selected. The database covers the significant accidents all over the world and is managed by experienced academia. The accident reports are carefully reviewed by a committee and they contain detailed information on the accident often including process flow diagram, plant layout and fault tree analysis.

3. Types of equipment failure

The 364 equipments related accidents cases in chemical industry were analyzed to identify their root cause of failure. In case of a domino effect, the first failed equipment that triggered the unwanted incident is counted as the cause of failure. Fig. 1 presents the distribution of the 12 equipment that most frequently involves in accidents. The equipment is treated here as a system, which includes also its closest auxiliary systems. In Fig. 1 ‘piping’ means cases, in which the accident cause was the piping system connection between process units, not any piece of equipment. The ‘others’ category includes various less common accident causing equipment such as flare stack, incinerator, tank truck, etc. For a more detailed discussion of the equipment categories see Section 4.

As seen from Fig. 1 the majority of the process accidents in this study were caused by the piping system failures (25%). These resulted to material releases, which initiated unwanted events such as fires, explosions or pollution. The reactor and storage tank failures come in the second place (14% each) followed by process vessel (10%), heat transfer equipment; i.e. exchangers and fired heaters (8%) and separation equipment failures (7%). The causes of specific equipment failures are discussed later in Section 4.

Table 1 compares the results of this paper with the earlier analyses of equipment involved in accidents. Because the equipment classifications in the papers are different, their data was rearranged to correspond. The average of the values was calculated and presented in the rightmost column in Table 1. In general, the results of this paper correspond quite well with the average of previous studies, even the ranking is not exactly the same. Piping is the most frequent accident cause in both (24% in average; 25% in this paper). The second in the average are the storage tanks (13% in average; 14% in this study). The third place in average share reactors and heat transfer equipment (both 10% in average, in this paper 14 and 8%, respectively). The fourth are the pressure vessels (9% in average, 10% in this study).

The differences of values in Table 1 are partly due to the different scope and focus of the analyses. Marsh Inc. (1987) and Instone (1989) analyzed only hydrocarbon industry accidents. Nearly all of the accidents were fires and explosions. Marsh Inc. (1987) focused only on very large accidents; i.e. 100th largest damages based on the impact. Vílchez et al. (1995) discussed process plant and storage plant accidents separately, which lead to a low share of storage tank accidents in the process plant category. They also had a large share of undefined equipment (33%), making the percentages of other categories lower. Some of the papers did not analyze separation equipment as an individual category at all. Instone (1989) had a large amount of heat exchanger and fired heater accidents possibly

Table 1 – The most commonly accident causing equipment.

Type of process equipment	Percent of accidents, %					
	This paper	Duguid (2001)	Vílchez et al. (1995)	Instone (1989)	Marsh Inc. (1987)	Average
Piping system	25	33	16	14	33	24
Reactors	14	9	14	5	10	10
Storage tanks	14	20	2	14	17	13
Pressure vessels	10	9	18	3	5	9
Heat transfer equipment	8	11	6	19	4	10
Separation equipment	7	–	–	5	3	5
Other equipment + unknown	22	18	44	40	28	30

because their scope in hydrocarbon industry. This gave a large share of fired heater and boiler related accidents (15%). The average in CPI for fired heater accidents is about 4% (Duguid, 2001; Vílchez et al., 1995). The remaining share (4%) of heat exchanger caused accidents in Instone's (1989) data however corresponds to the CPI average.

The accident data discussed in this paper is based on all the areas of chemical process industry, so the analysis should be valid for general conclusions on the accident causing frequency of different equipment categories.

4. The contributors to equipment accidents

The accidents are normally caused by several contributors. In the 284 cases studied on the six most commonly process equipment involve in accident, 623 causes to the accidents were found. 15 different types of accident contributors were discovered. Table 2 presented the proportions of the contributors on the six types of equipment. A more detailed analysis of the accident contributors is presented in Appendix 1.

As seen from Table 2, in overall, human and organizational causes is the largest category (20%). The main share, however (78%) are technically oriented causes including design and operator interface errors. External causes such as earthquake, bad weather, lighting, etc. cover 2%. The accidents have typically 2.2 contributors. Piping has the largest number of contributors per accident (2.5), the same as heat transfer equipment.

On average human and organizational causes are the largest contributor category in most equipment types. It is the largest contributor in storage tank, piping and heat transfer equipment accidents. Other important contributors are; process contamination (12%), which is the most frequent contributor to process vessel and separator accidents; heat transfer (12%) most common for reactor accidents; flow-related contributors (11%) present in all types of equipment; and reaction oriented contributors (9%), which are typical to reactor accidents.

4.1. *Piping system accidents*

The piping system is the most common but also risk prone part of the chemical process and needs special consideration during design and operations. As seen from Table 2, the typical accident contributors of the piping are related to human and organization aspects (18%), fabrication/construction/installation (13%), layout (11%), flow (10%), corrosion (9%), and construction material (8%) related causes. In fact there are 6–8 large contributors to piping accidents. Of these, layout, fabrication/construction/installation and corrosion come up as more frequent than average accident contributors. Piping accidents have also more contributors (2.5) per accident than other equipment on average (2.2). The distribution of causes to each accident contributor is presented in Appendix 1.

Table 2 – Number and proportion of contributors in equipment related accidents.

Accident contributor	Piping system	Storage tank	Reactor	Heat transfer Eq.	Process vessel	Separation Eq.	Total
Human/organizational (a)	**41 (18%)**	**36 (33%)**	12 (16%)	12 (16%)	12 (17%)	9 (15%)	122 (20%)
Contamination[a] (b)	17 (7%)	6 (5%)	**12 (16%)**	**11 (15%)**	**14 (19%)**	**15 (25%)**	75 (12%)
Heat transfer[a] (c)	17 (7%)	**10 (9%)**	**17 (23%)**	**11 (15%)**	8 (11%)	**9 (15%)**	72 (12%)
Flow related[a] (d)	**23 (10%)**	**15 (14%)**	6 (8%)	**9 (12%)**	**10 (14%)**	**8 (13%)**	71 (11%)
Reaction[a] (e)	10 (4%)	3 (3%)	**17 (23%)**	2 (3%)	**12 (17%)**	**9 (15%)**	53 (9%)
Layout[a] (f)	**25 (11%)**	6 (5%)	1 (1%)	4 (5%)	5 (7%)	3 (5%)	44 (7%)
Fab. const. and inst.[a] (g)	**30 (13%)**	5 (5%)	2 (3%)	5 (7%)	1 (1%)		43 (7%)
Corrosion[a] (h)	**22 (9%)**	4 (4%)	3 (4%)	8 (11%)	1 (1%)		38 (6%)
Construction material[a] (i)	**19 (8%)**	4 (4%)	3 (4%)	8 (11%)	2 (3%)	1 (2%)	37 (6%)
Static electricity[a] (j)	2 (1%)	6 (6%)	2 (2%)	3 (4%)	5 (7%)	3 (5%)	21 (3%)
Mechanical failure[a] (k)	8 (3%)	4 (4%)			2 (3%)	1 (2%)	15 (2%)
External factor (l)	4 (2%)	**9 (8%)**					13 (2%)
Vibration[a] (m)	8 (3%)			1 (1%)			9 (1%)
Erosion[a] (n)	6 (3%)						6 (1%)
Utility related[a] (o)	2 (1%)					23 (%)	4 (1%)
Total contributors	234 (37%)	108 (17%)	75 (12%)	74 (12%)	72 (12%)	60 (10%)	623
Contributors per accident	2.5	2.2	1.4	2.5	2.1	2.4	2.2

[a] Classified as technical contributors.

Human and organizational aspects are the most common (18%) accident causes piping accidents. These contributors are operational issues, since technically oriented human aspects such as faults in design and in operator–technical interface were classified as technical errors in this study. Most of the human and organizational causes are organizational (63%) and due to lack of planning and supervision of piping operations, such as poor contractor control (18%), poor hazardous work permit system (12%) and poor management system (10% of organizational failures) as shown in Appendix 1. Meanwhile, no double/physical check of pipe lineup on site, misjudgment and not following procedures is usual contributor under the human failure (37%) subcategory.

The layout problem of piping system is related to incorrect physical arrangement (52%) and shape (48%). Faulty design details are wrong positioning, sharing pipes, dead-end, elbows/sharp bends, U-shape, belt-shaped and short size reduction. Inappropriate construction materials due to chemical (47%) and mechanical (26%) specifications also contribute to piping failures. In Appendix 1, combination of several types of accident contributors (e.g. technical, design and operational faults) seem to be significant contributors to piping failures due to poor fabrication/construction/installation, flow related and corrosion. Their common failure mechanism is combination of material deposition and blockage, aggressive material accumulation, unwanted reactions, corrosion and erosion problems.

Piping failures due to problems in operator–technical interface are also significant. As seen on Appendix 1, this issue appears in layout and flow related contributors. Human–technical interface caused accidents commonly occur in complex system (Kletz, 1995). Piping systems in the CPI are often complicated and difficult to manage, thus increasing the changes of human errors. Earlier research (Kidam et al., 2010) shows that the best way of preventing piping accidents is designing simpler piping systems. Simplification was a relevant corrective action in 55% of piping accidents, when it was in general applicable only to 15% of accidents as corrective action. Simplification can be done by removing dead-ends and pockets, unnecessary valves, drains and by-pass lines and using welded fittings. Simpler and user friendlier piping system reduces the likelihood of accidents through lower failure rate of the system (because of less components) and better operability (i.e. less errors). Also Wolf (2001) found that the accident rates are directly proportional to the degree of complexity of the facility.

4.2. *Reactor accidents*

The causes of reactor failures include the reaction vessel, agitator, heating and cooling system in the reactor (e.g. jacketed heater and coil cooling system) is investigated. Failures of external heater, boiler, condenser and piping system are not included here but in heat transfer equipment and piping system categories. Analysis shows that the reactors cause 14% of accidents (Fig. 1) and majority of them (71%) are related to batch/semi-batch reactors operations. The higher number of failures in batch reactors is expected due to the dynamic character of batch reactions, variable products, partly manual operations, the reactive materials handled and difficulties in design caused by the previous aspects.

Reactor accidents are related to inadequate process analysis on heat transfer (23%), reaction problems (23%) and process contamination (16%), which all are much above the average in the accident statistic in Table 2. Majority of them has known root causes and could be prevented through better design (e.g. thermal safety and proper cooling capacity, agitator system design) and proper operations (e.g. adequate mixing, proper feeding).

The most critical aspect of reactor design is the thermal safety. It is related to the quantity of heat generated by the reaction and the safe limit of total energy that can be allowed in the reactor from the inherent safety point of view. Thermal safety analysis produces design information that becomes the basis of process conditions and physical reactor design. Hence, any inadequate or misleading thermal data during process development creates a major impact to the reactor design and safe operations. Many accidents occur due to plant modifications that did not consider the earlier basis of design. This is the issue of management of change.

Organizational faults (16% of contributors) caused operation related accidents. Typical accident causes were lack of analysis in reaction monitoring (27%), lack of procedures (19%) and poor safety culture (12% of the human and organizational faults). Contamination contributed 16% of reactor accidents. Main problems were the in-flow of material, because of pressure difference and insufficient draining, etc. of the equipment.

The analysis found out that the reactor failures could be avoided by better design and operation. The keyword is proper analysis on the reaction kinetics; thermal stability and reactivity/incompatibility of substance at operational conditions.

4.3. *Storage tank accidents*

Storage tanks cause third highest number of accidents (14%; see Fig. 1). This category includes all types of tanks, such as in-process, intermediate, product, off spec and waste handling tanks and containers. However, it does not cover pails, drums, cylinders, and portable containers.

Statistically, human and organizational causes (33% of contributors) are clearly the most common causes of storage tank failures in Appendix 1. This cause is dominated by organizational failures (69% of human and organizational contributors) such as poor planning and lack of analysis e.g. in chemical transfer and tank cleaning or maintenance. Misjudgment of hazard and not following procedure are usual human errors in the storage tank operations. Compared to other equipment, storage tanks are relatively simple in design, easy to handle and involve routine tasks. Since the tank farms are not often the core business of a company, this may appear as low interest on maintenance, low staff motivation and poor safety culture. Proper working procedures (e.g. work permitting), hazard communication program (training or briefing) and contractor control are essential.

Other accident contributors are flow related (14%), heat transfer (9%) and external factors (8% of contributors). Significant contribution of human–technical interface to storage tank failures is identified especially in flow related (33%) and heat transfer (20%) category. Matters to be considered during design are the clarity of control display, equipment positioning (e.g. visibility and accessibility) and complex or difficult work procedures. Sloshing phenomena due to earthquakes causes almost all accidents in external factors.

4.4. *Process vessel accidents*

Process vessels cause 10% of accidents in the CPI (Fig. 1). Process vessel category includes process related tanks as an opposite to storage tanks. Typical to process vessels are their complex interactions with other equipment through piping. Therefore contamination is the most common (19%) accident contributor. Most common reason is the flow-in (43%) because of failure in operator–technical interface. The contamination may result also from accumulation (22%) or process residues (14%); see Appendix 1.

Unwanted chemical reaction in the vessel is the second largest accident contributor (17%). Most of them are caused by unwanted reactions (75%), which are mainly due to chemical contamination (38%). On other hand, the initiation of the process contamination and reaction problems may be caused by the flow related (14%) causes. Equally large accident contributor (17%) are the human and organizational causes. 83% of them being organizational failures mostly due to lack of procedure or system for double/physical check (32%).

To minimize the operational risks of process vessels, simpler and dedicated processing is suggested with adequate design for safety and adequate operator–technical interface and proper operating procedures to minimize operator errors. The chemical flows should use separate pipeline and have positive isolation measures based on the results of chemical reactivity and incompatibility analysis.

4.5. *Heat transfer equipment accidents*

This category includes in addition to normal heat exchangers also air coolers, hot oil systems, refrigeration and cryogenic systems, cooling towers and furnaces. As shown in Fig. 1, about 8% of accidents in the CPI are related to heat transfer equipment failures. Most common accident contributors are human and organizational (16%), process contamination (15%) and heat transfer (15%) related causes (Table 2).

Most of human and organizational causes are due to organizational errors (80%). They are caused most commonly by lack of inspection and testing (25%), no procedures or lack of check (19%) and poor maintenance (19%); Appendix 1.

For process contamination the main contributing factor is flow in (46%) due to wall failure. The second is presence of process residue (18%). Another large technical contributor is heat transfer (15%). Here the main problem is hot spot (46%) because of structure, layout and positioning (33%) of internal parts of heat exchangers causing uneven flow.

Material selection is important, since corrosion (11%) and construction material (11%) caused accidents are much above average (6%) in heat transfer equipment.

4.6. *Separation equipment accidents*

Distillation column, evaporator, crystallizer, filter, centrifuge, concentrator are among equipment classified under separation equipment. About 7% of accidents in the CPI were found to be due to separation equipment failures and 80% of them are related to the distillation operations. Many of accidents have been related to batch distillation in the data used. Common accident contributors are process contamination (25%), heat transfer (15%), human and organizational (15%), reaction (15%), and flow related (13%) aspects.

Contamination (2.1 times) and chemical reactions (1.7 times more common than average) are very pronounced in separation equipment accidents. Inadequate detection and analysis of contaminants is the key contributing factor in these separation equipment failures. Even though the concentration is low at the beginning, the unwanted chemicals may concentrate too much at the bottom of the column and decompose at a high temperature. Early detection of hazardous chemicals and adequate removal of residues is necessary to keep the concentration of hazardous compounds low enough.

High number of accidents is reported in the waste/solvent recovery plants. Waste handling is difficult due to their properties (e.g. viscous, fouling, solids containing, etc.), their varied composition and sometimes limited or wrong information given by the waste producer on the composition. Typical contaminants are waste oil, sticky process residue in feed or in distillation generated contaminant. Almost all of the solvent recovery used batch distillation in vacuum. The accidents were often related to high temperature and pressure (condenser being fouled or blocked) or distilling into too high contaminant concentrations or even dry. Appendix 1 gives more details of the results.

4.7. *The contributors to be focused*

It is obvious that focus should be given to the most common accident contributors as presented in Table 2 (highlighted as bold) and Appendix 1. However, the less frequent accident contributors with high impact are also important. These resemble the 'black swan' events, which are defined as rare, hard to predict events with high impact, to which we are blind before the accident has taken place (Taleb, 2010). In the CPI, recent 'black swan' events such as Deepwater Horizon rig explosion in the Gulf of Mexico and earthquake and tsunami in Japan that shocked the nuclear industry, triggered the needs for proper safety analysis on rare event (Murphy, 2011). In similar contact, Hendershot (2011) explained that sometimes unexpected hazards must be identified and managed using the best tools available. He added, the best ways to control the risk by eliminate the hazard whenever it is feasible; i.e. implement inherent safety.

Considering this factor (rare or unexpected hazard/event) the analysis on which contributors are more frequent than average in the accidents of particular equipment are carried out. Based on data in Table 2, the ratio to average value was calculated for each accident contributors (e.g. friction of equipment-based contributor divided with the friction of overall contributors). The results are presented in Table 3. For example, erosion is relatively 2.7 times (e.g. {6/234}/{6/623}) more frequent accident cause in piping accidents than on average in equipment accidents in general. On the other hand it should be bear in mind that some of the contributors have a low absolute frequency (rare or unexpected event/hazard). For example erosion is an accident cause only in 3% of piping accidents (Tables 2 and 3).

Special safety consideration should be given to rare and unexpected accident contributors for effective accident prevention efforts. As seen from Table 3, among rare and unexpected accident contributors are erosion and vibration (piping system); external factor and static electricity (storage tank); unwanted chemical reaction (reactor); static electricity, unwanted chemical reaction and process contamination (process vessel); and utility setup, unwanted chemical reaction and process contamination (separation equipment). Ideally, the contributors with high relative frequency should be

Table 3 – More frequent than average accident contributors for the certain equipment types.

Equipment types	Accident contributors	Ratio to average value	Frequency as contributor, %
Piping system	Erosion	2.7	3
	Vibration	2.4	3
	Fabrication/constr./inst.	1.9	13
	Corrosion	1.5	9
	Layout	1.5	11
Storage tank	External factor	4.0	8
	Human and organizational	1.7	33
	Static electricity	1.7	6
	Mechanical failure	1.5	4
Reactor	Reaction oriented	2.7	23
	Heat transfer	2.0	23
Heat transfer equipment	Construction material	1.8	11
	Corrosion	1.8	11
Process vessel	Static electricity	2.1	7
	Reaction oriented	2.0	17
	Contamination	1.6	19
Separation equipment	Utility	5.0	3
	Contamination	2.1	25
	Reaction oriented	1.8	15

focused in design and operation of the specific equipment, especially if the absolute frequency is also high.

5. Accident main contributors

The accident data was further analyzed to evaluate the potential of each accident contributor to initiate an equipment accident. First, the main and sub-contributors for each accident case were identified. Main contributor of accident is the contributor that initiates or triggers the accident (i.e. it is the main cause of accident). Other accident contributors are sub-contributors. Thus, the potential of accident contributor as main contributor called "share as main contributor" (SMC) can be calculated. The SMC indicates, how often the contributor acts as a main contributor compared to its overall presence as a contributor. The share is calculated by dividing the frequency as the main contributor by the total frequency as a contributor. The results are summarized in Table 4. Those accident contributors that act most frequently as main contributors should be focused, especially if they have a large SMC. They have a higher potential to cause an accident as such. In Table 4 these values are highlighted as bold.

The most frequent main contributors in equipment accidents are human and organizational issues (16%), contamination (14%), flow related aspects (13%), heat transfer (12%) and layout (11%). These top five accident contributors correspond 2/3 of all main contributors (Table 4).

In Table 4 the accident contributors that had large SMC are poor layout (70%) and fabrication/construction/installation (63%). This can be compared to the average SMC value of all contributors (46%). It can be noticed that human and organizational contributors have a low SMC (38%) but the occurrence frequency is the largest. This means that human and organizational contributors are frequent but they are not often the main causes of accidents (38%). Reaction related contributors have also a relatively low SMC (43%). From types of equipment aspect, reactor has the highest average SMC (69%). Therefore only single contributor was enough to cause an accident for reactors in 56% of cases on average, when there are on average 2.2 contributors for all types of equipment. This means that reactors as equipment are quite sensitive to reaction, heat transfer, contamination and flow related accident contributors. Only one fault in these can cause an accident without presence of other contributors.

Highest SMC are found with construction material and fabrication/construction/installation faults in storage tanks (both 100%; yet they have a low frequency), reaction related causes in reactors (94%) and contamination faults in process vessels (93%). The latter two have also a high frequency and should therefore be focused in design and operation. The largest single reason for reaction oriented accidents in reactors is the unfinished reaction e.g. because of power failure. Process vessel contamination is caused most often by in flow of wrong material by operator–technical interface related error (e.g. confusion between valves due to poor positioning and orientation). See Appendix 1.

Fig. 2 presents the SMC vs. the frequency of occurrence of accident contributors for different equipment. The figures are divided into four quadrants by average values of frequency and SMC in that equipment (Table 4). The four-quadrant analysis aims to point out the risky contributors for each equipment type. The risky contributors are those, which tend to be frequent and in addition have a high SMC (i.e. they tend to be relatively often the primary causes of accidents). Obviously the contributors located in the quadrant with high frequency and high SMC are the most risky and should be focused.

As shown in Fig. 2, different equipment types have different critical accident contributors: For *piping system* accidents the most critical accident contributors are the layout (f), fabrication/construction/installation (g) and construction material (i). Unwanted reactions (e) are the dominating contributor the *reactor* failures. For *storage tank*, it is important to deal with the flow-related (d) problems that cause e.g. unintended chemicals mixed but also human and organizational errors because of very high frequency. For *pressure vessel* and *separator* failures contamination (b) is the most risky contributor while corrosion (h) is an important cause of *heat transfer equipment* failures. Human and organizational errors are very common but not so.

Fig. 3 shows the average SMC and accident contributor frequency for the selected equipment types. The reactor has very

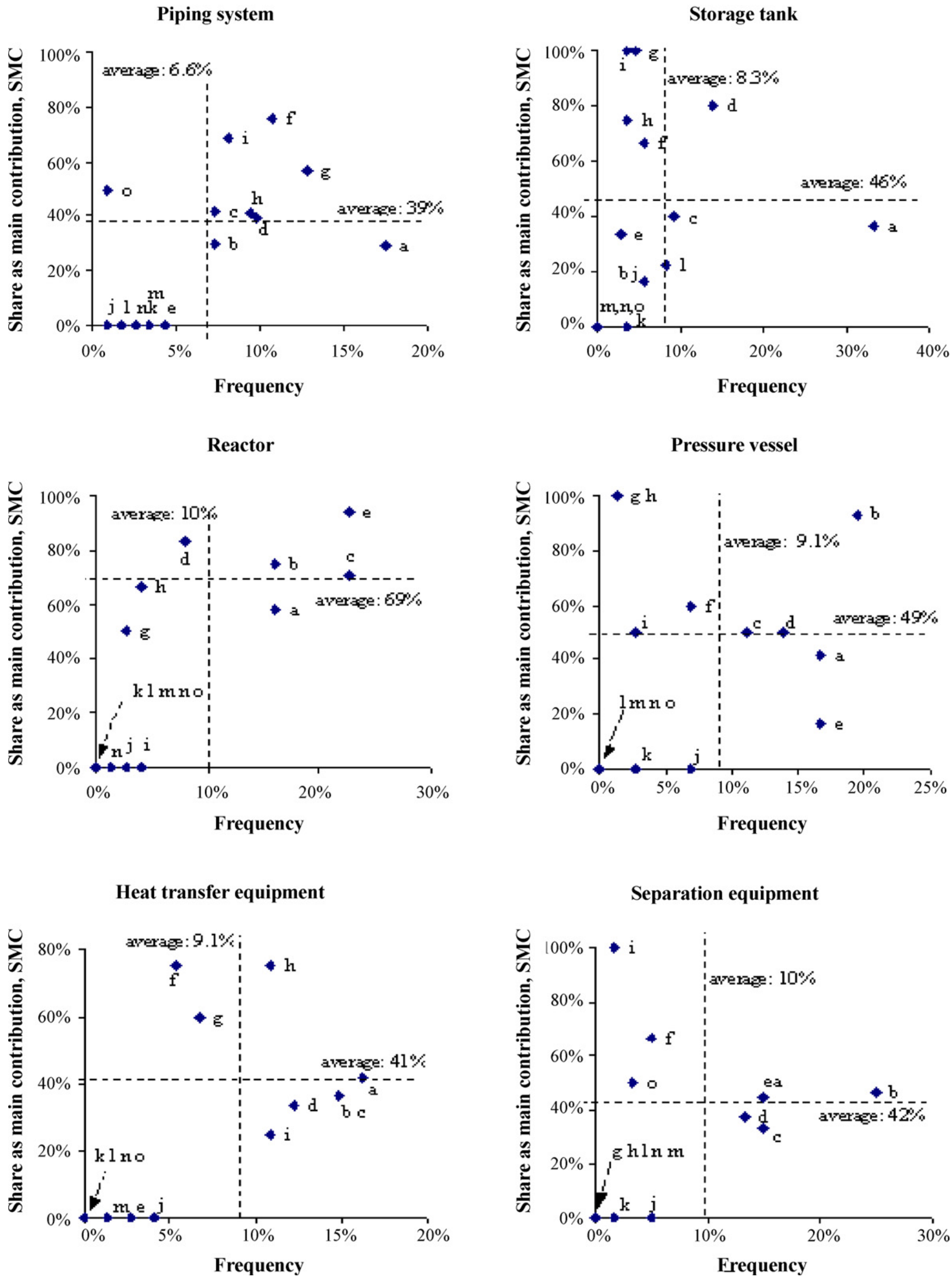

Fig. 2 – SMC vs. contributor frequency four quadrant presentations of the accident contributors for different equipment types (for notation see Table 2).

high SMC, meaning a single contributor has a potential of causing an accident without sub-contributors. Therefore reactor clearly can be considered the most risky equipment type. Storage tank have a balance average value for SMC and frequency that positioning its close to the most risky quadrants, however the risk could be reduces by implementing effective safety management system. Piping has a very high accident frequency (Fig. 1) but low SMC (Table 2) meaning a large number of contributors.

A cluster is formed by process vessel, separation and heat transfer equipment (i.e. they have a relatively similar SMC and contributor frequencies). There are similarities in some of the accidents contributors such as contamination, flow related, heat transfer, human/organizational and layout (see Table 4 and Appendix 1). The study shows that, in general, the reactor is the riskiest types of process equipment in the CPI, heat transfer equipment is the safest, while piping system is most accident – prone component of chemical processing facilities.

Table 4 – Accident main contributors.

Accident contributors	Piping system		Storage tank		Reactor		Heat transfer eq.		Process vessel		Separation eq.		Overall	
	MC	SMC, %	MC	SMC, %	MC	SMC, %	MC	SMC, %	MC	SMC, %	MC	SMC, %	MC	SMC, %
Layout (f)	**19**	**76**	4	67			3	**75**	3	60	2	**67**	**31**	**70**
Fab. const and installation (g)	**17**	57	5	**100**	1	50	3	60	1	100			27	**63**
Construction material (i)	**13**	**68**	4	**100**			2	25	1	50	1	100	21	57
Corrosion (h)	9	41	3	75	2	67	**6**	**75**	1	100			21	55
Flow related (d)	9	39	**12**	**80**	5	**83**	3	33	5	50	3	38	**37**	52
Contamination (b)	5	29	1	17	9	**75**	4	36	**13**	**93**	**7**	47	**39**	52
Utilities related (o)	1	50									1	50	2	50
Heat transfer (c)	7	41	4	40	**12**	**71**	4	36	4	50	3	33	**34**	47
Reaction (e)			1	33	**16**	**94**			2	17	4	44	23	43
Human and organizational (a)	**12**	29	**13**	36	7	7	5	42	5	40	4	44	**46**	38
External factor (l)			2	22									2	15
Static electricity (j)			1	17									1	5
Erosion (n)													0	
Mechanical failure (k)													0	
Vibration (m)													0	
Total/SMC average	92	39	50	46	52	69	30	41	35	49	25	42	284	46

Notation: MC – count as main contributor; SMC – share as main contributor in percentage.

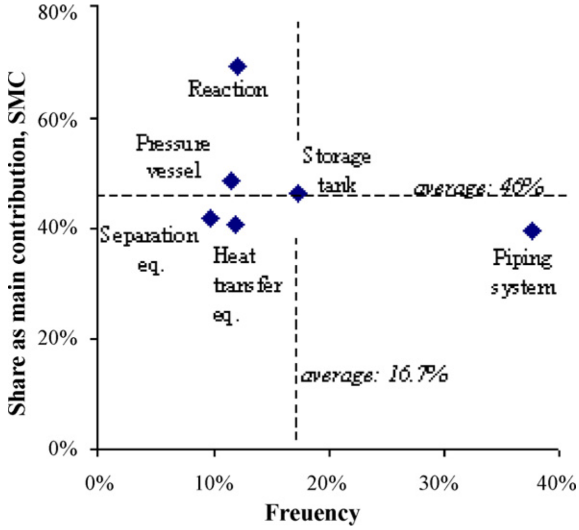

Fig. 3 – The average share as main contributor and contributor frequency for the equipment.

6. Interconnection of accident contributors

The interconnection study between the accident main and sub-contributors has been carried out for the accident cases. The occurrence of main contributing factors and sub-contributors of each accident case was studied and their interaction identified. The results are presented in Table 5. The accident main contributors are shown on left and the sub-contributors on the top. The numbers showed the frequency of interconnections. A high number of combinations represent a strong connection between the accidents contributors.

In *piping* systems, the design related accident contributors such as poor layout and inappropriate fabrication/construction/installation and the construction material are known as main contributors of system failures. Poor layout is connected to human and organizational, contamination and flow-related events that lead to unwanted reaction, loss of containment, fires and explosions. The flow-related faults have also a strong connection with human and organizational sub-contributor. In fact human and organizational is the largest sub-contributor to piping accidents. Appendix 1 shows that both layout and flow have also a large share on operator–technical interface faults. Many of piping system failures due to technical faults could potentially be avoided by implementing a better safety management system on site. Layout has also a connection to flow and contamination related sub-contributors. Some material and mechanical engineering contributors have also strong interconnections: The fabrication/construction/installation main contributor is connected to mechanical and vibration sub-contributors. Construction material is connected to corrosion resulting to spillage and leakages.

In *reactor* accidents strong connection exists between reaction and heat transfer as sub-contributor. This is obvious because the chemical reaction potential is function of temperature and some unintended chemical reaction generates huge amount of energy that increase significantly the surrounding temperature.

In *storage tank* accidents flow-related causes are strongly connected to human and organizational faults. Construction material is connected to static electricity, and

Table 5 – Number of interconnections between main and sub-contributors to accidents for certain equipment types.

Process equipment	Sub-contributors / Main contributors	Main contributors (cases)	Human/organizational (a)	Contamination (b)	Heat transfer (c)	Flow related (d)	Reaction (e)	Layout (f)	Fab. const. & inst. (g)	Corrosion (h)	Construction material (i)	Mechanical failure (j)	Static electricity (k)	External factor (l)	Vibration (m)	Erosion (n)	Utility related (o)
Piping system	Human/organizational (a)	12		3	3	2	2	3	1	1		1				1	
	Contamination (b)	5	3		1		2			2	1	1					
	Heat transfer (c)	7	3						4		1		2				
	Flow related (d)	9	**6**	2			2	1		1						1	1
	Layout (f)	19	**8**	**7**	2	**5**	3		1	2					1	1	
	Fab. const. & inst. (g)	17	4		4	1		1			2	**5**			**6**		
	Corrosion (h)	9	2			2		1	2		2			4		2	
	Construction material (i)	13	3			3	1		4	**7**		1			1	1	
	Utility related (o)	1				1			1								
	Sub contributor total	**92**	**29**	**12**	**10**	**14**	**10**	**6**	**13**	**13**	**6**	**8**	**2**	**4**	**8**	**6**	**1**
	No main contributors for reaction, mechanical failure, static electricity, external factor, vibration, and erosion.																
Reactor	Human/organizational (a)	7		1				1	1								
	Contamination (b)	9	1				1						2				
	Heat transfer (c)	12	2							1	1						
	Flow related (d)	5		1							1						
	Reaction (e)	16	2		**5**												
	Fab. const. & inst. (g)	1				1											
	Corrosion (h)	2		1							1						
	Sub contributor total	**52**	**5**	**3**	**5**	**1**	**1**	**1**	**1**	**1**	**3**	**0**	**2**	**0**	**0**	**0**	**0**
	No main contributors for layout, const. material, mech. failure, static elec., external factor, vibration, erosion, and utility related.																
Storage tank	Human/organizational (a)	13		1	3	2		1					2	1			
	Contamination (b)	1	1				1										
	Heat transfer (c)	4	3			1											
	Flow related (d)	12	**10**	2										1			
	Reaction (e)	1	1		1												
	Layout (f)	4	3	1													
	Fab. const. & inst. (g)	5	2							1		2		3			
	Corrosion (h)	3		1								2		1			
	Construction material (i)	4	3		1		1						3	1			
	Static electricity (j)	1			1			1									
	External factor (l)	2															
	Sub contributor total	**50**	**23**	**5**	**6**	**3**	**2**	**2**	**0**	**1**	**0**	**4**	**5**	**7**	**0**	**0**	**0**
	No main contributors for mechanical failure, vibration, erosion, and utility related.																
Pressure vessel	Human/organizational (a)	5				2							1				
	Contamination (b)	13	3		1	2	**5**	2				1	2				
	Heat transfer (c)	4					**4**										
	Flow related (d)	5	2		1						1		2				
	Reaction (e)	2	1			1											
	Layout (f)	3	1		1		1										
	Fab. const. & inst. (g)	1			1												
	Corrosion (h)	1								1		1					
	Construction material (i)	1		1													
	Sub contributor total	**35**	**7**	**1**	**4**	**5**	**10**	**2**	**0**	**1**	**1**	**2**	**5**	**0**	**0**	**0**	**0**
	No main contributors for mechanical failure, static electricity, external factor, vibration, erosion, and utility related.																
Heat transfer equipment	Human/organizational (a)	5		1	1	**3**		1					2				
	Contamination (b)	4	2		2								1				
	Heat transfer (c)	4	1	1		1	1		1								
	Flow related (d)	3			2					1	1						
	Reaction (e)																
	Layout (f)	3	1	1							2						
	Fab. const. & inst. (g)	3			2					1							
	Corrosion (h)	6	2	**3**		1			1		**3**				1		
	Construction material (i)	2	1	1		1	1										
	Sub contributor total	**30**	**7**	**7**	**7**	**6**	**2**	**1**	**2**	**2**	**6**	**0**	**3**	**0**	**1**	**0**	**0**
	No main contributors for reaction, mechanical failure, static electricity, external factor, vibration, erosion, and utility related.																
Separation equipment	Human/organizational (a)	4		1		2							1				1
	Contamination (b)	7	**3**		1	1	2										
	Heat transfer (c)	3		2		1	2										
	Flow related (d)	3	1	2								1					
	Reaction (e)	4		1	**3**			1					1				
	Layout (f)	2	1	1	1	1											
	Construction material (i)	1											1				
	Utility related (o)	1		1			1										
	Sub contributor total	**25**	**5**	**8**	**5**	**5**	**5**	**1**	**0**	**0**	**0**	**1**	**3**	**0**	**0**	**0**	**1**
	No main contributors for fab/const/inst, corrosion, mechanical failure, static electricity, external factor, vibration, and erosion.																
GRAND TOTAL		**284**	**76**	**36**	**37**	**34**	**30**	**13**	**16**	**18**	**16**	**15**	**20**	**11**	**9**	**6**	**2**

fabrication/construction/installation with external factors. According to Appendix 1, the main issues of storage tank failures are design related faults, especially inappropriate construction material selection, sub-standard design realization and human–technical interface that makes the operation error-prone. On the other hand the organizational failures are frequent.

Pressure vessel failures show that the process contamination and heat transfer have a strong connection with unwanted chemical reactions. The reactivity and incompatibility issues of chemicals handled must be studied in detail. The number of pipe connections should be limited. *Heat transfer equipment* accidents have several main contributors. The biggest are corrosion which is related to construction material faults and contamination. Human and organizational causes have a strong interconnection with flow related sub-contributors.

The *separation systems* are quite robust, as shown by a relatively low accident number. Especially in the multipurpose and waste recycling separations unsuitable feedstock is the main cause of separator failures. Therefore the contamination has a strong interconnection organizational to failures. The resulting reactions have a connection to heat transfer through fouling, blocking which result to insufficient heat transfer. Implementing a good safety management system could improve this situation.

7. Discussion and conclusion

A study of equipment based process accident has been carried out. The study reveals that about 78% of equipment failures in the CPI are technically oriented including design and human/technical interface errors. Most frequent equipment involves in accidents is piping 25%, because of large number and complexity. The second are reactors 14% because of their general risky nature. The results of proportions of accident causing equipment are in good agreement with earlier average data. The study showed that single variables are capable of causing reactor accidents in over 50% of cases, while in piping systems there are typically 2.5 accident contributors.

The accident data was further analyzed for accident contributors. 15 common accident contributors were detected, 13 of which are technical categories. The study shows that on average human and organizational accident causes are the largest category (20%), contamination as second (12%), followed by heat transfer (12%), flow (11%), reaction (9%) and layout (7%) oriented contributors.

Further study reveled which accident contributors are most typical for each equipment type: human and organizational reasons are most common accident contributors for storage tanks, piping and heat transfer equipment. For reactors the common contributors are heat transfer and reaction related problems and for process vessels the contamination. The contributors were also analyzed in detail for each equipment type. The result has been shown as the Appendix 1.

In main contributor analysis the main cause of accident was analyzed. The most frequent main contributors in equipment accidents are human and organizational issues (16%), contamination (14%), flow related aspects (13%), heat transfer (12%) and layout (11%). These six correspond 2/3 of all main contributors. It can be seen that the share of human and organizational main contributors is less than in the sub-contributors list. Also there are few reaction related main contributors.

The accident data was further analyzed to estimate the risk from each accident contributor to cause an equipment accident. For this purpose the SMC of contributors was studies. The SMC of accident contributor tells how often it acts as a main contributor compared to its overall presence as a contributor. Those accident contributors that act most frequently as main contributors should be focused, especially if they have a high SMC. The largest SMC are poor layout (70%) and fabrication/construction/installation (63%), where the average SMC of all contributors is 46%. It can be noticed that the human and organizational contributors have a low SMC (38%) but the occurrence frequency is the highest.

Also the SMC's of accident contributors for each equipment type were analyzed and presented vs. contributor frequency in a four-quadrant analysis figure, which aims to point out the risky contributors for each equipment type. The risky contributors are those, which tend to be frequent and in addition have a high SMC. For *piping system* accidents the most critical accident contributors are the layout, fabrication/construction/installation and construction material. Unwanted reactions are the dominating the *reactor* failures. For *storage tank*, the main issue is the *flow-related* problems and also human and organizational errors, because of very high frequency. For *pressure vessel* and *separator* failures contamination is the most risky contributor responsible while corrosion is an important cause of *heat transfer equipment* failures.

In general reactor can be considered relatively the most risky equipment, it has relatively few accident contributors but they SMC are high. This means that a single contributor is capable of causing an accident alone. As an opposite piping has a low SMC meaning there are typically several contributors to an accident. On the other hand there are a high number of piping failures.

An interconnection study between the accident main and sub-contributors was done to analyze which main and sub-contributors go together. For certain pairs large interdependency was found. For example in storage tank accidents flow related main contributor goes 83% together with human and organizational sub-contributor.

The interconnection of accident contributors provides an early sign of process accidents especially for the low SMC of equipment (i.e. the other than reactors, which often have only one accident contributor). The combined effects of contributors at the same time worsen the equipment condition and shorten the equipment life that directly increases the risk of equipment caused accidents.

Results also points out that the contribution of technical aspects to accidents is very significant. Most technical contributors are directly related to design and some to installation. In this study the design errors and faults in operator–technical interface were included to technical categories. Only the operation related human and organizational causes and external reasons were out of technical categories. The share of non-technical is 22% of all contributors and 17% of main contributors. Hence, accident prevention through design changes is a very effective way to eliminate risks.

Table 6 summarizes the main points of the findings to be used for the accident prevention in process plant design and operation. The table presents the ranking of most frequent accident contributors for each equipment type. The relatively much more frequent than average contributors are presented by X, XX and XXX signs. The contributors with highest SMC

Table 6 – Checklist for equipment safety enhancement; most important main and all contributors, relative contributor importance and SMC compared to all equipment average.

Equipment/contributors	Main	All	Relative	SMC	Most common reasons
Piping system					
Human and organizational		1			Contractor management, no procedure, no physical/double check
Layout	1		X	S	Operator–technical interface, accumulation in U shape and dead-end
Fab/const/inst	2	2	X		Poor installation, structure, support, welding and finishing work
Construction material	3		X		Wrong chemical/mechanical spec and material miss-match
Corrosion			X		Contamination, flow pattern, material aging
Vibration			XX		Inadequate support, flow movement, pumping operation
Erosion			XX		Thickness spec, 2-phase and turbulence flow, particles, etc.
Storage tank					
Human and organizational	1	1	X		Poor planning/analysis/check, misjudgment, not follow procedure
Flow related	2		X	S	Operator–technical interface, blockage, overflow
Fab/const/inst				SS	Insufficient foundation work, poor installation – stress concentrated
Corrosion				S	More corrosive feedstock, management of change
Construction material				SS	Non-conductive components/parts especially 'buy-item'
Static electricity			XX		Non-conductive components/parts of sampling thief
Mechanical failure			X		Stress-concentrated-creaking, low-cycle fatique, poor welding
External reason			XXX		Sloshing phenomena due to earthquake, lightning, and heavy rain
Reactor					
Reaction	1	1	XXX	SS	Unfinished reaction, no mixing, power fail, operator–technical interface
Heat transfer	2	1	X		Incorrect capacity; reduced flow, no or poor mixing, power failure
Flow related				S	Imbalance reactant ration, blockage, reserve flow and poor valve setting
Contamination	3			S	Flow in by pressure difference, process residues, impurity accumulation
Heat transfer equipment					
Corrosion	1		XX	S	Contamination, unsuitable const. material, stress concentrated cracking
Human and organizational	2	1			Lack of inspection; organizing, lack of maintenance
Contamination	3	2			Flow in from wall failure, incompatible heat transfer medium
Heat transfer	3	2			Hot spot, high heating/cooling rate, low flowrate
Flow related		3			Uneven flow due to fouling, coking, clogging or wrong valve setting
Construction material			X		Inappropriate physical, mechanical and chemical spec. and miss-match
Layout				S	Internal flow restriction, shape error and dead-end
Process vessel					
Contamination	1	1	XX	SS	Flow in; operator–technical interface, pressure difference
Human and organizational		2			Organization; no procedure, no double/physical check
Reaction		2	X		Reaction due to contamination, unfinished reaction/hold too long
Static electricity			XX		Non-conductor material, moving object, spray/mist condition
Separation equipment					
Contamination	1	1	XX		Waste oil, sticky residue, flow-in, operator–technical interface
Reaction	2	2	X		Unwanted reaction; contamination, residue accumulation, high temp
Human and organizational		2			Organization; no procedure, check, MOC
Heat transfer		2			Hot spot due to dry condition, no or reduce flow
Utility			XXX		Power failure, no or inadequate nitrogen blanket

Notation: number = contributor ranking; relative importance, X = 150–199%, XX = 200–300%, XXX = ≥300%; share as main contributor (SMC) S = 75–89%, SS = 90–100%.

are shown with S and SS. Typical reasons for accidents are summarized also. A more detailed analysis of accident contributors is presented in Appendix 1, which can be used as a further checklist in enhancing process safety.

In conclusion, the study provides a better understanding of failure mechanism of selected process equipment accident contributors. In the paper several critical points to be focused in design and operation of different equipment has been pointed out. The presentation of accident contributor details in Table 6 and Appendix 1 is a checklist for findings out the most important accident contributors and their background for each equipment type. These tools are suitable for enhancing the safety in plant design and in safety audits at an existing plant.

Appendix 1. Details of contributors to equipment accidents

(A) **Piping system accidents**

1.0 **Human & organizational**, 41 out of 234 (18%)
- 1.1 Organizational failure, 26 out of 41 cases (63%)
  - 1.1.1 Contractor management, 18%
  - 1.1.2 Work permitting, 12%
  - 1.1.3 Poor management system, 10%
  - 1.1.4 No procedure-problem reporting, 8%
  - 1.1.5 Lack of inspection, 8%
  - 1.1.6 Poor communication, 8%
  - 1.1.7 Poor planning, 8%
  - 1.1.8 Lack of maintenance, 6%
  - 1.1.9 Lack of supervision, 6%
  - 1.1.10 Poor safety culture, 6%
  - 1.1.11 Improper used of equipment, 4%
  - 1.1.12 Management of change, 4%
  - 1.1.13 Misjudgment, 2%
- 1.2 Human failure, (37%)
  - 1.2.1 No procedure-double/physical check, 25%
  - 1.2.2 Misjudgment, 14%
  - 1.2.3 Not follow procedure, 14%
  - 1.2.4 Poor training, 11%
  - 1.2.5 Poor/wrong instruction, 11%
  - 1.2.6 Carelessness, 7%
  - 1.2.7 Work permitting, 7%
  - 1.2.8 Improper use of equipment, 4%
  - 1.2.9 Knowledge based/ignorance, 4%
  - 1.2.10 Poor management system, 4%

2.0 **Fab., const. and installation**, 30 out of 234 (13%)
- 2.1 Poor installation (31%)
  - 2.1.1 Poor installation- bad setting, 41%
  - 2.1.2 Part miss-match, 18%
  - 2.1.3 Bolts tightening-loose, 12%
  - 2.1.4 No painting, 12%
  - 2.1.5 Part-reused/temporary, 12%
  - 2.1.6 Human–technical related, 6%
- 2.2 Bolts tightening, (22%)
  - 2.2.1 Bolts tightening-loose, 38%
  - 2.2.2 Unbalance bolting, 38%
  - 2.2.3 Bolt broken/damage, 15%
  - 2.2.4 Positioning, 8%
- 2.3 Structural/layout/positioning, (19%)
  - 2.3.1 Shape, 36%
  - 2.3.2 Stress concentrated, 18%
  - 2.3.3 Bolts tightening-loose, 9%
  - 2.3.4 Buried piping, 9%
  - 2.3.5 Part miss-match, 9%
  - 2.3.6 Positioning, 9%
  - 2.3.7 Human–technical related, 9%
- 2.4 Support, (19%)
  - 2.4.1 Attachment mechanism, 30%
  - 2.4.2 Stress concentrated, 30%
  - 2.4.3 Positioning, 20%
  - 2.4.4 Part miss-match, 20%
  - 2.4.5 Part-reused/temporary, 20%
- 2.5 Work method, (6%)
  - 2.5.1 No double/physical check, 50%
  - 2.5.2 Insulation-flammable, 50%
- 2.6 Welding, (3%)
  - 2.6.1 Poor heat treatment, 100%

3.0 **Layout**, 25 out of 234 (11%)
- 3.1 Physical arrangement, 13 out of 25 (52%)
  - 3.1.1 Human–technical related, 31%
  - 3.1.2 Positioning, 23%
  - 3.1.3 Share line, 23%
  - 3.1.4 Flow restricted, 8%
  - 3.1.5 U shape-accumulate, 8%
  - 3.1.6 Positive isolation, 8%
- 3.2 Shape, (48%)
  - 3.2.1 U shape-accumulate, 33%
  - 3.2.2 Dead-end, 27%

4.0 **Flow related**, 23 out of 234 (10%)
- 4.1 Human–technical related, 7 out of 23 (30%)
  - 4.1.1 Equipment/instrument setting, 43%
  - 4.1.2 Emergency setting, 29%
  - 4.1.3 By-pass, 14%
  - 4.1.4 Trap/closed condition, 14%
- 4.2 Fluid movement, (26%)
  - 4.2.1 Capacity/sizing, 31%
  - 4.2.2 Speed/rate/velocity, 31%
  - 4.2.3 Shape, 15%
  - 4.2.4 Turbulent, 15%

3.2.3 Flow restricted, 13%
3.2.4 90° elbow, 7%
3.2.5 Belt-shaped, 7%
3.2.6 Sizing (reduce sharply), 7%
3.2.7 Vertical piping, 7%

4.2.5 Symmetrical vortex, 8%
4.3 Valve leaking, (26%)
4.3.1 Object trap, 33%
4.3.2 Human–technical related, 33%
4.3.3 Maintenance/servicing, 17%
4.3.4 Single for high pressure system, 17%
4.4 Reverse flow, (9%)
4.4.1 Check valve malfunction, 50%
4.4.2 Pressure difference, 50%
4.5 Blockage (fully/partially), (4%)
4.5.1 Valve setting, 100%

5.0 **Corrosion**, 22 out of 234 (9%)
5.1 Contamination, 9 out of 22 (41%)
5.1.1 Corrosive environment-sulfur, 36%
5.1.2 Sea water, 27%
5.1.3 Corrosive environment-chlorine, 18%
5.1.4 Sizing, 9%
5.1.5 Inadequate waterproofing, 9%
5.2 Flow, (23%)
5.2.1 No flow, 38%
5.2.2 Turbulent flow, 25%
5.2.3 Scale/sludge accumulated, 12%
5.2.4 Local attack, 12%
5.2.5 Elbow part, 12%
5.3 Aging deterioration, (14%)
5.3.1 No maintenance/replacement, 75%
5.3.2 External - buried, 25%
5.4 Fabrication/installation, (9%)
5.4.1 Miss match connection, 67%
5.4.2 Local attack, 33%
5.5 Wrong specification, (9%)
5.5.1 Unsuitable construction material, 50%
5.5.2 Thickness, 50%
5.6 Layout/structure, (5%)
5.6.1 Inlet shape, 100%

6.0 **Construction material**, 19 out of 234 (8%)
6.1 Chemical specification, 9 out of 19 (47%)
6.1.1 pH rating, 70%
6.1.2 Incompatibility study, 20%
6.1.3 Wrong wall thickness, 10%
6.2 Mechanical specification, (26%)
6.2.1 Physical & impact rating, 60%
6.2.2 Pressure rating, 40%
6.3 Material miss-match, (11%)
6.3.1 Miss match connection, 50%
6.3.2 Thermal expansion, 50%
6.4 Unsuitable component/part, (10%)
6.4.1 Shape, 50%
6.4.2 Fire rating, 50%

(B) **Reactor accidents**

1.0 **Heat Transfer**, 17 out of 75 (23%)
1.1 Incorrect capacity, 7 out of 17 (41%)
1.1.1 Flow reduce, 38%
1.1.2 Poor mixing, 25%
1.1.3 Emergency setting, 12%
1.1.4 Insufficient detection, 12%
1.1.5 Power failure, 12%
1.2 Hot spot, (29%)
1.2.1 Poor mixing, 40%
1.2.2 Wrong heating sources, 20%

2.0 **Reaction**, 17 out of 75 (23%)
2.1 Unfinished reaction, (35%)
2.1.1 Power failure, 43%
2.1.2 Human–technical related, 29%
2.1.3 Emergency shutdown, 14%
2.1.4 Insufficient acid removal, 14%
2.2 No mixing – two layer, (23%)
2.2.1 Human–technical related, 50%
2.2.2 Motor fail/trip, 33%
2.2.3 Power failure, 17%

1.2.3 Structural/layout/positioning-not covered by liquid, 20%
1.2.4 Excessive heating, 20%
1.3 Human–technical related, (18%)
1.3.1 Excessive heating, 43%
1.3.2 No cooling, 29%
1.3.3 Hold at T high, 29%
1.4 Heat generation/accumulate, (12%)
1.4.1 Unwanted reaction, 100%

2.3 Poor mixing, (12%)
2.3.1 Excessive quantity- high liquid level, 50%
2.3.2 Insufficient automation, 50%
2.4 High charging rate, (12%)
2.4.1 Human–technical related, 67%
2.4.2 Manual handling, 33%
2.5 More reactant, (12%)
2.5.1 Computer & control error, 50%
2.5.2 Volume–density factor, 50%
2.6 Unwanted reaction, (6%)
2.6.1 Contaminations-water, 50%
2.6.2 Incompatibility-heat transfer media, 50%

3.0 **Contamination**, 12 out of 75 (16%)
3.1 Flow in, 6 out of 12 (50%)
3.1.1 Pressure difference, 50%
3.1.2 Human–technical related, 33%
3.1.3 Wall failure/crack, 17%
3.2 Process residue, (42%)
3.2.1 Insufficient draining/drying/removal, 50%
3.2.2 Sticky/gummy material, 33%
3.2.3 Poor cleaning, 17%
3.3 Process change/ upset, (8%)
3.3.1 Process upset- upstream, 100%

4.0 **Human & organizational**, 12 out of 75 (16%)
4.1 Organizational failure, 12 out of 12 (100%)
4.1.1 Lack of analysis, 27%
4.1.2 No procedure/system-double/physical check, 19%
4.1.3 Poor safety culture, 12%
4.1.4 Lack of cleaning/maintenance, 8%
4.1.5 Lack of supervision, 8%
4.1.6 Management of change, 8%
4.1.7 Knowledge based/ignorance, 4%
4.1.8 Lack of inspection/testing, 4%
4.1.9 Poor communication, 4%
4.1.10 Poor planning, 4%
4.1.11 Wrong instruction/reaction data, 4%

(C) **Storage tank accidents**

1.0 **Human & organizational**, 36 out of 108 (33%)
1.1 Organizational failure, 25 out of 36 (69%)
1.1.1 Poor planning, 18%
1.1.2 Lack of analysis, 16%
1.1.3 No procedure-double/physical check, 14%
1.1.4 Improper use of equipment, 10%
1.1.5 Work permitting, 10%
1.1.6 Lack of supervision, 8%
1.1.7 Lack of inspection, 6%
1.1.8 Lack of maintenance, 6%
1.1.9 Contractor management, 4%
1.1.10 Management of change, 4%
1.1.11 Poor communication, 2%
1.1.12 Poor safety culture, 2%
1.2 Human failure, (31%)
1.2.1 Misjudgment, 32%
1.2.2 Not follow procedure, 32%
1.2.3 Knowledge based/ignorance, 21%
1.2.4 Carelessness, 11%
1.2.5 Poor training, 5%

2.0 **Flow related**, 15 out of 108 (14%)
2.1 Human design related, (33%)
2.1.1 Equipment/instrument setting, 40%
2.1.2 Accessibility, 40%
2.1.3 Valve positioning, 20%
2.2 Blockage, (27%)
2.2.1 No venting/vacuum breaker, 43%
2.2.2 Trap/closed condition, 43%
2.2.3 Lack of cleaning, 14%
2.3 Over flow, (20%)
2.3.1 Human–technical related, 67%
2.3.2 Valve setting, 33%
2.4 Fluid movement, (7%)
2.4.1 Transfer mechanism-compressed air, 100%
2.5 Structural/layout, (7%)
2.5.1 Positioning, 100%
2.6 Valve leaking, (7%)
2.6.1 Object trap-water frost then melted, 100%

3.0 **Heat Transfer**, 10 out of 108 (9%)
- 3.1 Heat generation/accumulate, (70%)
  - 3.1.1 Unwanted reaction, 30%
  - 3.1.2 Trap/closed condition, 20%
  - 3.1.3 Ambient heat absorbed, 20%
  - 3.1.4 Structural/layout/positioning-dead end, 10%
  - 3.1.5 Heat tracing, 10%
  - 3.1.6 Friction/impact, 10%
- 3.2 Human–technical related, (20%)
  - 3.2.1 Heating control, 50%
  - 3.2.2 Work sequence, 50%
- 3.3 Incorrect cooling/ heating (capacity), (10%)
  - 3.3.1 Low temperature - heat of vaporization, 100%

4.0 **External factor**, 9 out of 108 (8%)
- 4.1 Earthquake, (67%)
  - 4.1.1 Vibration – mechanical failure, 33%
  - 4.1.2 Floating tank – sloshing, 25%
  - 4.1.3 Vibration-spark generation, 25%
  - 4.1.4 Corrosion, 17%
- 4.2 Freezing, (11%)
  - 4.2.1 Ice – cannot close valve, 50%
  - 4.2.2 Design-single valve, 50%
- 4.3 Heavy rain, (11%)
  - 4.3.1 Floating tank - water got into two pontoons, 50%
  - 4.3.2 Drain line blocked by dust, 50%
- 4.4 Lightning, (11%)
  - 4.4.1 Lack of protection, 100%

(D) **Process vessel accidents**

1.0 **Contamination**, 14 out of 72 (19%)
- 1.1 Flow in, 8 out of 14 (43%)
  - 1.1.1 Human–technical related, 50%
  - 1.1.2 Pressure difference, 38%
  - 1.1.3 Check valve leak, 12%
- 1.2 Accumulated, (22%)
  - 1.2.1 Wear and tear/aging-iron rust, 67%
  - 1.2.2 Iron rust–corrosion, 33%
- 1.3 Process residue, (14%)
  - 1.3.1 Insufficient draining/drying/removal, 100%
- 1.4 Generated, (14%)
  - 1.4.1 Insufficient exhaust/venting, 50%
  - 1.4.2 Unwanted reaction, 50%
- 1.5 Cleaning activity, (7%)
  - 1.5.1 Unsuitable method, 50%
  - 1.5.2 Work sequence, 50%

2.0 **Human & organizational**, 12 out of 72 (17%)
- 2.1 Organizational failure, (83%)
  - 2.1.1 No procedure/system-double/physical check, 32%
  - 2.1.2 Lack of analysis, 21%
  - 2.1.3 Improper used of equipment, 11%
  - 2.1.4 Lack of supervision, 11%
  - 2.1.5 Work permitting, 11%
  - 2.1.6 Lack of cleaning/maintenance, 5%
  - 2.1.7 Poor communication, 5%
  - 2.1.8 Poor planning, 5%
- 2.2 Human failure, (17%)
  - 2.2.1 Not follow procedure, 67%
  - 2.2.2 Poor training, 33%

3.0 **Reaction**, 12 out of 72 (17%)
- 3.1 Unwanted reactions, (75%)
  - 3.1.1 Contaminations, 38%
  - 3.1.2 Formed an explosive gas–air mixture, 31%
  - 3.1.3 Repeated adiabatic compression, 8%
  - 3.1.4 Heat generated/ accumulate, 8%
  - 3.1.5 Human–technical related, 8%
  - 3.1.6 Abnormal heating, 8%
- 3.2 Unfinished reaction, (17%)
  - 3.2.1 High temperature, 100%
- 3.3 Heat generated/accumulate, (8%)
  - 3.3.1 Heat of adsorption-activated carbon, 100%

4.0 **Flow related**, 10 out of 72 (14%)
- 4.1 Human technical related, (30%)
  - 4.1.1 Material charging mechanism, 33%
  - 4.1.2 Confusing utility connection, 33%
  - 4.1.3 Instrument positioning, 33%
- 4.2 Structural/layout, (20%)
  - 4.2.1 Difference level, 50%
  - 4.2.2 Positioning, 50%
- 4.3 Fluid movement, (20%)
  - 4.3.1 Equipment/instrument setting-ventilation, 50%
  - 4.3.2 Speed/rate/velocity, 50%
- 4.4 Valve leaking, (10%)

- 4.4.1 Equipment/instrument setting-drain valve, 50%
- 4.4.2 Siphon- liquid seal in the branch piping broke, 50%

4.5 Over flow, (10%)

- 4.5.1 Capacity/sizing, 100%

4.6 Reverse flow, (10%)

- 4.6.1 Pressure difference, 100%

(E) **Heat transfer equipment accidents**

1.0 **Human & organizational**, 12 out of 74 (16%)

- 1.1 Organizational failure, 8 out of 23 (80%)
  - 1.1.1 Lack of inspection/testing, 25%
  - 1.1.2 No procedure-double/physical check, 19%
  - 1.1.3 Lack of maintenance, 19%
  - 1.1.4 Poor safety culture, 13%
  - 1.1.5 Wrong instruction, 6%
  - 1.1.6 Poor planning, 6%
  - 1.1.7 Management of change, 6%
  - 1.1.8 Lack of analysis, 6%
- 1.2 Human failure, (20%)
  - 1.2.1 Not follow procedure, 75%
  - 1.2.2 Misjudgment, 25%

2.0 **Contamination**, 11 out of 74 (15%)

- 2.1 Flow in, (46%)
- 2.1.1 Wall failure/crack, 44%
  - 2.1.2 Human–technical related, 33%
  - 2.1.3 Lack of detection, 11%
  - 2.1.4 Lack of incompatibility analysis, 11%
- 2.2 Process residue, (18%)
  - 2.2.1 Insufficient draining/drying/removal, 100%
- 2.3 Process change/ upset, (9%)
  - 2.3.1 Lack of analysis, 50%
  - 2.3.2 Modification, 50%
- 2.4 Concentrated, (9%)
  - 2.4.1 Lack of analysis, 50%
  - 2.4.2 Temperature too low, 50%
- 2.5 Cleaning activity, (9%)
  - 2.5.1 Insufficient draining/drying/removal, 50%
  - 2.5.2 Unsuitable method, 50%
- 2.6 Accumulation, (9%)
  - 2.6.1 Wear and tear/aging-iron rust, 50%
  - 2.6.2 Insufficient purging/ removal/ cleaning, 50%

3.0 **Heat transfer**, 11 out of 74 (15%)

- 3.1 Hot spot, (46%)
  - 3.1.1 Structural/layout/positioning, 33%
  - 3.1.2 Flow reduces, 17%
  - 3.1.3 Friction/impact-moving part, 17%
  - 3.1.4 Uneven flow-distribution, 17%
  - 3.1.5 Lack of detection, 17%
- 3.2 Human–technical related, (27%)
  - 3.2.1 Heating empty/wrong tank, 33%
  - 3.2.2 Heat flux-uneven coking prevention, 33%
  - 3.2.3 Excessive cooling/heating, 33%
- 3.3 Thermal expansion, (18%)
  - 3.3.1 Support error, 50%
  - 3.3.2 Repeated rising-lowering of temperature, 50%
- 3.4 Heat generation/accumulate, (9%)

3.4.1 Friction/impact-moving part, 100%

4.0 **Flow related**, 9 out of 74 (12%)

- 4.1 Blockage, (22%)
  - 4.1.1 Scaling, 100%
- 4.2 Fluid movement, (22%)
  - 4.2.1 Capacity/sizing, 33%
  - 4.2.2 Speed/rate/velocity, 33%
  - 4.2.3 Uneven flow, 33%
- 4.3 Human–technical related, (22%)
  - 4.3.1 Equipment/instrument setting, 100%
- 4.4 Valve leaking, (11%)
  - 4.4.1 Single valve & share line, 100%
- 4.5 Structural/layout, (11%)
  - 4.5.1 Shape, 100%
- 4.6 Over flow, (11%)
  - 4.6.1 Capacity/sizing, 100%

(F) **Separation equipment accidents**

1.0 **Contamination**, 15 out of 60 (25%)
- 1.1 Waste oil, 3 out of 15 (20%)
  - 1.1.1 Lack of analysis, 50%
  - 1.1.2 Lack of detection, 50%
- 1.2 Process residue, (20%)
  - 1.2.1 Sticky/gummy material, 50%
  - 1.2.2 Insufficient draining/drying/removal, 25%
  - 1.2.3 Air purging, 25%
- 1.3 Flow in, (20%)
  - 1.3.1 Human–technical related, 67%
  - 1.3.2 Valve setting/leaking, 33%
- 1.4 Generated, (13%)
  - 1.4.1 Unwanted reaction, 67%
  - 1.4.2 Sticky/gummy material, 33%
- 1.5 Cleaning activity, (13%)
  - 1.5.1 Human–technical related, 67%
  - 1.5.2 Unsuitable method, 33%
- 1.6 Process change/ upset, (7%)
  - 1.6.1 Instrument failure, 100%
- 1.7 Concentrated, (7%)
  - 1.7.1 Fluid vaporized, 100%

2.0 **Heat transfer**, 9 out of 60 (15%)
- 2.1 Hot spot, (56%)
  - 2.1.1 Dried condition, 50%
  - 2.1.2 No flow/reduces, 17%
  - 2.1.3 Uneven flow-distribution, 17%
  - 2.1.4 Hold at high temperature, 17%
- 2.2 Human–technical related, (22%)
  - 2.2.1 Valve setting, 50%
  - 2.2.2 Insufficient detection, 50%
- 2.3 Incorrect cooling/ heating (capacity), (22%)
  - 2.3.1 Emergency setting, 50%
  - 2.3.2 Tube blocked, 50%

3.0 **Human & organizational**, 9 out of 60 (15%)
- 3.1 Organizational failure, 6 out of 9 (67%)
  - 3.1.1 The causes are similar to process vessel
- 3.2 Human failure, (33%)
  - 3.2.1 The causes are similar to process vessel

4.0 **Reaction**, 9 out of 60 (15%)
- 4.1 Unwanted reactions, (44%)
  - 4.1.1 Contaminations, 29%
  - 4.1.2 Hold at high temperature/pressure, 29%
  - 4.1.3 Hazardous material accumulate/concentrated, 29%
  - 4.1.4 Chemical reactivity, 14%
- 4.2 Dried condition/ concentrated, (22%)
  - 4.2.1 Higher solvent recovery rate, 25%
  - 4.2.2 Low liquid level, 25%
  - 4.2.3 High heating rate, 25%
  - 4.2.4 More light friction, 25%
- 4.3 Heat generated/ accumulate, (11%)
  - 4.3.1 Unwanted reactions, 50%
  - 4.3.2 Contaminations, 50%
- 4.4 High charging rate, (11%)
  - 4.4.1 Human–technical related, 100%
- 4.5 No mixing, (11%)
  - 4.5.1 Hot spot-wall temperature high, 100%

5.0 **Flow related**, 8 out of 60 (13%)
- 5.1 Blockage, (63%)
  - 5.1.1 Lack of cleaning/purging, 20%
  - 5.1.2 Sticky/gummy material, 20%
  - 5.1.3 Trap/closed condition, 20%
  - 5.1.4 No venting/vacuum breaker, 20%
  - 5.1.5 Human–technical related, 20%
- 5.2 Reverse flow, (25%)
  - 5.2.1 Pressure difference, 50%
  - 5.2.2 Human–technical related, 50%
- 5.3 Fluid movement, (12%)
  - 5.3.1 Capacity/sizing, 100%

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