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Origin of equipment design and operation errors

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ABSTRACT

The paper discusses the origin of chemical process equipment accidents by analyzing past accident cases available in the Failure Knowledge Database (FKD). The design and operation errors of the process equipment that caused the accidents were analyzed together with their time of occurrence. It was found that design errors contributed to 79% of accidents while the rest were only due to human and organizational errors in the operation stage and external factors. The most common types of errors were related to layout, organizational errors in the operation stage, considerations of reactivity and incompatibility, and wrongly selected process conditions (each approx. 13% of total accident contributors). On average there were about 2 design errors per accident. The timing of the errors was quite evenly distributed between various lifecycle stages. Nearly half (47%) of the errors were made in process design-oriented stages, one fourth (26%) in detailed engineering, and one fifth (20%) in operation. In addition, the most frequent design and operation errors for each equipment type were identified. A points-to-look-for list was created for each equipment type, showing also the typical time of occurrence of the error. The knowledge of type and timing of design errors can be utilized in design to focus the hazard analysis in each stage on the most error-prone features of design.

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1. Introduction

Earlier studies in the chemical process industry (CPI) have shown that the contribution of both management & organization and design to accidents is significant (Duguid, 2001; Nivolianitou, Konstandinidou, & Michalis, 2006; Sales, Mushtaq, Christou, & Nomen, 2007; Taylor, 2007). Even though the studies have identified the common contributors to accidents, similar accidents still recur. As pointed out by Kletz (1993) and others (e.g. Jacobsson, Sales, & Mushtaq, 2010; Lindberg, Hansson, & Rollenhagen, 2010), accidents occur due to the poor dissemination of accident information and the lessons learned. Limited research has been done on disseminating information gained from past accidents in such a form that a common user such as a design engineer could employ the knowledge easily.

The current practice in design is to use checklists for various types of equipment and design stages (e.g. CCPS, 1998, 2009) and accident analyses at the end of process design (e.g. Hazop). Both of these are based on human experience only. Bringing statistical

knowledge on errors made from accident databases into practical design use would require a design error point of view: what was wrongly designed or operated and in which stage of the project. Therefore, the aim of this paper is to identify the reasons for errors leading to accidents in design and operation in the CPI, based on accident reports, and also to detect the timing of errors made in projects. The result of the analysis will be summarized as a simple points-to-look-for list for easier utilization.

2. Earlier studies on process equipment accidents

In earlier statistical analyses, the most accident-causing equipment type is piping (on average 24% of accidents), storage tanks (13%), reactors (10%), heat transfer equipment (10%) and pressure vessels (9%), as compiled by Kidam and Hurme (in press).

The contribution of design to accidents is significant (Kidam & Hurme, 2012; Taylor, 2007). At the process equipment level, Drogaris (1991, 1993) claims that design inadequacies are present in about 70% of accidents notified to the EU Major Accident Reporting System (MARS). About 81% of chemical reactor accidents are due to design inadequacies. In chemical plants and refineries, 53% of piping system failures (in which the reason of failure was known) were related to design errors (Blything & Parry, 1984).

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Previously, in our study on process equipment failures (Kidam and Hurme, in press), the majority of accident contributors were technically oriented (78%), including design, analysis, and human–technical interface related faults. A multiple cause of accident approach was used and the accident contributors were analyzed in two categories: as main contributors and all contributors.

Because of the limited availability of design error information on different types of equipment, the paper makes a deeper analysis on the contribution of errors to process equipment accidents. The analysis includes errors in the design stage and human & organizational errors as well as external factors in the operation stage.

3. Research approach

In this paper, process equipment related accident cases from the Failure Knowledge Database (FKD, 2011) were analyzed. 284 cases were found of equipment accidents, concerning six main types of equipment: piping, reactors, storage tanks, process vessels, heat transfer and separation equipment. These types of equipment are responsible for about 80% of equipment-related accidents (Kidam & Hurme, in press).

The analysis covers both the design errors and operational failures of process equipment related accidents. In general, the accident contributors are classified as 1) *organizational & human failures* in chemical plant operation (i.e. operation-based errors), 2) *design errors*, which include failures in design & analysis, the operator–technical interface, design procedures, and designer & organizational failures during the design project (i.e. design-based errors) and 3) *external reasons*. Here, the definition of design error used is a wide one, including as design errors all the design and procedure changes proposed after an accident (Taylor, 1975). The classification of design errors is presented in an earlier paper (Kidam & Hurme, 2012).

The Japanese FKD was selected for the study in order to minimize the problems of insufficient and inaccurate data discussed by Kletz (2009). This accident database covers the most significant accidents all over the world and is managed by experienced academics from Japan under the close monitoring of the Japan & Science Technology (JST) Agency. The accident reports are carefully reviewed by the nominated committee and contain extensive information on the accident. Availability of the technical and engineering information enables the drawing of conclusions from root causes and the timing of the errors made. The basic structure and case expression of the database are well discussed by Hatamura, Iino, Tsuchiya, and Hamaguchi (2003).

4. Reasons for the accidents

The analysis of the design and operational causes of accidents was made based on the FKD data. In total, 661 accident causes were found in the 284 cases for the six main types of equipment. This gives 2.3 causes per accident on average. 224 of the 284 accident cases included equipment design errors (79% of cases). The rest (21%) were due to organizational & human errors in the plant operation stage or external causes.

Next, a study was made on the specific reasons for the accidents. The results are presented in Table 1. As seen from the table, the most common accident causes are: poor layout, organizational error, wrong consideration of chemical reactivity & incompatibility (13% of causes each), wrong process conditions chosen (12%), inadequate protection (11%) and unsuitable construction materials (9%).

The most common causes of *piping system* failures were related to poor layout design (27%) and unsuitable construction materials (22%). Common layout errors include improper piping shape and dead ends. The analysis also highlights the fact that incorrect mechanical and chemical piping specifications (e.g. construction material and wall thickness) increase the probability of piping failure. The contribution of poor operations to piping system failures is also significant, with accidents caused by organizational (16%) and human (9%) error.

For *storage tanks* the most common cause of failure is organizational errors (20%), followed by design errors such as lack of protection (14%), poor layout, usage of unsuitable parts (11% each), and incorrect construction material specifications (9%). Typical organizational failures include poor planning, lack of analysis etc. Protection errors are related to ignition control inside the tank since static electricity is a very common cause of accidents in storage tanks.

The fundamental issue for *reactor* design is an adequate safety analysis, providing the data for safe design. The most critical design errors are chemical reactivity & incompatibility (15%), selection of process conditions (14%), utility set-up (12%), protection system (11%), and automation & instrumentation (10%). Often the design faults are correlated; e.g. chemical reactivity, stability, and incompatibility have cause and effect dependencies with process deviations such as temperature, pressure, contamination or generation of by-products. Incorrect reaction data affects the design decisions on the scale-up of a reactor system, the method of operation selected and the safety limits used. Organizational faults (11%) also affect reactor failures quite often.

Table 1

The distribution of design and operational errors and external causes in process equipment accidents (661 contributors in 284 accidents).

Accident contributors	Piping system		Storage tank		Reactor		Process vessel		Separation eq.		Heat transfer eq.		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Layout	44	27	14	11	9	8	12	11	3	3	7	11	89	13
Organizational failure ^a	26	16	25	20	12	11	10	9	6	7	8	12	87	13
Reactivity/incompatibility	4	2	4	3	17	15	29	26	22	26	7	11	83	13
Process condition	10	6	3	2	16	14	15	14	25	29	13	20	82	12
Protection	9	5	17	14	12	11	19	17	8	9	7	11	72	11
Material of construction	37	22	11	9	5	4	3	3	1	1	3	5	60	9
Utility set-up	1	1	7	6	13	12	4	4	11	13	4	6	40	6
Unsuitable equipment/part	3	2	13	11	7	6	10	9	3	3	3	5	39	6
Human failure ^a	15	9	11	9			2	2	3	3	4	6	35	5
Fab/const/installation	11	7	5	4	2	2	4	4			7	11	29	4
Automation/instrumentation					11	10			3	3	1	2	15	2
External factors ^a	4	2	9	7									13	2
Sizing					5	4	3	3	1	1	1	2	10	2
Operating manual	1	1	3	2	3	3							7	1
Total / overall percentage	165	25	122	18	112	17	111	17	86	13	65	10	661	100

^a in plant operation.

Table 2

Usual design tasks and their timing in the process lifecycle.

Design error and operational failure	Piping system	Reactor	Process vessel	Storage tank	Separation eq.	Heat transfer eq.
Process condition	P	R&D	P	P	P	P
Reactivity & incompatibility	P	R&D	P	P	P	P
Unsuitable equipment/part	D	P/D	P/D	P/D	P/D	P/D
Material of construction	B	B	B	B	B	B
Sizing	B	B	B	B	B	B
Utility set-up	B	B	B	B	B	B
Protection	B	B	B	B	B	B
Automation & instrumentation	B	B	B	B	B	B
Layout	D	B	B	B	B	B
Operating manual	D	D	D	D	D	D
Fab/Const/Installation	C&S	C&S	C&S	C&S	C&S	C&S
External factors	O			O/D		
Organizational failure	O	O	O	O	O	O
Human failure	O	O	O	O	O	O

Note: R&D - Research and Development; P - Preliminary Engineering; B - Basic Engineering; D - Detailed Engineering; C&S - Construction & Start-Up; O - Operations.

The majority of *process vessel* failures are related to the design, mainly chemical reactivity & incompatibility (26%), protection system (17%), process conditions (14%), and layout (11%). Depending on the purpose of the vessel, process contamination may occur because of the desire for process flexibility, sharing or multi-purpose usage and the complex connectivity between process equipment. Process vessels such as dosing systems, holding tanks, buffer tanks, mixing tanks, silos, and blow-down tanks are sometimes used as multi-purpose tanks for more than one chemical. In this case, there is a strong likelihood of process contamination with incompatible materials creating unwanted chemical reactions such as decompositions, polymerizations, and oxidations. The reactions may create a large amount of energy or produce a hazardous chemical, which can trigger an unwanted event, e.g. a vessel rupture, fire, or explosion.

The most significant accident causes in *separation equipment* are associated with selection of process conditions (29%), reactivity & incompatibility of chemicals (26%), and utility set-up (13%). Lack of safety analysis on chemical reactivity and stability is the main cause of separation equipment failures. Hazardous chemicals such as peroxide and nitro compounds can accumulate or concentrate due to recycle, reuse or separation operations. In many cases, these compounds accumulate in specific locations (e.g. on certain trays or at the bottom of a column) and their concentration continues to increase during operation. At a critical concentration, the compound becomes unstable and an unwanted reaction occurs. It can be seen from *Table 1* that the causes of accidents for separation, reaction equipment and process vessels were quite similar and related to reactivity, incompatibility and the process conditions used.

For *heat transfer equipment* the most common design errors are inappropriate process conditions (20%), followed by faults in fabrication & installation, protection system, layout, and chemical reactivity & incompatibility (11% each). Similar to other process

equipment failures, the main problem is the lack of safety analysis during the process and equipment design. Detailed studies on the effect of process deviations and chemical contaminations should be done during process pre-design. Heat transfer equipment is also sensitive to poor operation: several failures are directly caused by organizational (12%) and human (6%) error.

5. The time of errors committed

Next, the design errors found were linked with their time of occurrence in the design project. The design tasks and decisions in a typical design project phase were discussed in detail by *Kidam and Hurme (2012)* and are summarized in *Table 2*. By combining the information on design errors (*Table 1*) and the timing of the design decisions (*Table 2*), it is possible to identify the frequency of design errors in each design stage. The results are presented in *Table 3*.

Table 3 shows that the design errors are mainly located in the R&D and preliminary (21%), basic (26%), detailed (26%), and operation phases (20% of faults). Only a small percentage of design errors originate from construction & start-up (4%) and plant modification (3%). Two thirds of design-related errors are generated at early phases of plant design, which are mainly tasks related to process design, with the remaining one third in detailed engineering. Therefore, correct process design at the beginning is a must for better accident prevention in the CPI. Operation-related human & organizational failures are located in the operations stage (by definition). They account for 20% of all faults leading to an accident.

According to *Table 3*, most faults leading to accidents for separators, process vessels and reactors are created at process design related phases (research & development, preliminary and basic engineering); while storage tanks, piping and heat transfer

Table 3

The time of origin of design and operational accident contributors in the process lifecycle.

Design phases	Piping system		Storage tank		Reactor		Process vessel		Separation eq.		Heat transfer eq.		Total	
R&D and preliminary eng. *	10	6%	8	7%	28	25%	42	38%	41	48%	13	20%	142	21%
Basic engineering *	56	34%	15	12%	31	28%	31	28%	21	24%	16	25%	170	26%
Detailed engineering	45	27%	50	41%	28	25%	21	19%	15	17%	13	20%	172	26%
Construction & start-up	6	4%	7	6%	2	2%	5	5%	0	0%	6	9%	26	4%
Operations – H&O failures	45	27%	39	32%	12	11%	12	11%	9	10%	12	18%	129	20%
Plant modification	3	2%	3	2%	11	10%					5	8%	22	3%
Total	165	100%	122	100%	112	100%	111	100%	86	100%	65	100%	661	100%
Shared of process development & design *		40%		19%		53%		66%		72%		45%		48%

* Denotes the sum of R&D, preliminary and basic engineering phases.

Abbreviations: R&D – research and development; H&O – human and organizational failures.

equipment have more faults at later phases from detailed engineering onwards. The difference is great, since separation equipment has 72% of faults created in the early phases when storage tanks have only 19% (Table 3).

Each type of equipment has its own fault characteristics. Storage tanks and piping are prone to fail due to poor operation. Separation equipment and process vessels have quite similar fault profiles; almost all (>85%) of the faults originate at preliminary, basic and detailed design phases. They are most sensitive to errors in conceptual design (the first stages of design, 48% and 38% respectively). Reactor design is affected greatly by the R&D stage data on chemical reactivity and has relatively many faults based on plant modifications. Piping, reactors and heat transfer equipment are most sensitive to faults in basic engineering. Storage tanks are most sensitive to failures in detailed engineering (41%). Heat transfer equipment has a fairly even distribution of faults over the various design and operation stages. The operation stage is an important accident contributor to storage tank and piping accidents due to the number of organizational failures.

6. Design and operation errors at specific design stages

The most frequent design and operation errors involved in process equipment accidents were identified based on the accident data and presented in Tables 1 and 3. The data was plotted to present the frequency of accident-causing faults in process lifecycle phases, see Fig. 1. This mapping is useful to pinpoint the critical accident contributors of equipment design and provides the typical timing when it occurred during design activity. Dotted lines show the average frequency of errors per error class for each specific design stage and were used as the benchmark. The errors listed above the dotted lines (i.e. higher than average) have a high potential to cause an accident and should be managed early through design changes. Details on accident contributors are given in Appendix 1.

6.1. Piping system

Appendix 1 shows that piping system accident faults occur during basic engineering (34% of faults), where the selection of construction material and mechanical strength is the main problem (55% of faults in basic engineering). Detailed engineering (27% of faults) comes second. Here the problem area is piping layout (69% of faults in detailed engineering). The third is the operation stage (29% of faults), where several types of organizational contributors are the cause (60% of faults in operating stage).

The most common contributors to piping accidents are (Fig. 1) faulty specifications in basic engineering (31 faults), layout design in detailed engineering (31), and organizational failures in the operating phase (29).

Piping design starts in the basic engineering stage, where the process and instrumentation diagrams (PIDs) and the process data for piping schedules are prepared, i.e. the piping is designed from the process engineering point of view. 55% of contributors in basic engineering were related to material selection and mechanical strength problems. To eliminate these, it is most important to give the correct physical, chemical and mechanical specifications for piping. The actual composition of the chemicals used is essential for correct selection of construction material. The effect of process deviations (i.e. temperature, pressure, concentration, and flow-related issues) on piping design should be anticipated. The reactivity of the chemical being processed to the construction material and their corrosion products (i.e. rust) must be evaluated.

27% of piping accident contributors were recorded in detailed engineering. In this phase the piping design is done from the

mechanical and layout engineering viewpoint. The piping isometric drawings and the mechanical design are done based on the process data given in basic engineering. Special care should be given to piping layout, which corresponds to 69% of accident contributors in detailed engineering. Piping layout should also consider piping vibration, liquid hammer and mechanical stress related issues. An important aspect is the uniformity of pipe construction material. If different materials are used, the risk of local corrosion increases.

Although inspections and maintenance planning for by-pass and stand-by pipelines for example are similar to those for main pipelines, less attention is given to them in operation. Thus, unnecessary pipelines should be avoided in design. These design faults could be minimized through a simple piping system with few connections. Complex connectivity is good for plant flexibility but bad for process safety. It increases risk of process contamination and flow-related problems such as reverse flow. Further, all no-flow or dead-end parts of the piping system should be eliminated. They tend to accumulate chemical residues that promote corrosion and unwanted chemical reactions.

In the operation phase, organizational (60%) and human (33%) causes of accidents can be minimized through good safety management systems (e.g. contractor control) and design focusing on error tolerance and user-friendliness. Pipelines and their components should be clearly visible, easily accessible and labeled correctly. For safe chemical transfer, the pipeline structure and valve positioning must be simple and logical. Portable hoses should be easily recognizable, dedicated to a particular process and fixed with specific couplings (i.e. different shape or sizing).

In conclusion, the integrity of the piping system depends on many factors and good design is the key for reliable performance. Generally, most piping layout problems are in principle easily predicted or recognized through proper physical checks. It is strongly suggested that periodic design reviews should be conducted especially on piping to reduce accidents.

6.2. Storage tanks

Most of the accident-causing design faults of the storage tank originate in detailed engineering (41% of faults), as shown by Appendix 1. These are typically related to tank protection (32% of faults in detailed engineering), unsuitable part/component (30%), and internal layout (18%).

The most typical accident-causing faults of storage tanks are (Fig. 1) organizational failures in the operating stage (28 contributors) and protection problems in detailed engineering (16 contributors). 94% of the protection problems concern a lack of nitrogen blanketing or static electricity problems.

The majority of static electricity problems are related to 'buy-item' purchasing such as components of piping or instrumentation. When choosing ready-made items, static electricity issues are often overlooked. The conductivity of the items must be checked, the components should have a low discharge tendency and they should be bonded to other metal parts.

For storage tanks of flammable liquids the risk of fire is very high, if nitrogen blanketing is not available. Spark-generating materials should be avoided, especially if the earthquake risk is considerable. Most likely, sparks are produced due to vibration and vertical movements of liquid (sloshing phenomena) especially in floating roof storage tanks.

Poor mechanical design and civil engineering may cause stress on the storage tank structures. If there are mistakes in the foundation work and support structure, a wall failure is likely to occur. The main failure mode is related to stress corrosion cracking, which is caused either by mechanical stress in the structures or inadequate stress relieving after welding.

The storage tank design is quite straightforward compared to process units. An important issue is the operation phase, which is responsible for a substantial proportion of accident causes (33%). Errors are mainly (66%) related to various organizational failures such as poor planning and lack of analysis, as shown in [Appendix 1](#). Safer storage tank operation can be achieved by minimizing the likelihood of human error through more user-friendly and error-tolerant design. Complicated control systems and confusing operation panels should be eliminated. A competent workforce, clear written work instructions, adequate supervision, and monitoring with appropriate checking on site are basic requirements for safe tank operations.

6.3. Reactors

Causes of reactor accidents are quite evenly distributed throughout the plant lifecycle: accident causes mostly originate from the basic (28%), R&D/preliminary design (25%) and detailed engineering (25%) phases. The design is made based on the reaction chemistry and thermal safety data produced in the research and development phase. Plant operation and modification are responsible for 21% of faults.

Most typical causes are faults in the selection of process conditions (13 faults) and consideration of reactivity or incompatibility (13 faults), both in the R&D phase. The common problem here seems to be the inadequate consideration of process contaminants (14 faults out of 26). Next most common are various organizational failures in operation (12 faults) and in plant modification (11 faults). In the design stages typically the utility set-up is wrong (typically too hot: 8 cases) in basic engineering or there is an automation or instrumentation problem created in detailed engineering (7 faults). Protection problems in design are also common (12 faults altogether). For details see [Appendix 1](#).

The majority of reactor failures in the data analyzed involved batch reactors. Common design errors are related to process scale-up (e.g. heating, cooling, mixing), multi-reaction steps, relief sizing (e.g. single- or two-phase), and servicing required between batches (i.e. cleaning, residue removal, purging). Batch or semi-batch reaction systems have a high safety load because of high inventory, maximum human involvement, and the high number of cycles or batches due to low throughput. Proper heat transfer design is essential, since a number of runaway reactions have been reported due to excessive heating, poor heat removal, and inadequate mixing.

In reactor design, safety evaluation should start early. The design should be based on the worst-case scenario. Detailed safety analysis on thermal safety, process contamination, chemical reactivity, incompatibility and stability are required to generate process information for reactor design and the protection and mitigation system. Focus should be given to the effect of contamination, by-products, impurities, trace and hazardous chemical formation. [Hendershot \(2002\)](#), [Hendershot and Sarafinas \(2005\)](#), and [CCPS \(2009\)](#) proposed several guidelines and examples of safer chemical reaction systems design.

6.4. Process vessels

The design errors in process vessels mostly originate in preliminary engineering (38% of faults), basic engineering (28%), and detailed engineering (19%). The most common accident-causing faults are related to reactivity and incompatibility issues in preliminary engineering (28 faults), protection faults in detailed engineering (12 faults), and organizational failures in operation (10 faults). The reactivity and incompatibility issues represent 67% of faults in preliminary engineering. Therefore, process contamination

and other secondary reactions seem to be a major problem in process vessel design and operation.

Process vessels are relatively simple to design; however, their functions may be complicated e.g. multi-purpose. In many cases, their connectivity with other unit operations is high and complex due to the demand for process flexibility. Therefore unwanted reactions due to process contamination are possible. Moreover, their physical arrangement (e.g. at elevated level) may lead to flow-related problems.

The demand for process flexibility, plant modification, and multiple usage also affects the protection system of the process vessel. During equipment design, the designer may only have considered the main purpose and the main chemicals handled. Later process changes may have been made without upgrading the protection system. Proper design review is needed for a safety and mitigation system, especially for sizing and selecting the type of relief valves.

In an inherent safety approach, the keyword 'minimize' can be used for reducing the risks of process vessel failures. In reactive material handling, a dedicated system is mandatory. Vessel sharing is prohibited unless all chemicals handled are compatible. Minimizing the connectivity between process vessels can reduce the potential of incorrect chemical charging.

6.5. Separation equipment

The accident-causing faults of separation equipment are quite similar to those of process vessels; the most common faults are related in general to reactivity, incompatibility and contamination issues in preliminary engineering (process condition: 22 faults and reactivity & incompatibility: 18 faults) and utility set-up faults in basic engineering (7 faults). Most of the design errors originate in preliminary engineering (48% of faults), basic engineering (24%), and detailed engineering (17%).

The safety of separation equipment suffers from the operation characteristics of reactor systems; complex mixtures of reactor effluents increase the separation and safety load. Low selectivity, excess and un-reacted reactants, impurities, and formation of hazardous trace compounds make the separation system more complex and difficult to design and operate. Analysis of possible process contaminations and their impact at elevated temperature and pressure conditions is crucial for safe design of the separating system. Proper analysis of unwanted reactions should be done to identify and eliminate the formation of hazardous compounds e.g. nitro and peroxide compounds. In the case of hazardous compounds existing in a separation system, systems for detecting their concentration and removing them are required. The key is to keep the concentration low.

Moderation and minimization are the inherent safety keywords, which can be used to reduce the risk of decomposition, polymerization or oxidization of reactive materials. Operating at moderate temperatures and pressures is favored, far away from the critical conditions of the reactive compounds. Operating under vacuum conditions can reduce the temperature of the system. Temperature levels of heating and cooling utilities should be selected properly to prevent excessive temperatures.

6.6. Heat transfer equipment

The main accident-causing faults of heat transfer equipment resemble those of process vessels and separation equipment but have more operation-related errors than reactors. The timing of faults is distributed quite evenly along the lifecycle. Most of the faults originate in the operation & modification phase of the plant (26% of faults), in basic engineering (25%), preliminary engineering (20%), and detailed engineering (20%).

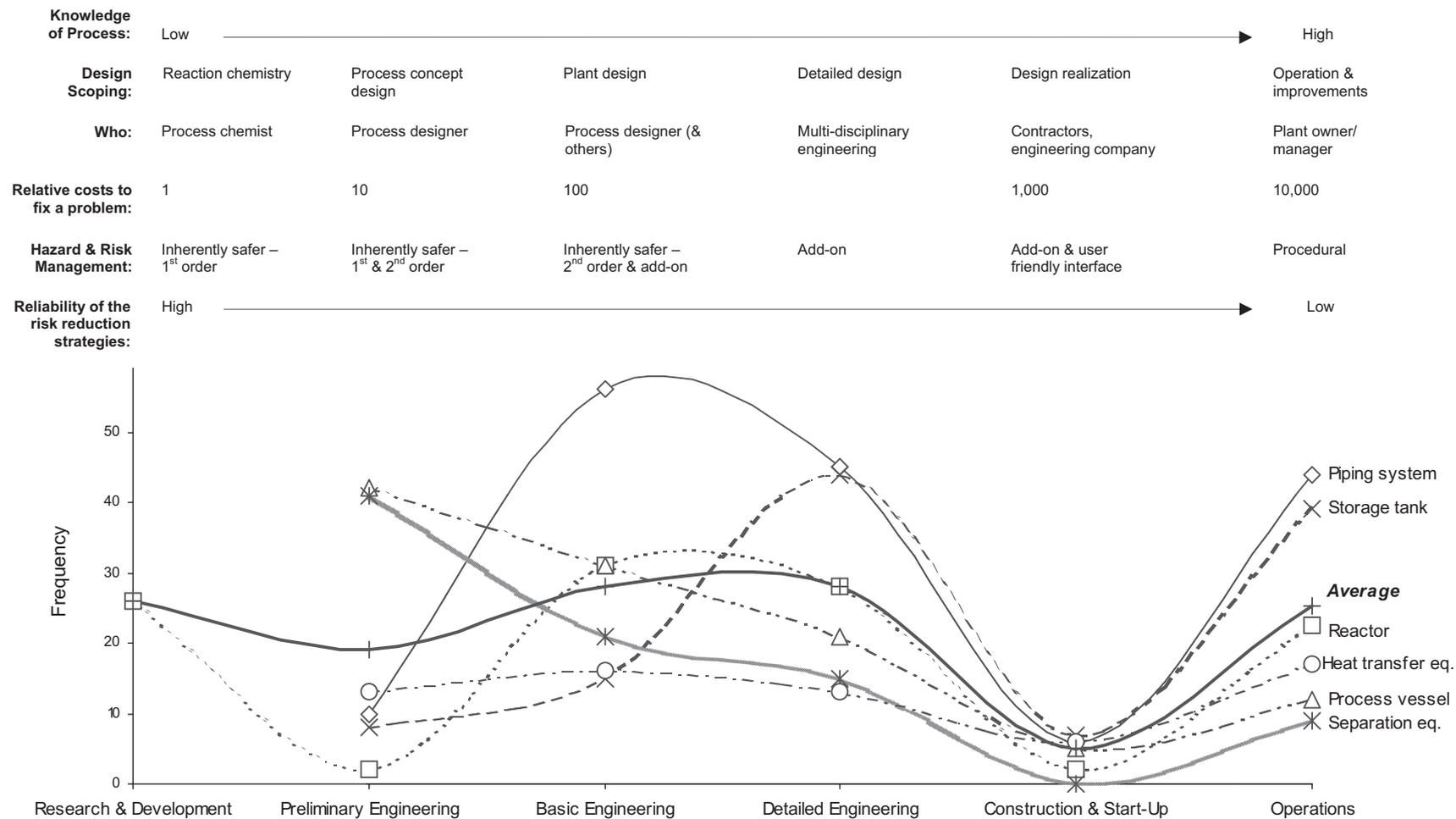


Fig. 2. Timing and frequency of process equipment design and operation errors and typical design stage characteristics.

Table 4

List of most frequent design and operation errors per lifecycle stage for chemical process equipment.

Equipment	Piping system	Storage tank	Reactor	Process vessel	Separation eq.	Heat transfer eq.	All
Process R&D and Pre-design	-Process contaminations, 6		-Reaction with contaminants, 4 -Process contaminations, 3 - Uneven flow/dry condition, 3 - Reactive heat transfer medium, 3	- Reaction with contaminants, 6 - Secondary reaction, 6 - Process contaminations, 6 - Hazardous material generated, 4 - High temperature, 3 - Waste handling, 3 - Friction/impact, 3 - Physical arrangement, 3	- Process contaminants, 7 - Reaction with contaminants, 7 - Secondary reaction, 7	- Process contaminations, 3	- Process contaminants, 26 - Reaction with contaminants, 17 - Secondary reaction, 13
Basic Engineering	- Mechanical specification, 13 - Chemical specification, 11 - Physical arrangement, 9 - Sizing/Thickness, 7 - Shared piping, 4 - Single valve, 3	- Physical arrangement, 3 - Friction/impact, 3 - Flammable sealing/cleaning agent, 3	- Extreme heating/cooling source, 4 - Physical arrangement 4 - Chemical resistance spec, 3 - Lack of detection by automation, 3		- Incompatible heat transfer medium, 3 - Utility set-up: various	- Incompatible heat transfer medium, 3 - Single valve, 2	- Mechanical & chemical spec., 27 - Physical arrangement, 19 - Sizing, 7 - Incompatible heat transfer medium, 6
Detailed Engineering	- Physical arrangement, 9 - Dead end, 8 - Support arrangement, 5 - U-shape, 5 - Flow restriction, 3	- Spark-generating parts, 9 - No nitrogen blanket, 8 - Static electricity, 7 - Non-conductive part, 6	- Setting error, 4 - No nitrogen blanket, 4 - Feeding mechanism, 4 - Maintenance/repair (operating manual), 3 - Welding defect, 2	- Non-explosion-proof, 4 - Static electricity, 4 - No nitrogen blanket, 3	- Static electricity, 3 - No nitrogen blanket, 2 - Sensor failed, 2	- No nitrogen blanket, 2 - Static electricity, 2	- No nitrogen blanket, 19 - Static electricity, 19
Construction & start-up	- Bolt tightening related, 2 - Poor fabrication/construction quality, 2	- Stress concentration, 3		- Poor fabrication/construction quality, 3		- Stress concentration, 4	- Mechanical stress, 7 - Poor fabrication/construction quality, 5
Operation	- Contractor mgt/control, 5 - Lack of maintenance, 5 - No double & physical check, 4 - Work permit related, 3 - Poor mgt system, 3 - No problem-reporting system, 3	- Poor planning, 5 - Lack of maintenance, 5 - Lack of analysis, 4 - Misjudgment, 4 - Not following procedure, 4 - No double & physical check, 4	- Lack of analysis, 3 - No double & physical check, 2	- No double & physical check, 3 - Lack of analysis, 2	- No double & physical check, 2 - Not following procedure, 2	- Not following procedure, 3 - Lack of inspection/testing, 2	- No double & physical check, 15 - Lack of maintenance/inspection/testing, 12 - Lack of analysis, 9 - Not following procedure, 9
Modification			Various, 11			Various, 5	

Note: The numbers show the frequency of accident contributors.

The largest group of accident-causing faults is the selection of process conditions in preliminary engineering (process condition: 10 faults). The second largest group of faults is organizational issues in operation (8 faults).

The main design error of heat transfer equipment is the lack of analysis of possible process deviations (e.g. high temperature) or process change/upgrade (e.g. use of more corrosive feedstock).

Care is needed especially when dealing with heat-sensitive, reactive or incompatible chemicals and heat transfer media. If incompatible chemicals are present, prevention of heat exchanger leaks is critical. In many accident cases, the contact of liquids was caused by less than adequate mechanical or chemical specifications. For heat-sensitive materials it is necessary to assure an even fluid flow in the system and limit wall temperatures, both of which will prevent formation of local hot spots caused either by a too small or uneven fluid flow or high temperature in the liquid film. Inherent safety keywords such as substitution, moderation and error tolerance can reduce the risk of heat transfer equipment failures.

7. Overview of the results and their link to current design practices

The interconnection between accident data and their sources and timing was analyzed based on typical design tasks and their timing (Table 2). Fig. 2 presents the results: the time of origin and the frequency of process equipment accident-causing errors from the process lifecycle standpoint. Some typical characteristics of the design phases have been shown above the figure.

It can be seen that on average the accident-causing errors originate quite evenly at all design stages, as shown by the dark line in Fig. 2. The frequency is less only in the construction and start-up phases. However, specific equipment types have unique characteristics, as followings:

- i. Reactors (when R&D and preliminary stages are combined) and heat transfer equipment present an even profile of contributor frequency similar to the average equipment profile
- ii. Process vessels and separation equipment have a decreasing contributor frequency through the design stages, the maximum being in preliminary engineering
- iii. Piping and storage tanks have a maximum contributor frequency for piping in basic engineering and for storage tanks in detailed engineering.

This implies that the priorities of accident prevention may vary depending on the type of equipment.

8. Most frequent errors and their timing in the plant lifecycle

The results of the analysis are summarized in Table 4, which presents the most common accident-causing design and operating errors for each equipment type and lifecycle stage. The numbers after the accident contributors represent the frequency, how often the error has been present in the accident data. In the rightmost column, the most frequent contributors are listed for each design stage. This general list has been made since there are certain common contributors present for most equipment types.

The main findings are that in the R&D and preliminary design phases the most important contributors are process contaminants and secondary reactions, which cause unexpected reactions and corrosion problems. These are relevant to nearly all types of equipment. Therefore it is important to check the reaction

chemistry and the actual composition of the technical grade of feedstock used.

In basic engineering, the main design errors are mechanical and chemical specifications as well as the physical arrangement of piping and equipment. Lack of knowledge of process chemistry causes a significant amount of design errors in basic engineering too, such as unsuitable selection of construction material. The most common detailed engineering accident contributors are related to flammability i.e. inert gas blanketing and static electricity prevention.

In construction and start-up, the quality of fabrication and prevention of mechanical stress in equipment and piping are important. In the operation phase, lack of physical & double checks and inspection & maintenance are the most critical faults causing a significant amount of equipment failures. In later modifications there are various errors especially regarding reactors. Details can be found in Appendix 1.

The list of most frequent accident-causing errors in Table 4 and the more detailed list in Appendix 1 can be compared with the checklists published by Wells, Seagrave, and Whiteway (1976), CCPS (1998, 2009) and Kletz and Amyotte (2010). The majority of contributors are found in all the lists but Appendix 1 gives a wider spectrum of errors including less common ones. In addition, Table 4 and Appendix 1 provide the frequency of the contributors in earlier accidents, which gives an estimate of their relative importance in accident prevention. The timing of the error in the lifecycle is also given. These two aspects provide the user with additional information compared to the previous checklists.

The aim of the points-to-look-for list (Table 4) and the more complete list in Appendix 1 is to support the designer in checking the aspects that are commonly overlooked, based on accident statistics. Often these aspects have remained undetected in Hazop analyses or have been created after the analysis. The list does not aim to substitute Hazop or other safety methods but tries to complement them by providing a quantitative-based checklist for the designer to be consulted during the design.

9. Discussion and conclusions

The contribution of design and operation errors to process equipment accidents has been studied from the process lifecycle point of view. The paper found that approx. 80% of accidents involved design errors as contributory factors. The errors and their timing are quite characteristic depending on the type of equipment considered. Also, many common errors were found. Quite surprisingly, process contaminants, reactions with them and secondary reactions were the most significant accident contributors for nearly all types of equipment in the early phases of design.

The Shared of design-based contributors is very large in the accidents analyzed, even though safety analysis methods such as Hazop have been used for tens of years. This is partly explained by the fact that the paper used a wide definition of design error; if a technical change was proposed in the accident report, it was concluded that there was a design error present. In addition, human error due to engineering and human–technical interface errors in operation were classified as design errors. On average, there were nearly two (1.9) design errors per accident and 0.5 other accident contributors (i.e. operation-related organizational or human failures or external reasons). Nearly half (47%) of the accident contributors were generated in process design oriented design stages, one fourth (26%) in detailed engineering, and one fifth (20%) in operation. Plant modifications accounted for very little (3%).

Although the large Shared of design errors can be partly explained by the definition of design error used, it is still obvious that the existing safety analysis methods do not find all design errors. Therefore a points-to-look-at list (and a more detailed list

as in Appendix 1) was created, presenting the frequency of accident-causing design and operation error categories in the typical stages of a design project. The list was made for the six most common types of equipment, which cover about 80% of accidents. It can provide quantitative support in searching for potential design errors during a project. The list guides the designer to pinpoint the

most accident-prone decisions and their timing in a project. The early correction of errors is known to have large safety-cost benefits, since it allows better implementation of inherently safer conceptual design principles (hazard reduction) instead of added-on protective systems, which reduce risk but do not reduce the hazard.

Appendix 1. Details of accident-causing design and operation errors of equipment.

A) Piping; 165 out of 661 errors (25%)

Preliminary Eng., 10/165 (6%)

- Process Condition, 7/10 (70%)
 - Process contaminations, 86%
 - More corrosive, 14%
- Reactivity/incompatibility, 30%
 - Incompatible raw material, 33%
 - React with contaminants, 33%
 - Unstable at high temperature, 33%

Basic Eng., 56, 34%

- Construction Material, 55%
 - Mechanical spec, 42%
 - Chemical resistance spec, 35%
 - Sizing/Thickness, 23%
- Layout, 23%
 - Physical arrangement, 69%
 - Shared piping, 31%
- Protection, 11%
 - Single valve, 50%
 - No check valve, 33%
 - No insulation, 17%
- Installation, 4%
 - No insulation, 100%
- Process Condition, 4%
 - Flow velocity, 100%
- Reactivity/incompatibility, 2%
 - Reactive with cleaning agent, 100%
- Unsuitable Equipment/Part, 2%
 - Small volume, 100%

B) Storage tanks; 122 out of 661 (18%)

Preliminary Eng., 8/122 (7%)

- Process Condition, 3/8 (38%)
 - High temperature, 33%
 - More corrosive, 33%
 - Store at high temperature, 33%
- Reactivity/incompatibility, 38%
 - Contaminated/reactive waste, 33%
 - Heat generated, 33%
 - Secondary reaction, 33%
- Construction Material, 13%
 - React with content, 100%
- Unsuitable Equipment/Part, 13%
 - Open storage, 100%

Basic Eng., 15, 12%

- Utility Set-up, 33%
 - Flammable sealing/cleaning agent, 60%
 - Extreme heating/cooling source, 40%
- Layout, 27%
 - Physical arrangement, 75%
 - Single valve, 25%
- Construction Material, 20%
 - Friction/impact, 100%
- Unsuitable Equipment/Part, 13%
 - Mechanical spec, 50%
 - Wrong absorption system, 50%
- Protection, 7%
 - No flame arrester, 100%

Detailed Eng., 45, 27%

- Layout, 69%
 - Physical shape error, 29%
 - Dead end, 26%
 - Support arrangement, 16%
 - U-shape, 16%
 - Flow restriction, 10%
 - Vertical positioning, 3%
- Construction Material, 9%
 - Thermal expansion, 50%
 - Fire rating, 25%
 - Non-conductive material, 25%
- Protection, 7%
 - No coating/painting, 67%
 - Drain without cap, 33%
- Installation, 7%
 - No coating/painting, 33%
 - Support arrangement, 33%
 - Wrong connection, 33%
- Unsuitable Equipment/Part, 4%
 - Shape miss-match, 100%
- Utility Set-up, 2%
 - Direct connection, 100%
- Operating Manual, 2%
 - Cleaning procedure, 100%

Detailed Eng., 50, 41%

- Protection, 32%
 - No nitrogen blanket, 50%
 - Static electricity, 44%
 - Non-explosion proof, 6%
- Unsuitable Equipment/Part, 30%
 - Spark generation part, 60%
 - Sampling tools, 20%
 - Non-conductive part, 13%
 - Part positioning, 7%
- Layout, 18%
 - Support arrangement, 33%
 - Dead end, 22%
 - Venting shape, 22%
 - Trap condition, 11%
 - Venting positioning, 11%
- Construction Material, 12%
 - Non-conductive material, 100%
- Operating Manual, 6%
 - Waste handling, 67%
 - Transfer mechanism, 33%
- Utility Set-up, 2%
 - No vacuum/exhaust, 100%

Construction & Start-Up, 7, 6%

- Fab/Const/Installation, 71%
 - Stress concentration, 60%
 - Foundation weak, 20%
 - Welding defect, 20%
- Unsuitable Equipment/Part, 14%
 - Poor/under construction, 100%
- Utility Set-up, 14%
 - Poor/under construction, 100%

Construction & Start-Up, 6, 4%

- Fab/Const/Installation, 100%
 - Bolt tightening related, 33%
 - Poor fab/const quality, 33%
 - Support weak, 17%
 - Stress concentration, 17%

Operations & Modification, 48, 29%

- Organizational failure, 60%
 - Contractor management, 17%
 - Lack of maintenance, 17%
 - Work permitting, 10%
 - Poor management system, 10%
 - No procedure- problem reporting, 10%
 - Lack of inspection, 7%
 - Poor communication, 7%
 - Poor planning, 7%
 - Lack of supervision, 5%
 - Poor safety culture, 5%
 - Management of change, 3%
- Human failure, 33%
 - No double/physical check, 25%
 - Misjudgment, 14%
 - Not following procedure, 14%
 - Poor training, 14%
 - Poor/wrong instruction, 14%
 - Carelessness, 6%
 - Work permitting, 6%
 - Improper use of equipment, 6%
- Plant Modification, 7%
 - M-Mechanical spec, 33%
 - M-Thermal expansion, 33%
 - M-Process contaminations, 33%

Operations & Modification, 42, 33%

- Organizational failure, 66%
 - Poor planning, 18%
 - Lack of maintenance, 18%
 - Lack of analysis, 14%
 - No double/physical check, 14%
 - Improper use of equipment, 10%
 - Work permitting, 10%
 - Lack of supervision, 8%
 - Lack of inspection, 4%
 - Contractor management, 2%
 - Management of change, 2%
- Human failure, 28%
 - Misjudgment, 32%
 - Not following procedure, 32%
 - Knowledge based/ignorance, 21%
 - Carelessness, 11%
 - Poor training, 5%
- Plant Modification, 7%
 - L-Trap condition, 33%
 - M-React with content, 33%
 - R-Hazardous material generated, 33%

C) Reactors; 112 out of 661 (17%)

R&D, 26/112 (23%)

Process Condition, 13/26 (50%)
 Process contaminations, 23%
 Uneven flow/dry condition, 23%
 High temperature, 15%
 More corrosive, 15%
 Hold too long, 8%
 Unbalance reactant ratio, 8%
 Wrong reaction data, 8%
 Reactivity/incompatibility, 50%
 React with contaminants, 31%
 Reactive heat transfer medium, 23%
 Unstable at high temperature, 15%
 Heat generated, 8%
 Incompatible raw material, 8%
 Reactive with cleaning agent, 8%
 Unstable in dry condition, 8%

Preliminary Eng., 2, 2%

Unsuitable Equipment/Part, 100%
 Measurement error, 50%
 Mixing effects, 50%

Basic Eng., 31, 28%

Utility Set-up, 26%
 Extreme heating/cooling source, 50%
 Incompatible heat transfer medium, 25%
 No mixing effects, 13%
 Sharing cooling source, 13%
 Protection, 19%
 Single valve, 33%
 No check valve, 17%
 No gas treatment, 17%
 No relief valve, 17%
 No vacuum breaker, 17%
 Layout, 16%
 Physical arrangement, 80%
 Shared piping, 20%
 Construction Material, 16%
 Chemical resistance spec, 60%
 Non-conductive material, 20%
 Sizing/Thickness, 20%
 Automation/Instrumentation, 10%
 Lack of detection, 100%

Sizing, 10%

Small venting, 67%
 Normal condition sizing, 33%
 Unsuitable Equipment/Part, 3%
 Heating/cooling error, 100%

D) Process vessels; 111 out of 661 (17%)

Preliminary Eng., 42/111 (38%)

Reactivity/incompatibility, 28/42 (67%)
 React with contaminants, 21%
 Secondary reaction, 21%
 Hazardous material generated, 14%
 Contaminated/reactive waste, 11%
 Heat generated, 7%
 Incompatible raw material, 7%
 Unstable at high temperature, 7%
 Unstable new material, 4%
 Unstable off-spec product, 4%
 Water reactive, 4%
 Process Condition, 31%
 Process contaminations, 46%
 High temperature, 23%
 Hold too long, 8%
 More corrosive, 8%
 More reactant, 8%
 Secondary reaction, 8%
 Unsuitable Equipment/Part, 2%
 Open tank, 100%

Basic Eng., 31, 28%

Protection, 23%

Detailed Eng., 28, 25%

Automation/Instrumentation, 25%
 Setting error, 57%
 No interlock, 29%
 Sensor failed, 14%
 Protection, 21%
 No nitrogen blanket, 67%
 Static electricity, 33%
 Layout, 14%
 Venting positioning, 50%
 Direct connection, 25%
 Similar appearance, 25%
 Unsuitable Equipment/Part, 14%
 Feeding mechanism, 100%
 Operating Manual, 11%
 Maintenance/repair, 100%
 Utility Set-up, 11%
 Difficult to clean, 33%
 Positioning, 33%
 Power failure - no back up, 33%
 Sizing, 4%
 Size miss-match, 100%

Detailed Eng., 21, 19%

Protection, 57%
 Non-explosion proof, 33%
 Static electricity, 33%
 No nitrogen blanket, 25%
 Aging/tear & wear, 8%
 Layout, 33%
 Dead end, 29%
 Vertical positioning, 29%
 Physical shape error, 14%
 U-shape, 14%
 Venting shape, 14%
 Sizing, 5%
 Size miss-match, 100%
 Unsuitable Equipment/Part, 5%
 Non-conductive part, 100%

Construction & Start-Up, 2, 2%

Fab/Const/Installation, 100%
 Welding defect, 100%

Operations & Modification, 23, 21%

Organizational failure, 52%
 Lack of analysis, 27%
 No double/physical check, 19%
 Poor safety culture, 12%
 Lack of cleaning/maintenance, 8%
 Lack of supervision, 8%
 Management of change, 8%
 Knowledge based/ignorance, 4%
 Lack of inspection/testing, 4%
 Poor communication, 4%
 Poor planning, 4%
 Wrong instruction/reaction data, 4%
 Plant Modification, 48%
 R-Contaminated/reactive waste, 9%
 R-Hazardous material generated, 9%
 R-React with contaminants, 9%
 R-Secondary reaction, 9%
 PC-Effect of by-product, 9%
 PC-Process contaminations, 9%
 PC-Wrong reaction data, 9%
 US- Extreme heating/cooling source, 9%
 US-Incompatible heat transfer medium, 9%
 A-Setting error, 9%
 S-Smaller after modify, 9%

Construction & Start-Up, 5, 5%

Fab/Const/Installation, 80%
 Poor fab/const quality, 75%
 Stress concentration, 25%
 Unsuitable Equipment/Part, 20%
 Poor/under construction, 100%

Operations, 12, 11%

Organizational failure, 83%
 No double/physical check, 32%
 Lack of analysis, 21%
 Improper used of equipment, 11%
 Lack of supervision, 11%
 Work permitting, 11%
 Lack of cleaning/maintenance, 5%
 Poor communication, 5%
 Poor planning, 5%
 Human failure, 17%
 Not following procedure, 67%
 Poor training, 33%

continued on next page

Appendix (continued)

Friction/impact, 43%
 Single valve, 29%
 No check valve, 14%
 No flame arrester, 14%
 Unsuitable Equipment/Part, 23%
 Miss-used, 29%
 Chemical resistant spec, 14%
 Difficult to clean, 14%
 Lack of vacuum/exhaust, 14%
 Mechanical spec, 14%
 Small volume, 14%
 Layout, 16%
 Physical arrangement, 60%
 Positive isolation, 20%
 Shared piping, 20%
 Utility Set-up, 13%
 Extreme heating/cooling source, 25%
 No cooling/natural, 25%
 Single valve, 25%
 Waste handling, 25%
 Construction Material, 10%
 Sizing/Thickness, 67%
 Chemical resistance spec, 33%
 Process Condition, 6%
 Inadequate ventilation/exhaust, 100%
 Sizing, 6%
 Small overhead volume, 50%
 Small volume, 50%
 Reactivity/incompatibility, 3%
 Reactive with cleaning agent, 100%
 E) Separation equipment: 86 out of 661 (13%)
Preliminary Eng., 41/86 (48%)
 Process Condition, 54%
 Process contaminations, 32%
 Secondary reaction, 18%
 Hazardous material generation/accumulation, 9%
 High temperature, 9%
 Hold too long, 9%
 Uneven flow/dry condition, 9%
 Effect of physical condition, 5%
 More reactant, 5%
 Store at high temperature, 5%
 Reactivity/incompatibility, 44%
 React with contaminants, 39%
 Secondary reaction, 17%
 Hazardous material generated, 11%
 Heat generated, 11%
 Contaminated/reactive waste, 6%
 Unstable at high temperature, 6%
 Unstable by-product, 6%
 Unstable in dry condition, 6%
 Protection, 2%
 No inhibitor, 100%
Basic Eng., 21, 24%
 Utility Set-up, 33%
 No cooling/natural, 29%
 Blockage-gummy material, 14%
 Corrosive heat transfer medium, 14%
 Incompatible heat transfer medium, 14%
 Incompatible purging medium, 14%
 Normal condition sizing, 14%
 Reactivity/incompatibility, 19%
 Reactive heat transfer medium, 75%
 Reactive with cleaning agent, 25%
 Process Condition, 14%
 Inadequate ventilation/exhaust, 100%
 Protection, 10%
 No check valve, 50%
 Single valve, 50%
 Unsuitable Equipment/Part, 10%
 Lack of sensor, 50%
 Waste handling, 50%
 Automation/Instrumentation, 5%
 Lack of detection, 100%

Detailed Eng., 15, 17%

Protection, 33%
 Static electricity, 60%
 No nitrogen blanket, 40%
 Utility Set-up, 20%
 Difficult to clean, 33%
 Positioning, 33%
 Power failure - no back up, 33%
 Automation/Instrumentation, 13%
 Sensor failed, 100%
 Layout, 13%
 Dead end, 50%
 Positive isolation, 50%
 Construction Material, 7%
 Non-conductive material, 100%
 Sizing, 7%
 Small venting, 100%
 Unsuitable Equipment/Part, 7%
 Non-conductive part, 100%

Operations, 9, 10%

Organizational failure, 67%
 No double/physical check, 32%,
 Lack of analysis, 21%,
 Improper used of equipment, 11%,
 Lack of supervision, 11%,
 Work permitting, 11%,
 Human failure, 33%
 Not following procedure, 67%,
 Poor training, 33%,

Layout, 5%
 Physical arrangement, 100%
 Sizing, 5%
 Small volume, 100%
 F) Heat transfer equipment; 65 out of 661 (10%)
Preliminary Eng., 13/65 (20%)
 Process Condition, 10/13 (77%)
 Process contaminations, 30%
 Effect of physical condition, 10%
 High pressure, 10%
 High temperature, 10%
 Hold too short, 10%
 Long usage/aging, 10%
 More corrosive, 10%
 Uneven flow/dry condition, 10%
 Reactivity/incompatibility, 15%
 Contaminated/reactive waste, 50%
 Unstable at high temperature, 50%
 Protection, 8%
 Reactive with iron rush, 100%
Basic Eng., 16, 25%
 Utility Set-up, 19%
 Incompatible heat transfer medium, 100%
 Protection, 19%
 Single valve, 67%
 Friction/impact, 33%
 Reactivity/incompatibility, 19%
 Reactive heat transfer medium, 67%
 Reactive with cleaning agent, 33%
 Layout, 13%
 Physical arrangement, 50%
 Shared piping, 50%
 Installation, 6%
 Lack of detection, 100%
 Construction Material, 6%
 Mechanical spec, 100%
 Process Condition, 6%
 Flow velocity, 100%
 Sizing, 6%
 Small volume, 100%
 Unsuitable Equipment/Part, 6%
 Waste handling, 100%

Detailed Eng., 13, 20%
 Protection, 31%
 No nitrogen blanket, 50%
 Static electricity, 50%
 Layout, 31%
 Accessibility, 25%
 Dead end, 25%
 Too closed, 25%
 Vertical positioning, 25%
 Unsuitable Equipment/Part, 15%
 Feeding mechanism, 50%
 Spark generation part, 50%
 Automation/Instrumentation, 8%
 Uneven speed, 100%
 Construction Material, 8%
 Thermal expansion, 100%
 Process Condition, 8%
 Inadequate ventilation/exhaust, 100%

Construction & Start-Up, 6, 9%
 Fab/Const/Installation, 100%
 Stress concentration, 67%
 Bolt tightening related, 17%
 Welding defect, 17%
Operations & Modification, 17, 26%
 Organizational failure, 47%
 Lack of inspection/testing, 25%,
 No double/physical check, 19%,
 Lack of maintenance, 19%,
 Poor safety culture, 13%,
 Wrong instruction, 6%,
 Poor planning, 6%,
 Management of change, 6%,
 Lack of analysis, 6%,
 Plant Modification, 29%
 L-Flow restriction, 20%
 M-Mechanical spec, 20%
 PC-Uneven flow/dry condition, 20%
 R-React with contaminants, 20%
 US-Flow restriction, 20%
 Human failure, 24%
 Not following procedure, 75%,
 Misjudgment, 25%,

Notation for Plant Modification category: A – Automation & instrumentation; L – Layout; M – Material of construction; PC – Process condition; R – Reactivity & incompatibility; S – Sizing; US – Utility set-up.

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